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Viability Of Hybrid Ground Source Heat Pump System With Solar Thermal Collectors

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VIABILITY OF HYBRID GROUND SOURCE HEAT PUMP SYSTEM WITH SOLAR THERMAL COLLECTORS

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Abstract

This thesis presents a study for examining the viability of hybrid ground source heat pump (GSHP) systems that use solar thermal collectors as the supplemental component in heating dominated buildings. Loads for an actual house in the City of Milton near Toronto were estimated. TRNSYS, a system simulation software tool, was used to model the yearly performance of conventional GSHP as well as the proposed hybrid GSHP system.

The house was equipped with a data monitoring system which was installed to read and record fluid flow, temperature and electricity consumption in different components of the system. The actual yearly data collected from the site was examined against the simulation results. In addition, a sensitivity analysis was carried out to determine the relationship between the solar collector area and the ground loop heat exchanger (GHX) length. It was shown that the ratio of GHX length reduction to solar panel area of 4.7 m/m^2 results in the optimum ratio, which corresponds to 32 m GHX length reduction with a 6.81m^2 solar collector area.

This study demonstrates that a hybrid GSHP system, combined with solar thermal collectors, is a feasible choice for space conditioning for heating dominated houses. It was shown that the solar thermal energy storage in the ground could reduce a large amount of ground loop heat exchanger length. Combining three solar thermal collectors with a total area of 6.81m^2 to the GSHP system will reduce GHX length by %15 (from 222 m to 188 m). System malfunctioning in the cooling season was also detected, and options for fixing the problem were presented. A sensitivity analysis was carried out on different cities in Canada, and results demonstrated that Vancouver, with the mildest climate compared to other cities, was the best candidate for the proposed solar hybrid GSHP system with 7.64 m/m^2 GHX length reduction to solar collector area ratio. Overall system economical viability was also evaluated using a 20-year life-cycle cost analysis. The analysis showed that there is a economic benefit in comparing to GSHP. The net present value of the proposed hybrid system and GSHP system were estimated to be $44,834 and $41,406, respectively.

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Nomenclature

GHP	Ground Source Heat Pump
GHX	Ground Loop Heat Exchanger
SAGSHP	Solar Assisted Ground Source Heat Pump
BNL	Brookhaven National Laboratory
GROCS	Ground Coupled System
SESHPS	Solar-Earth Heat Pump System
SAHP	Solar Assisted Heat Pump
SSHP	Solar Energy Source Heat Pump
SGSHP	Solar-Ground Source Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
UTES	Under Ground Thermal Storage
TMY	Typical Meteorological Year
ASHREA	American Society of Heating, Refrigeration and Air-Conditioning
IGSHPA	International Ground Source Heat Pump Association
USGPM	US Gallon per Minute
COP	Coefficient of Performance
RSI-value	Thermal Resistance to Heat Flow- SI Unit
R-value	Thermal Resistance to Heat Flow- Imperial Unit
ACH	Air Change per Hour
HDD	Heating Degree Day
CDD	Cooling Degree Day
HRV	Heat Recovery Ventilation
Pa	Pascal
GJ	Giga Joules
MJ	Mega Joules
kW	Kilo-Watt
DB	Dry Bulb
WB	Wet Bulb
RH	Relative Humidity

DHW	Domestic Hot Water
UA	Overall Heat Transfer Coefficient
EFF	Efficiency
EFT	Entering Fluid Temperature
IAM	Incident Angel Modifier
Q	Energy Transfer, J
q	Heat Transfer Rate, W
atm	Atmosphere
l_T	Global Radiation Incident, kJ/h-m^2
a_0	Intercept efficiency
a_1	Efficiency Slope
a_2	Efficiency Curve
b_0	First Order Incident Angel Modifier
b_1	Second Order Incident Angel Modifier
C_p	Specific Heat at Constant Pressure, J/kg.K
ρ	Mass Density, kg/m^3
ν	Kinematic Viscosity, m^2/s
α	Thermal Diffusivity, m^2/s
β	Volumetric Thermal Expansion, 1/K
Pr	Prandtl Number
Ra	Rayleigh Number
T	Temperature, °C
Nu	Nusselt Number
h	Convective Heat Transfer Coefficient, W/m^2.K
$\dot{m}$	Flow Rate, m/s
y	Solar Collector- Heat Pump Flow Fraction

Chapter 1

Introduction

1.0 Introduction

The claimed advantages of ground-source heat pump (GSHP) systems over their conventional alternatives, such as air-source and water source heat pumps make these systems attractive for space heating and air conditioning for residential and commercial as well as institutional buildings. GSHP, which exchange heat to and from the underground environment to provide cooling and heating, have an increasing number of applications, such as space heating and cooling, water heating, crop drying, agricultural greenhouse, housing facilities, and so on. The primary advantage of ground source/sink versus air source/sink is that the underground environment has a more moderate temperature swing than the ambient air temperature and, therefore, has a better thermodynamic advantage. Having an underground thermal source incurs a higher initial cost, and must be offset by reduced operating costs leading to a lower life cycle cost.

Geothermal applications for buildings are mostly limited to full dependence on ground soil temperatures for 100% of the heating and cooling energy. Although there are advantages of low energy and maintenance costs in favour of this approach, space limitations and high initial costs may restrict a full geothermal installation. Restrictive regulations, such as mandating a minimum borehole size, grouting materials, wage rates and heat exchange methods, generally increase the cost of such a system. The initial cost may put the project above the budget, and in some cases, the drilling conditions may prevent the use of a large conventional closed-loop bore field [1, 2].

In many buildings, annually, the amounts of heat extracted from and injected into the ground are not balanced. The vertical closed-loop is a common type of earth coupling mostly used in buildings that have limited land areas. In designing this type of system, consideration must be made of the thermal response of the ground throughout the expected project life (i.e., 25 years). An annual imbalance in ground load will lead to lower heat pump entering fluid temperatures (EFT) in heating-dominated buildings, or higher heat pump EFT in cooling-dominated buildings, to a point where equipment capacity may be compromised if the ground loop heat exchanger is not large enough. This imbalance requires either a very large ground loop heat exchanger or some mechanism for assisting the system by supplementing deficit heat or rejecting excess heat.

Because the cost of installing a very large ground loop heat exchanger may be excessive, there are a number of alternate ways to assist a GSHP. These include a solar collector, which injects additional heat into the ground for heating dominated buildings, and a cooling tower, which rejects excess heat into the atmosphere for cooling dominated buildings [3]. Systems that incorporate both a ground heat exchanger and an above-ground heat exchanger are commonly referred to as hybrid GSHP. In hybrid systems, the peak heat pump EFTs from year-to-year should be approximately equal. In this study, the system utilizes a solar thermal collector as an above- ground heat exchanger, called a solar assisted ground source heat pump (SAGSHP).

1.1 Benefits of Solar Assisted Ground Source Heat Pump Systems

When using a GSHP system that would not cover the heating and cooling load of a building, utilizing a hybrid system makes sense in order to benefit from GSHP systems with the assistance of other systems, such as solar thermal systems. The GSHP itself has several advantages over other systems [4], and combining it with other sources of energy, such as solar thermal, enhances the advantages.

Compared with other heating and cooling systems, it is possible to achieve significant energy savings. This is due to its use of a free resource of heat stored in the ground, solar energy and its high efficiency.

While most GSHP systems are initially more expensive than conventional building heating and cooling systems, their maintenance costs are generally lower, and their very high efficiency results in low operating costs. As a result, they can be the most cost effective heating and cooling system on a life-cycle cost basis.

GSHP require less space than conventional heating and cooling systems. Heating and cooling only requires one unit. In large buildings, where a conventional system would require voluminous air ducts to transport heating and cooling from a central plant to the extremities of the building, a compact liquid loop can be used to transport heat between the ground and multiple, smaller heat pumps scattered around the building.

The GSHP generally provides a more comfortable interior environment and better air quality than conventional heating and cooling systems. There are a number of reasons for this. The temperature of the air heated by a GSHP tends to be lower than that of a combustion system, and the volume of heated air is higher. In addition, in cooling mode, better air quality results from increased removal of humidity [4].

The cooling surfaces of a GSHP are often kept at a lower temperature than those of air-source heat pumps and conventional air conditioners; more water vapour condenses on these colder surfaces, reducing humidity levels.

A final advantage of GSHP is reduced peak electricity consumption during summer time. During this season, peak loads generally coincide with periods of high cooling loads, so GSHP, which are more efficient than conventional systems due to the relative constant sink temperature of the ground, can lower peak electricity load charges levied on commercial or industrial buildings, and can reduce strain on the electric network.

In addition to the above-motioned advantages, more savings can be realised when the GSHP systems provides part of the heating and cooling load along with other renewable energy sources.

The combination of solar collectors with ground-coupled heat pumps is a relatively recent development. There are two reasons for combining solar collectors with ground-coupled heat pumps: (1) the ground can act as a convenient and low-cost heat storage device for solar energy, and (2) by using the ground and solar collectors as heat sources together with a heat pump to upgrade ground heat to those high enough for space heating. Relative to reason (1), the ground could act as a seasonal storage device for solar energy. This would allow ample storage of solar energy during the summer for use in heating during the winter. Relative to reason (2), solar collectors can be operated at lower temperatures and thus higher efficiencies than if they were used directly for space heating or water heating.

1.2 Disadvantages of SAGSHP Systems

As heat is extracted from the deep ground (50 to150 m) under the earth's surface by a heat pump, and with the need for the sun's radiation for solar thermal panels, the main disadvantage is related to finding a suitable building location. Initial installation cost for this system is up to 2.5 times as expensive as other types of equipment, due to the cost of installing a ground heat exchanger and solar panels [2].

In solar thermal assisted GSHP, a very sophisticated control system is required for switching or redirecting the solar energy. This happens when the extra heat, usually during the summer, would be against the system's functionality. Dumping unwanted heat to the ground would be another issue that must be dealt with properly. Finally, not all air conditioning contractors are familiar with this technology.

1.3 Purpose and Goal of Research

The purpose of this study was to evaluate the performance and viability of hybrid geothermal heat pump systems with solar thermal collectors. The main objective was to perform a system simulation approach to assess the feasibility of this kind of hybrid systems in heating dominated buildings. An actual residential building was modelled and the results compared to the actual data collected by monitoring the related operation of equipments through specific months. It would be ideal if this study attracts the interest of researchers and contractors, and provides valuable information for designing and installing this kind of hybrid system in heating dominated buildings in Canada.

1.4 Scope of Work and Approach to Research

An existing residential house near Toronto was chosen and constructed as an energy efficient house, using a SAGSHP for heating and cooling. The as-built mechanical system of the house was not functioning in the cooling season. The house was modelled in TRNSYS 16 [5] and HOT2000 [6], and the results validated and compared to each other, as well as with the actual data derived from monitoring the operation of such system.

The study consisted of the following tasks:

1- Modeling the house in TRNBuild (a part of TRNSYS) to generate annual heating and cooling loads of the house, and to compare the simulation results with HOT2000 simulation results and to discuss reason for any deviations.
2- Modeling the SAGSHP system in TRNSYS software.
3- Finding the unknown parameters in the as-built system design, such as soil thermal conductivity, percentage of ground loop fluid diversion to solar collectors and system configuration and specifications.
4- Field study and verification of the SAGSHP system to validate this study. Detecting the problem of the existing system in the cooling season and suggesting solutions to resolve it.

5- Conducting a sensitivity analysis by varying the thermal conductivity of the ground and discussing the effects of this parameter in system design.
6- Finding an optimum fluid flow to the solar thermal panels in order to get the highest efficiency of the system in heating season, and proposing an improved system configuration for the cooling season.
7- Modeling the house with only a GSHP system (base case) and comparing the results with the SAGSHP system.
8- Conducting a sensitivity analysis on the variation of the solar thermal collector area to determine the optimum balance between ground exchanger length and solar collector area.
9- Conducting system cost analysis.
10- Feasibility study of SAGHP system for different cities of Canada with different climates.

Chapter 2

Literature review

2.1 Introduction

The published research to date on solar assisted ground source heat pumps (SAGSHP) contains four main aspects of study: technical feasibility, economic feasibility, detailed modeling, and field trial experiments. Historically these studies were examined on an individual basis and the authors typically generated their own algorithms to perform simulations. Recent improvements in computers and simulation software have allowed the complete integration of these aspects into all encompassing programs such as TRNSYS [5] and other simulation software.

In spite of the advancement of integrated simulation, published studies of SAGSHP continue to include major simplifying assumptions such as using a simple basic heat pump component (in early editions of TRNSYS) as well as a simplified ground loop heat exchanger with a long time step temperature response factor (Yavuzturk and Spitler [7]). In addition, the majority of the SAGSHP models were based on theory, not on real product performance and field experience. A research opportunity exists, since a number of new models based on actual ground source heat pumps (GSHP) with transient behaviour are currently being developed.

No study has been conducted to date on a residential house with existing equipments and actual monitoring data, in conjunction with the most advanced simulation modeling.

2.2 Early Solar Assisted Heat Pump Systems

Different studies and research on solar assisted heat pumps (SAHP) started in 1978 [8, 9].
In 1982 Metz [10] suggested a SAGSHP system using ground-coupled tanks and the earth as the heat source/sink or storage element. As a part of his research carried at the Brookhaven National Laboratory (BNL), four buried tank experiments were operated between December 1978 and March 1981 to determine the feasibility of using ground coupled tanks in series of SAHP systems. In these systems, solar heat was stored and delivered to the load via the heat pump when the storage temperature was too low for direct heating. Research questions included:

1- Do ground-coupled tanks have a thermal or economic advantage over conventional insulated tanks?

2- Can the ground-coupled tank reduce the amount of auxiliary heat required by buffering transient fluctuations in the storage temperature?
3- Can surplus solar heat, collected during the summer and fall, be retrieved in winter to reduce auxiliary heating or solar collector area?
4- Is the ground-coupled tank a useful space-cooling heat sink?
5- Can a model be developed to reliably simulate the behaviour of ground-coupled tanks?
6- What is the optimal design for a ground-coupled tank?

The experimental results from these tank experiments were compared to results from a model, GROCS [11] (GROund Coupled Systems) developed at BNL. Tank experiment designs and heat inputs were based on computer simulations of a moderately well-insulated 140 m^2 house with a full basement and a heating load of 19.0×10^6 J/°C-day. The local (New York) heating season was taken as 2.78×10^3°C-day/year, yielding an annual building heating requirement of 52.8×10^9 J/year. The annual space cooling load was 15.8×10^9 J/year. The simulated solar collector was a low-temperature single glaze collector. The heat pump was assumed to have an efficiency of 50% of the theoretical Carnot cycle. The results answered the question posed, at least for the climate and soil properties encountered in these experiments. The experimental data indicated that ground-coupled tanks have small thermal advantage over perfectly insulated tanks in a system with low (2-15 °C) winter storage temperatures. Both tank systems extract modest amounts of heat from the ground during the winter after little or no summer heat input.

Ground-coupled tanks can be built in large sizes (0.35 m^3/m^2 of solar collector) without requiring insulation or indoor space. The resultant large thermal inertia can buffer short term storage temperature fluctuations, preventing short-term "heat starvation," and thus reducing auxiliary heating. Heat added to these tanks during the summer and fall had no important effect on mid-winter experimental tank temperatures or heat retrieval.

Considerable amounts of heat can be dissipated by the ground-coupled tank in summer. Without summer solar heat input, such a tank can be a useful space cooling heat sink at lower temperatures, e.g., for daytime storage and nocturnal rejection of heat.

In summary, SAHP systems in series with low winter storage temperatures of ground-coupled tanks were found to have a modest wintertime thermal advantage over conventional insulated tanks. Ground-coupled tanks are also suitable for summer heat dissipation. No important carry-over of summer-collected heat to winter was observed in the experiment conducted at BNL.

2.3 Different Types of Solar and Ground Source Heat-Pump Systems

Yang *et al* [12] portrayed a numerical simulation of the performance of a solar-earth source heat pump system (SESHPS) in two system configurations: 1- Alternate operation mode and 2- Combined operation mode.

The alternate mode is defined as an operation in which SAHP is operating during the day and a GSHP is started in the evening. The aim of this mode is to overcome the problem of the GSHP, in that the earth temperature surrounding the buried coils drops very quickly with continuous heat extraction of ground heat from the earth, and that could deteriorate the performance of the heat pump. Integrating solar energy to GSHP makes it possible for the GSHP to operate intermittently and the resumption of earth temperature can be achieved during the day when the SAHP is started. At the same time, integrating earth energy to SAHP makes it possible for the system to work in the evening or on a rainy day when the GSHP is operating. Furthermore, the redundant energy collected by the solar collector during the day may be stored partly in the earth , so other energy storage equipment can be reduced.

Yang *et al* [12] classified the combined operation mode of SESHPS into three modes. Mode 1 is the coupling of the solar collector and buried coil connected in series. The heat-carrying fluid flows through the buried coil first and then through the solar collector. Mode 2 is with same coupling style, but the heat carrying fluid flows through the solar collector first and then through the buried coil. Mode 3 is a coupling of the solar collector and buried coil in parallel. In this mode, the ratio of the flow rate in the solar collector to the total flow rate in the heat pump is defined as "S", and three sub-cases are defined with the following ratios: S=0.25, 0.5, 0.75. A numerical simulation on the SESHPS was undertaken for the area of Qingdao, China. The heating load for the building was set to 5 kW. The borehole length was considered as 55 m with a PVC (Polyvinyl chloride) U-tube. The solar collector area was set to $6m^2$. A storage water tank with a volume of 0.5 m^3 was used for the simulation. By analysing the output data, it was found that when GSHP was operating continuously, the earth temperature variation near the buried coil was high. The magnitude of affected earth temperature gradually grew over the operating time. The earth temperature variation is significant when the GSHP started but it became steady with continuous operation. The earth temperature resumption rate was very dependent on the GSHP operation time during an alternate period. Considering the system economy, the energy efficiency and earth temperature resumption state, the proportion of operating time for the SAHP should be confined to 42 to 58 % with an alternate operating period of 24 hours.

The combined operation mode, compared with a GSHP, had a notable energy exchange effect. The energy saving rate with and without a water tank was 14.5% to 10.4%, respectively, for combined Mode 2 (flow passing through solar collector first and then through buried coil). As for the internal operation effect, the serial operation with Mode 2 was the best and could be used as an optimized scheme in practical engineering design and operation.

The climate condition, solar energy resources and the characteristics of the earth vary at different geographical regions and, therefore, the results in different modes will vary.

In 2004, Bi *et al* [13] published a combined theoretical and experimental study on a solar ground source heat pump (SGSHP) system, with a vertical double-spiral coil ground heat-exchanger (GHX). This was the basis for Yang *et al* [12] numerical simulation for different SGSHP combination systems. The heating mode of the SGSHP system was alternated between a solar energy source heat pump (SSHP) and a GSHP, using a low grade energy utilization system built by Bi *et al* [13]. The performances were measured for the SSHP, GSHP, and SGSHP systems, as well as the GHX.

When the alternating use of the SSHP and GSHP is controlled per time allocated in different months from weather data, the total average performance in the heating season was:

- For the SSHP system, the heating load was 2334 W and the COP (Coefficient of Performance) was 2.73;
- For the GSHP system, the heating load was 2298 W and the COP was 2.83;
- For the SGSHP system, the heating load was 2316 W and the COP was 2.78.

In 2005 Ozgener and Hepbasli [14] presented a study investigating the performance characteristics of a SAGSHP greenhouse heating system with a U-bend GHX using the exergy analysis method, along with a experimental performance analysis [15,16]. The system was installed at the Solar Energy Institute of Ege University, Izmir, Turkey. The exergy transport between the components and the destructions in each of the components of the SAGSHP greenhouse heating system were determined for the average measured parameters obtained from experimental results. The exergetic efficiencies of the system components were also calculated to assess their individual performance. Exergy analysis is a tool used in the thermodynamic analysis of energy systems. In order to calculate exergy, the environment must be specified. Because of the lack of thermodynamic equilibrium in the surrounding nature, only its common components can be used for the above-mentioned purpose. With a 32 mm diameter vertical 50 m U-band GHX, a flat plate solar collector was directly connected (in series) to the ground-coupled loop. In the modeling, the exergy balance for every single component of the system was employed to determine the rate of exergy decrease as well as irreversibility and exergy deficiencies.

In conclusion the exergetic efficiency values for both the GSHP unit and the whole system were shown to be 71.8% and 67.7%, respectively. The results show that a mono-source central heating operation (independent of any other system) cannot meet the overall heat loss of the greenhouse if the ambient temperature is very low. If peak load heating can be easily controlled, the bi-source operation (combined solar and geo-thermal system) is suggested as the best solution in Mediterranean region.

2.4 Viability of Hybrid Geothermal Heat Pump Systems with Solar Thermal Collectors

In 2003, Chiasson and Yavuzturk [17] presented a study of a system simulation approach to assess the feasibility of hybrid GSHP systems with solar thermal collectors in heating-dominating building. An actual school building was modelled using typical meteorological year weather data for six United States (U.S) cities with varying climates and insulation: Buffalo, New York; Cheyenne, Wyoming; Chicago, Illinois; Denver, Colorado; Omaha, Nebraska; and Salt Lake City, Utah. The building loads were calculated using Building Loads Analysis and System Thermodynamics (BLAST 2000) [18], and the system was modelled as a primary/secondary loop system using the TRNSYS simulation software tool [19]. The primary circuit was the building loop plus a ground loop heat exchanger and the secondary circuit was the solar collector loop. The flow circuits were separated by a plate-and-frame heat exchanger (TRNSYS component Type 5), and modelled with a constant effectiveness. The fluid in the building loop was an aqueous solution of 20% propylene glycol, the fluid in the solar collector loop was modelled with an aqueous solution of 50% propylene glycol to avoid extreme freezing conditions during night time winter hours. The heat pump model was a simple water-to-air heat pump model developed for this and other GSHP system simulations. Inputs to the heat pump model included the building loads, entering fluid temperature, and fluid mass flow rate. The model used quadratic curve-fit equations to manufacturer's catalogue data to compute the heat of rejection in cooling mode, heat of absorption in heating mode, and the heat pump energy consumption. The model's output included exiting fluid temperature, energy consumption and fluid mass flow rate.

The ground loop heat exchanger component used a model described by Yavuzturk and Spitler in 1999 [7]. This was an extension of the long time step temperature response factor model of Eskilson in 1987 [20]. It was based on dimensionless and time-dependent temperature response factors known as g-functions, which were unique for various borehole field geometries. Eskilson's long time step g-functions are not applicable for modeling borehole temperature responses corresponding to typical short time step (hourly) load fluctuations of buildings. Yavuzturk and Spitler [7] used a two-dimensional finite volume approach to model the heat transfer around a single borehole and extend the g-functions down to time scales of less than one hour. These short time step g-functions used by Yavuzturk and Spitler [7] were used to develop a GHX component model for system simulation programs such as TRNSYS (SEL 2000). The model included a flexible load aggregation algorithm that significantly reduces computing time. Inputs include EFT and mass flow rate. Model parameters include number and depth of boreholes, borehole radius, borehole thermal resistance, ground thermal properties, and the file containing the g-function response factors. The main output from the model was the exiting fluid temperature from the ground.

The solar collector model used a theoretical flat plate solar collector. The thermal performance of the collector was modelled using the Hottel-Whillier steady state model described by ASHRAE 1999 [21].

In this study energy simulations were run in three cases: 1) with only GSHP considered as base case; 2) with GSHP and fixed solar collectors; and 3) with GSHP and an azimuth-tracking solar collector.

The results of this study showed that hybrid solar geothermal heat pump systems are viable choice for space conditioning of heating-dominated buildings. For the school building simulated, the seasonal thermal solar energy storage in the ground in the hybrid configuration was sufficient to offset a larger ground storage volume that would have been required for a conventional geothermal heat pump system.

Based on a 20-year life-cycle cost analysis of system performance, there appears to be only small economic benefit in using an azimuth-tracking solar collector array as opposed to a fixed solar collector array. This is because the savings in the initial cost of the azimuth-tracking collector over the fixed collector are negligible compared to the annual system operating costs.

For the fixed solar collector cases, borehole length reductions per solar collector area ranged from 1.4 ft per ft^2 (4.5m per m^2) (Cheyenne, Wyoming) to 2.4 ft per ft^2 (7.7m per m^2) (Omaha, Nebraska). In all cases, hybrid GSHP systems with solar thermal collectors appeared to be economically viable as drilling costs exceeded a range of \$6/ft (\$19.68/m) (Cheyenne, Wyoming) to \$10/ft (\$32.8l/m) (Omaha, Nebraska). This range of breakeven points is due to varying building loads, insulation, and geographic location.

A sensitivity analysis of the ground thermal conductivity for the fixed solar collector case in Cheyenne, Wyoming, showed that doubling the thermal conductivity results in a 16% decrease in the reduction of the ground loop length per unit collector area. Halving the thermal conductivity resulted in an increase in the reduction of 159% in the ground loop length per unit collector area. An exponential relationship was observed between the thermal conductivity of the ground and the reduction in borehole length per collector area.

This study demonstrates the value in utilizing a system simulation approach to evaluating alternatives in complex systems. Specifically, the short time step simulation allows for the implementation of sophisticated control and operating strategies that enable the assessment of short-term transient system responses.

Some specific recommendations for further research arising from Chiasson's study [17]

Implementation of an optimization routine into the system simulations to verify optimum values of desired parameters would be beneficial. In particular, it would be useful to find the optimum balance between the ground loop size and the solar collector size. The objective function would aim to minimize the overall system life-cycle cost by optimizing the size of the ground loop heat exchanger versus the size (area) of the solar thermal collector by considering constraints defined by system parameters and economics.

Further research and development of low-cost solar thermal collectors, coupled with photovoltaic collectors, have the potential to make hybrid GHP systems highly attractive.

Field testing and verification of a hybrid GHP system with solar collectors is desirable to validate the conclusions of this study.

Finally Chiasson's research did not address any Canadian cites with cold climates, such as Toronto, Ontario. However, analysis of the results for the simulated cities reveals that the benefits of solar hybrid systems appear to be a function of the ratio of annual heat extracted from the ground to the annual heat rejected in to the ground (ranging from 2 to 20 for the simulated cases). All the cities simulated in his study had a moderate cooling load, since some summer occupancy (10%) for the school was assumed. The results showed benefits for the case where the above-mentioned ratio was as low as two (Salt Lake City, Utah). It is reasonable to assume that most Canadian sites would have a ratio of annual heating to cooling greater than two, so there should be some benefits. However, analysis of Canadian cities is the subject of future work.

Chapter 3
House Load Simulation

3.1 House Model Description

The house selected for the proposed study is located in the City of Milton, Ontario. The house was one of two energy efficient demonstration houses built by a local builder, Mattamy Homes [22] in 2005. Appendix A shows the house floor plans. It is a detached two storey building having 5,360 ft^2 (498 m^2) of heated area including the basement with the following characteristics:

Construction: Light wood frame, 50 × 150 mm (2×6 in) exterior wall construction installed on 610mm (24 in) centers.

Insulation: Spray foam insulation for walls with RSI 3.5 (R20), RSI 7 (R40) attic insulation.

Windows: Low E/Argon filled with insulated spacers, Vinyl, RSI 0.35 (R2)

Occupant: two adults and two children for 50% of time

Basement Flooring: Concrete floor, hydronic slab under heating, RSI 2.11 (R12).

Figure 3.1 shows the back of the house with solar thermal collectors on its roof.

Figure 3-1: A Mattamy house located in Milton, Ontario, with the back facing due south (*photo By FMRAD 2007)*

As per builder specifications, the house temperature is set at 21°C and 24°C in the heating and cooling periods, respectively. Air leakage at 50 Pa. is 1.41ACH (518 l/s) with an equivalent leakage area at 10 Pa. of 697 cm^2. A continuous ventilation of 0.3ACH (110 l/s) through heat recovery ventilation system (HRV) is also considered. The sensible internal heat gain from occupants is set to be 2.4 kWh/day. The occupancy of the house is two adult and two children for 50% of the time with a hot water consumption of 225 litres/day. The base loads are considered to be 22 kWh/day, including lighting, appliances, exterior use and others.

TRNBuild [23], a component of the TRNSYS simulation software was used to generate the house load profile. TRNBuild was developed as a part of TRNSYS for simulating multi-zone building. It works under Type 56 in the TRNSYS studio. This component models the thermal behaviour of a building divided into different thermal zones. In order to use it, a separate pre-processing program must be first executed. The TRNBuild program reads in and processes a file containing the building description, and then generates two files used by the TYPE 56 component during TRNSYS simulation. TRNBuild generates an information file describing the outputs and required inputs of TYPE 56. There are two ways to model the equipment for heating, cooling, humidification, and dehumidification. The two methods are similar to the "energy rate" and "temperature level" control modes available in the TYPE 12 and 19 load models. With the "energy rate" method, a simplified model of the air conditioning equipment is implemented within the TYPE 56 component. The user specifies the set temperatures for heating and cooling, set points for humidity control, and maximum cooling and heating rates. These specifications can be different for each zone of the building. If the user desires a more detailed model of the heating and cooling equipment, a "temperature level" approach is required. In this case, separate components are required to model the heating and/or cooling equipment. The outputs from the TYPE 56 zones can be used as inputs to the equipment models, which in turn produce heating and cooling inputs to the TYPE 56 zones.

To get the idea of the total house load in this chapter, internal TRNBuild equipment component characteristic are used and later in this study separate equipment components are externally linked to the house. It uses a simulation time step that may not be equal to the time base on which the wall transfer function relationships are based. Finally, the optical and thermal window model, the way in which solar and internal radiation are distributed within each zone, the moisture balance calculations and the integrated model for thermo-active walls are considered. Thermo-active building elements (slabs or walls of a building) are used to condition buildings by integrating a fluid system into massive parts of the building itself. An example is the radiant floor heating system used in the basement floor. The climate of Toronto, Ontario (which is about 60km east of Milton) was chosen for this study.

For the purpose of comparison and validation the house was also modelled with HOT2000 ver10.12 software developed by Natural Resources Canada [24].

HOT2000 is a simplified residential heat loss/gain analysis program, widely used in North America by builders, engineers, architects, researchers, utilities and government agencies and by a number of users in Europe and Japan [24]. Utilizing current heat loss/gain and system performance models, the program aids in the simulation and design of buildings for thermal effectiveness, passive solar heating and the operation and performance of heating and cooling systems. HOT2000 uses a bin based method and long term monthly weather files to analyze the performance of the house. HOT2000 is a three-zone model (attic, main floors and basement), which considers utilized solar and internal gains and heat transfer between zones when calculating loads. It also accounts for on and off cycling and part load factors when determining the performance of the heating system.

3.2 House Load Profile

The house load was calculated using both TRNBuild [23] and HOT2000 [24]. Figures 3-2, 3-3 and 3-4 show the results.

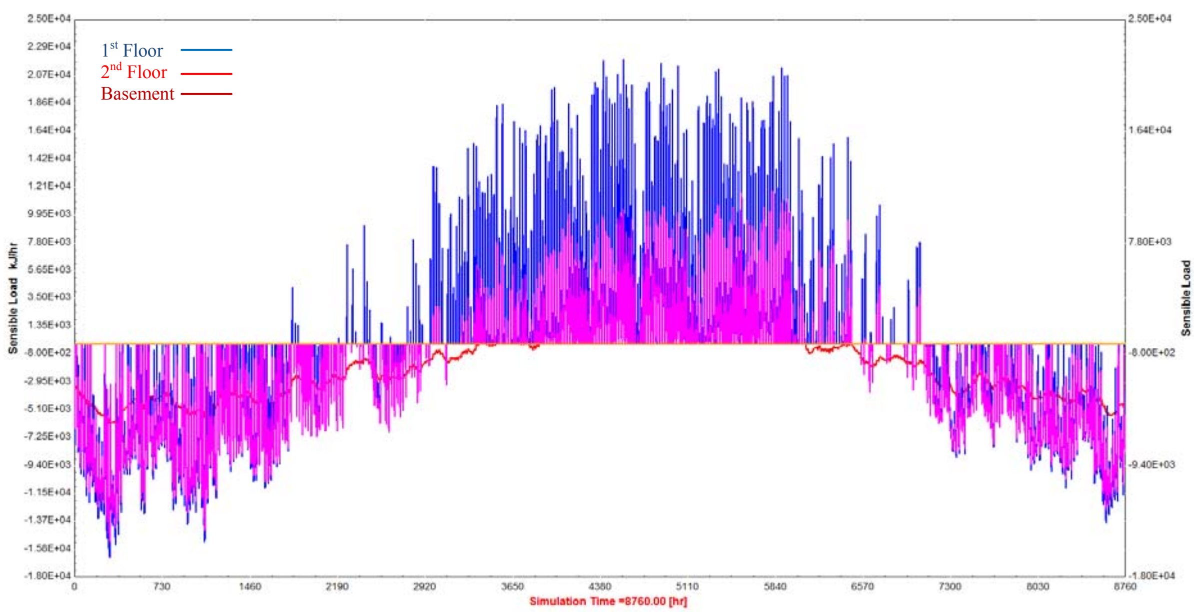

Figure 3-2: Hourly heating and cooling load for whole year simulation

In TRNbuild the house was separated in three zones: 1- Basement, 2- First floor 3- Second floor. The blue color shows the hourly load of the first floor and the pink color shows the second floor load. Maximum heating and cooling demand is 11.5 kW and 9.5 kW respectively. The annual space heating total load for the house was estimated to be 95 GJ, shown in Figure 3-3, with an annual space cooling load of 19 GJ, illustrated in Figure 3-4.

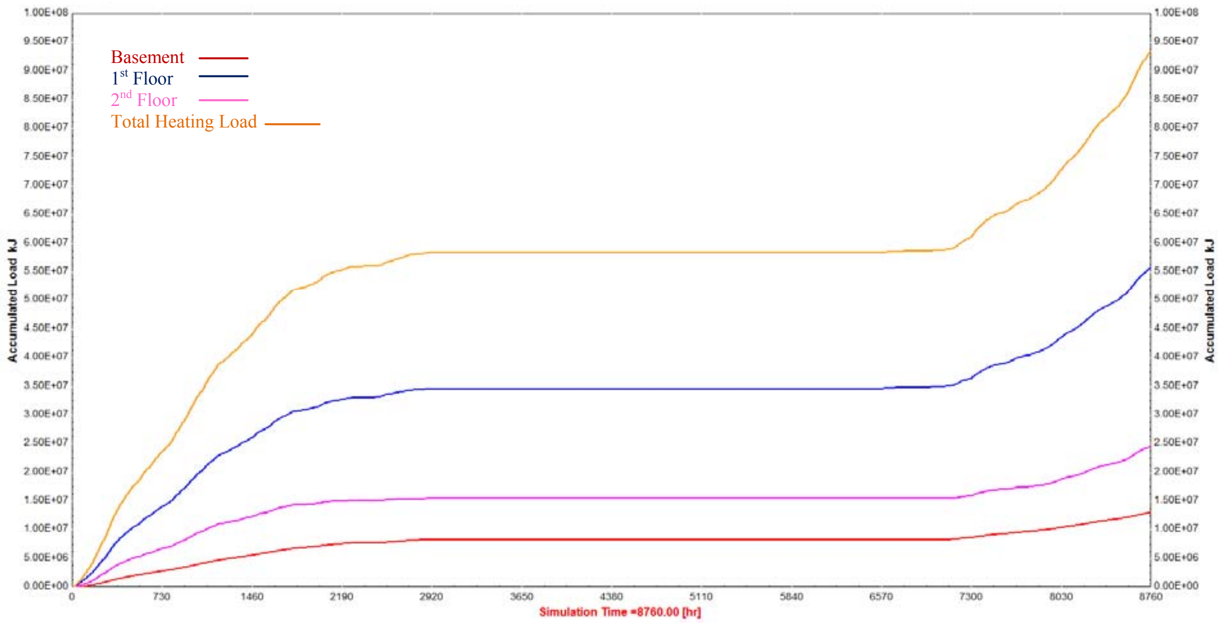

Figure 3-3: Accumulated space heating load.

The heating season was set from 1st of October (6552 hr) to 30th of April (2880 hr), and the cooling season from 1st of May (2881 hr) to 31st of September (6553 hr).

Table 3-1 shows the house load results from HOT2000. When comparing these with the TRNSYS results, it can be seen that there is good agreement between the two models. The differences between the two simulations are most likely attributed to the difference in analysis method between TRNSYS and HOT2000. As mentioned earlier TRNSYS is an hourly simulation program using the transfer function method, and HOT2000 uses the much simpler bin method which may be less accurate. Appendix B contains the detailed results of the HOT2000 simulation.

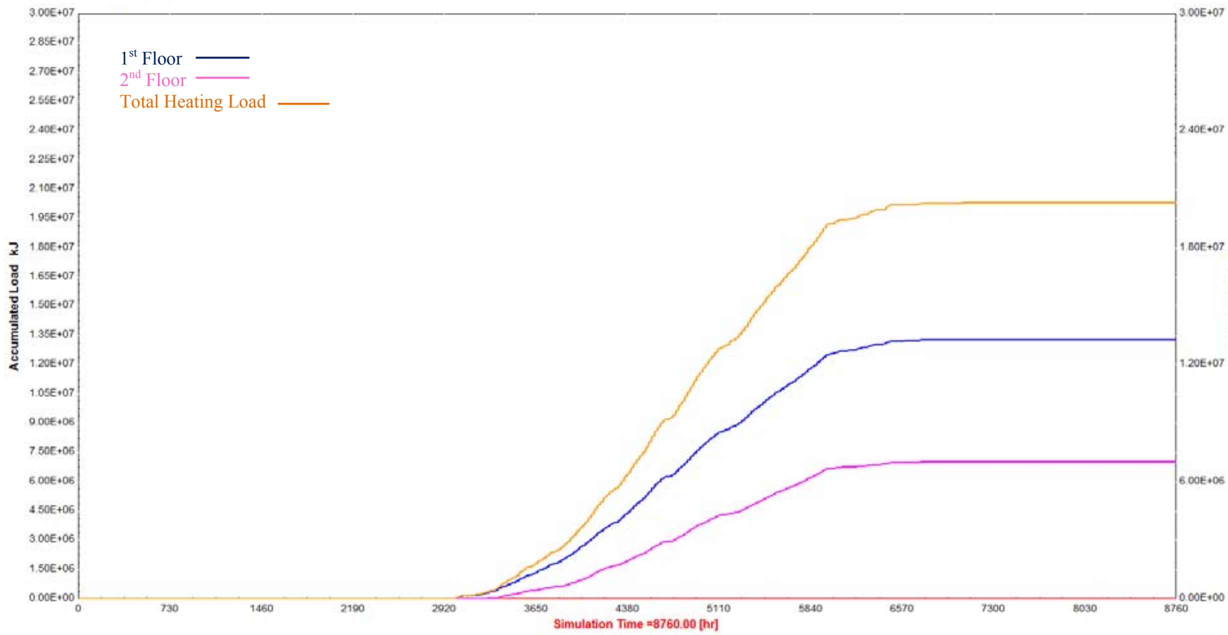

Figure 3-4: Accumulated space cooling load.

Table 3-1: House heating and cooling requirements – comparison of HOT2000 and TRNSYS

	TRNSYS Zone 1	TRNSYS Zone 2	TRNSYS Zone 3	**TRNSYS** Total	**HOT2000**
Total Heating Load (GJ)	25	33	37	**95**	**92**
Total Cooling Load (GJ)	0	12	7	**19**	**18.5**
Maximum Heating Demand (kW)	1.9	4.8	4.8	**11.5**	**17.6**
Maximum Cooling Demand (kW)	0	5.9	3.6	**9.5**	**9.4**

Chapter 4
Hybrid Ground Source Heat Pump with Solar Thermal Collector Model

4.1 System Equipment Configuration

Figure 4-1 shows a schematic of the solar assisted ground source heat pump (SAGSHP) system. The system is constructed from the following major components:

1- Atlas AT060 ground source heat pump (GSHP) with a desuperheater [25]
2- Enerworks solar thermal collector with three panels [26]
3- Rheem 620T hot water tank [27]
4- Power Pipe grey water heat recovery [28]
5- Venmar Vane 1.3HE Heat Recovery Ventilator (HRV) [29]

The ground heat exchanger (GHX) system consists of four vertical closed loop circuits, joined in parallel. Each borehole has 0.25 m (10 in) diameter and 55 m (180 ft) length. They are located 3.6 m (12 ft) apart from each other in the backyard and merge at 1.8 m (6 ft) below grade. Figure 4-2 shows this arrangement.

The GHX loop is connected in parallel to the solar thermal collectors. The solar collectors receive a percentage of the total flow from the ground loop exchanger. Two circulation pumps from part of the heat pump system, and they are located upstream and down-stream of the GHX flow. A solenoid valve and a control valve control the flow rate to the solar collectors.

The heat pump is selected to suit the space heating requirements of the house for both radiant floor heating and forced air heating. The same heat pump provides cooling in the summer. The heat pump has a dedicated domestic hot water generation through the desuperheater with internally mounted pump. The hot water from the desuperheater loop flows into the water tank. Both the hot water tank and heat pump are equipped with auxiliary electric heaters.

Domestic cold water is directed to the grey water heat recovery equipment and then sent to the hot water tank and/or desuperheater. Basement in-floor radiant heating is directly fed from the hot water tank, and its flow pressure is boosted by a dedicated pump included in the model.

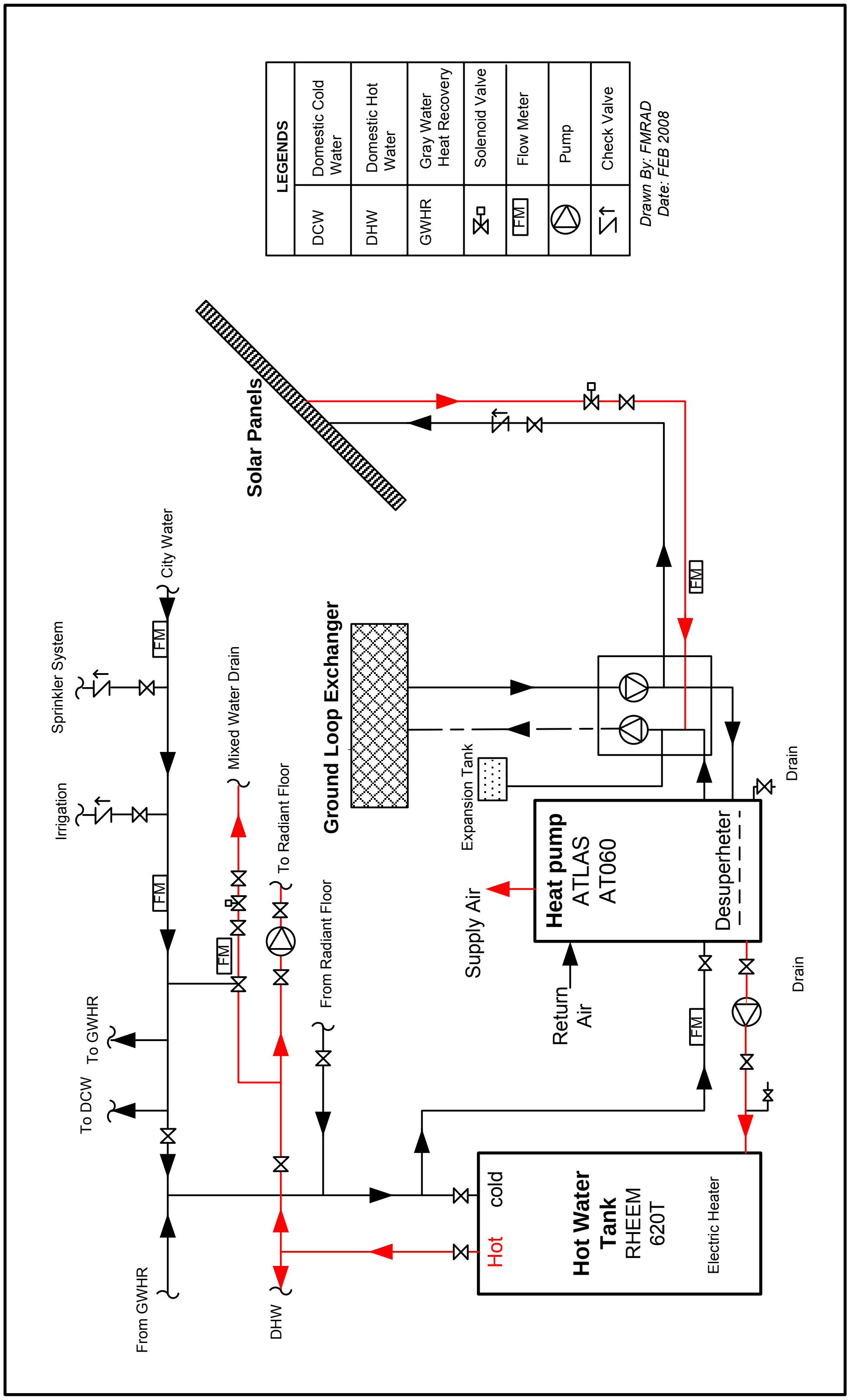

Figure 4-1: Schematic diagram of the SAGSHP system configuration

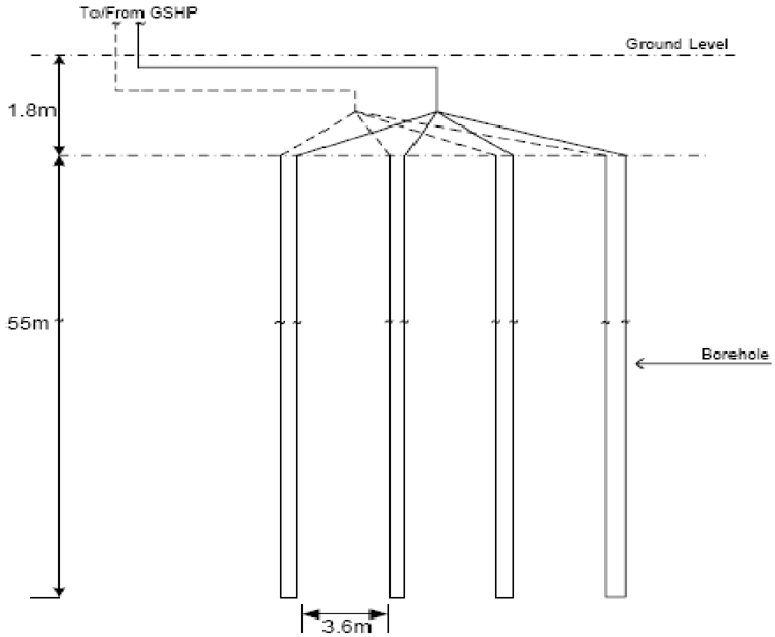

Figure 4-2: Ground loop borehole layout

4.2 SAGSHP Component Model Description

The TRNSYS modelling environment (studio) was used to construct the system using standard and non-standard component models. The component models and their functions are each described separately.

4.2.1 House Model

As described in Chapter 3, the house was modelled in TRNBuild, a separate component of TRNSYS. Type 56 was used to link the files generated with TRNBuild. Several parameters were defined as input variables for the house and are shown in Table 4-1.

The weather data reader and radiation processor, Type 109 is the main TRNSYS component that the house simulation relies on. This component serves the purpose of reading weather data from a data file at regular time intervals, and converting it to a desired system of units, and processing the solar radiation data to obtain the tilted surface radiation and angle of incidence for an arbitrary number of surfaces. Type 109 reads the file in a typical meteorological year (TMY2) format, which is same as used by the National Solar Radiation Data Base (USA) [30].

Two other TRNSYS components process the mentioned data to the house:

1- Type 69 calculates the effective sky temperature for long-wave radiation exchange.
2- Type 33 (Psychometrics) obtain the dry bulb temperature and relative humidity from weather data, and calculates the corresponding wet bulb temperature and percent relative humidity.

Table 4-1: Input parameters to the house

	Input Parameters	**Data source**
1	Ambient temperature	Weather data
2	Relative humidity	Weather data
3	Wind velocity	Weather data
4	Wind direction	Weather data
5	Atmospheric pressure	Weather data
6	Extraterrestrial radiation on horizontal	Weather data
7	Solar zenith angle	Weather data
8	Solar azimuth angle	Weather data
9	Total radiation on horizontal	Weather data
10	Beam radiation on horizontal	Weather data
11	Sky diffuse radiation on horizontal	Weather data
12	Ground reflected diffuse radiation on horizontal	Weather data
13	Angle of incidence on horizontal surface	Weather data
14	Slope of horizontal surface	Weather data
15	Total radiation on tilted surface	Weather data
16	Beam radiation on tilted surface	Weather data
17	Sky diffuse radiation on tilted surface	Weather data
18	Ground reflected diffuse radiation on tilted surface	Weather data
19	Angle of incidence for tilted surface	Weather data
20	Slope of tilted surface	Weather data
21	Slab Heat	Basement Slab
22	Forced air heating from heat pump	Heat Pump
23	Forced air cooling from heat pump	Heat Pump
24	Heat recovery ventilator (HRV)	HRV

The heat pump, through forced air system distribution and basement slab heating, provides heating or cooling to the house.

Fresh outdoor air is supplied to the house through the heat recovery system (HRV), which exchanges heat with exhaust air from the house. Type 667b in TRNSYS models this component. In this module, the fresh air temperature and relative humidity is fed by the weather data component. Otherwise, the exhaust air would be from the return air of the house. The heat recovery efficiency for selected equipment is dependent on the supply air temperature (fresh air) which in the worst case would read 69% [29]. The air change rate per hour for house ventilation is 0.3 and corresponds to 110 l/s.

Table 4-2 shows the selected output data from the house. Total simulation time has been set to one year (8760 hours). The online graphical plotter graphs house temperatures from different zones (Basement, 1st Floor and 2nd Floor), with the output file as Type 65. The same component is also used to plot and file the zone energy demands through simulation period.

For calculating the accumulated energy demand of different zones as well as the total accumulated energy demand of the house, Type 24, the Quantity Integrator has been utilized along with an equation component to obtain the desired report through a plot of the model.

Table 4-2: Selected output parameters from the house

	Output Parameters	**Data is sent to**
1	Air Temperature of Zone 1 (Basement)	House_Temp Plotter
2	Air Temperature of Zone 2 (1st Floor))	House_Temp Plotter
3	Air Temperature of Zone 3 (2nd Floor)	House_Temp Plotter
4	Sensible Energy demand of Zone 1	Load Plotter
5	Sensible Energy demand of Zone 2	Load Plotter
6	Sensible Energy demand of Zone 3	Load Plotter
7	Relative humidity of Zone 1	Load Plotter
8	Relative humidity of Zone 2	Load Plotter
9	Relative humidity of Zone 3	Load Plotter
10	Latent Energy demand of Zone 1	Total Load Plotter
11	Latent Energy demand of Zone 2	Total Load Plotter
12	Latent Energy demand of Zone 3	Total Load Plotter

4.2.2 Heat Pump Model

The water source heat pump is modelled as Type 505. This component models a single-stage liquid source heat pump with desuperheater for hot water heating. The heat pump conditions a moist air stream by rejecting energy to (cooling mode) or absorbing energy from (heating mode) a liquid stream. The desuperheater is attached to a secondary fluid stream. In cooling mode, the desuperheater relieves the liquid stream from some of the burden of rejecting energy. However, in heating mode, the desuperheater requires the liquid stream to absorb more energy than would be required for space heating only. This heat pump model is intended for residential GSHP application [31]. This model is based on user-supplied data files containing catalogue data for the capacity (both total and sensible in cooling mode) and power, based on the water temperature entering the heat pump, the entering water flow rate and the air flow rate. The model is also equipped with two stage auxiliary heater. The Atlas AT060 GSHP with a desuperheater [25] is a good match with Type 505. Table 4-3 shows the parameters from the technical manual of the chosen heat pump needed for simulation.

Table 4-3: Ground source heat pump parameters

Density of liquid stream	1036	kg/m^3
Specific heat of the liquid stream	3.6	kJ/kgK
Specific heat of DHW fluid	4.18	kJ/kgK
Blower Power	0.19	kW
Controller power	0.01	kW
Capacity of stage-1 auxiliary heater	5	kW
Capacity of stage-2 auxiliary heater	5	kW
Total air flow rate	944	l/s

The fluid in the GSHP exchanger loop is modelled as an aqueous solution of 50% propylene glycol [32] to avoid extreme freezing condition during winter, especially for the part that passes through the solar collectors. Table 4-3 shows the physical properties of the liquid streams at 30°C. Table 4-4 tabulates the unit input parameters. The coupled GHX fluid flow rate is set as per equipment capacity and its temperature input comes from the GHX loop. Air pressure to the house is fixed. The second floor temperature dictates the return air temperature with a fixed relative humidity of 50%, so this return air is mixed with a specified amount of ventilation air from the HRV before entering the heat pump. Heat recovery output parameters feed the fresh air temperature and relative humidity. Domestic hot water (DHW) inlet flow rate is as per equipment capacity with fixed inlet temperature. The thermostat and seasonal schedule in model control the cooling, heating control signal (On/Off). Overall heat transfer coefficient (UA) between the heat pump and the desuperheater flow stream in heating and cooling mode are as per equipment specification. The temperature of the refrigerant in the desuperheater when the heat pump is operating in heating or cooling mode is also set as per equipment manual. This temperature is used to calculate the heat transfer to the domestic hot water flow stream. The thermostat and seasonal schedule control the auxiliary heat signal for both cooling and heating, as well as heat pump fan operation.

Table 4-4: Ground source heat pump input parameters

Input parameter	Data source	
Inlet liquid temperature	from GHX	°C
Inlet liquid flow rate	1273	kg/hr
Return air temperature	2nd floor temp.	
Return air relative humidity	50%	
Return air pressure	1	atm
Fresh air temperature	from HRV	°C
Fresh air relative humidity	from HRV	
Fresh air pressure	1	atm
Inlet DHW temperature to heat pump	From bottom of tank	°C
Inlet DHW flow rate (from tank to heat pump)	500	kg/hr
Cooling control signal	0 or 1	
Heating control signal	0 or 1	
Stage 1 auxiliary signal	0 or 1	
Stage 2 auxiliary signal	0 or 1	
Fan control signal	0 or 1	
Cooling desuperheater temperature	60	°C
Heating desuperheater temperature	55	°C
Desuperheater UA-cooling	1500	kJ/hrK
Desuperheater UA-heating	1500	kJ/hrK

The parameters tabulated in Table 4-5 are outputs from the GSHP selected to feed heating and cooling to the house, as well as heating to the hot water tank.

Table 4-5: Ground source heat pump output parameters

Output parameter	Data is sent to
Exiting fluid temperature	to GHX
Exiting fluid flow rate	to GHX
Outlet air temperature	to house
Exiting DHW temperature	to water heater
Exiting DHW flow rate	to water heater
Total heat transfer to air	to house

The outlet air temperature from the heat pump is directly connected to the house whereas the total heat transfer to the air is split into two zones through a TRNSYS equation component. Exiting DHW flow rate and temperature is directed to the hot water heater.

4.2.3 Ground Loop Heat Exchanger Model

Type 557 models the vertical GHX that interacts thermally with the ground. GSHP applications commonly use this GHX model. This subroutine models identical vertical U-tube GHX or identical vertical tube-in-tube heat exchangers. A heat carrier fluid is circulated through the GHX and either rejects heat to or absorbs heat from the ground depending on the temperatures of the heat carrier fluid and the ground. In typical U-tube or tube-in-tube GHX applications, a vertical borehole is drilled into the ground. A U-tube or tube-in-tube heat exchanger is then pushed into the borehole. The top of the GHX is typically several feet below the surface. Finally, the borehole is filled with a fill material; either virgin soil or a grout of some type. The model assumes that the boreholes are placed uniformly within a cylindrical storage volume of ground. There is convective heat transfer within the pipes and conductive heat transfer to the storage volume. The temperature of the surrounding ground is calculated from three parts: a global temperature, a local solution, and a steady-flux solution. The global and local problems are solved with the use of an explicit finite-difference method. The steady-flux solution is obtained analytically. The resulting temperature is then calculated using superposition methods. This subroutine was written by the Department of Mathematical Physics at the University of Lund, Sweden, and is considered to be the state-of-the-art in dynamic simulation of ground heat exchangers [31, 33].

Table 4-6 tabulates the parameters and values used for the Type 557 GHX. These values are partly delivered by the house builder and some are estimated to the nearest suited value for the place.

The volume of the cylindrical shaped storage region which contains the boreholes is set to 2,470 m^3, with the boreholes placed uniformly within the storage volume. The properties of the ground within the storage volume are considered uniform while the properties of the ground outside the storage volume may be described for several vertical layers. In this study only one layer is considered because of insufficient ground soil information at site. By considering the spacing between the boreholes to be 3.6 m, the storage volume is calculated from the relationship suggested in TRNSYS manual [19] and shown in Eq. (4-1).

$$\textit{Storage Volume} = \pi \times \textit{Number of Boreholes} \times \textit{Borehole Depth} \times (0.525 \times \textit{Borehole Spacing})^2$$

$$\textit{Storage Volume} = \pi \times 4 \times 55 \times (0.525 \times 3.6)^2 = 2{,}470 \text{ m}^3 \qquad (4\text{-}1)$$

The depth of one borehole (from the surface) is 55 m, which is also considered the height of the storage volume for determining the cross-sectional storage area. This value is also the length of one of the U-tube heat exchangers from the ground surface to the bottom of the U-tube bend.

Header depth is the depth below the surface of the top of the U-tube GHXs. This value is also typically the depth below the surface of the horizontal header pipe which feeds the GHXs.

The total number of boreholes within the storage volume is four. If each borehole contains one U-tube GHX then this value is also the number of U-tube GHXs. The radius of one of the identical boreholes (the holes drilled for the heat exchangers) is 100 mm. The boreholes are connected in parallel. The flow rate per heat exchanger is then the total flow rate divided by the total number of boreholes.

The thermal conductivity of the ground comprising the storage volume is considered 2 W/mK [34, 35]. This is estimated for the regional soil properties. The properties of the ground are assumed uniform within the storage volume but can be specified for different ground layers beyond the storage volume boundary. The heat capacity (density × specific heat) of the ground comprising the storage volume is 1820 kJ/m^{3}K. The properties of the soil within the storage volume are considered uniform. Fill thermal conductivity is the material used to fill the borehole after the U-tube GHX has been installed. The thickness of the gap between the U-tube pipes and the fill material is set to zero. The reference fluid flow rate per borehole for the calculation of the fluid to ground thermal resistance (borehole thermal resistance) is 350 kg/hr. This parameter is very important and corresponds to the expected borehole flow rate during operation.

The general GHX model includes the heat transfer between the upward and downward flowing fluid in the U-tube GHX. The maximum temperature of the fluid entering the GHXs exchangers is 100 °C and as indicated in Section 4.2.2, heat exchanger fluid is modelled as an aqueous solution of 50% propylene glycol with a specific heat of 3.6 kJ/kgK and density of 1036 kg/m^3.

The number of unique vertical soil layers comprising the ground outside the boundary of the storage volume (assuming uniform soil storage volume) is one. The thermal conductivity of the specified vertical layer at the outside boundary of the storage volume is set as the storage volume thermal conductivity. The volumetric heat capacitance of the specified vertical soil layer at the outside boundary of the storage volume is 2016 kJ/m^{3}K and the thickness of the specified vertical soil layer at the outside boundary of the storage volume is 1000 m. Table 4-6 shows the ground loop exchanger parameters.

Table 4-6: Ground loop heat exchanger parameters

Storage volume	2470	m^3
Borehole depth	55	m
Header depth	1.8	m
Number of boreholes	4	
Borehole radius	100	mm
No. of borehole in series	1	
Storage thermal conductivity	2	W/mK
Storage heat capacity	1820	kJ/m^{3}K
Inner radius of U-tube	13.72	mm
Outer radius of U-tube	16.64	mm
Center to center half distance	25.4	mm
Fill thermal conductivity	1	W/mK
Pipe thermal conductivity	0.42	W/mK
Gap thermal conductivity	1.4	W/mK
Gap thickness	0	
Reference borehole flow rate	350	kg/hr
Reference temperature	10	°C
Pipe to pipe heat transfer	Considered	
Fluid specific heat	3.6	kJ/kgK
Fluid density	1036	kg/m^3
Number of simulation years	1	
Maximum storage temperature	100	°C
Number of preheating years	0	
Number of ground layers	1	
Thermal conductivity of layer	2	W/mK
Heat capacity of layer	2016	kJ/m^3/K
Thickness of layer	1000	m

Table 4-7 shows the input parameters to the GHX. The inlet fluid temperature is dictated by the heat pump module and solar panel return that are mixed and fed to the ground loop.

Temperature on top of the soil is considered as the ambient temperature as the boreholes are exposed to ambient air.

Table 4-8 shows the output parameters from the GHX loop. After pumping, flow from the ground loop is diverted to the solar panel and heat pump with adjustable ratio by a diverter valve.

Table 4-7: GHX loop input parameters

Input parameter	**Data source**
Inlet fluid temperature	Mixer/Pump
Inlet flow rate	1393 kg/hr
Air temperature	Ambient
Temperature on top of soil	Ambient

Table4-8: GHX loop output parameters

Output parameter	**Data is sent to**
Outlet temperature	Diverter/Pump
Outlet flow rate	Diverter
Average storage temperature	Plotter
Average heat transfer rate	Plotter

4.2.4 Solar Collector Model

The TRNSYS solar collector used for this study is Type 1. This component models the thermal performance of a flat-plate solar collector. The solar collector array consists of three collectors connected in series. The number of modules in series and the characteristics of each module determine the thermal performance of the collector array. In this instance of Type1, a second order quadratic function is used to compute the incidence angle modifier. The coefficients of the function are supplied by an ASHRAE or an equivalent test [19]. The manufacturer (Enerworks) provided the results from standard tests of collector efficiency versus a ratio of fluid temperature minus the ambient temperature to solar radiation. The fluid temperature is the average temperature of the inlet and outlet temperatures. In Type 1, there are five possibilities for considering the effects of off-normal solar incidence. In this instance, a second order quadratic function is used to compute the incidence angle modifier. The coefficients of the function are supplied by ASHRAE [37].

A general equation for solar thermal collector efficiency is obtained from the Hottel-Whillier Equation [36] as:

$$\text{Modifier} = a_0 - a_1 \frac{\Delta T}{l_T} - a_2 \frac{(\Delta T)^2}{l_T} \qquad (4-2)$$

where l_T [kJ/h-m²] is the global radiation incident on the solar collector (tilted surface) and ΔT is the difference between the inlet and ambient temperature.

The thermal efficiency is defined by three parameters: a_0, a_1 and a_2. These parameters are available for collectors tested according to ASHRAE 2003 [37]. Table 4-9 shows the parameters considered for the Type 1 module.

Table 4-9: Solar collector parameters

Number in series	3	
Collector area	8.7	m^2
Fluid specific heat	3.6	kJ/kgK
Efficiency mode	1	Eff.=f(T_{inlet})
Tested flow rate	40	$kJ/hr.m^2$
Intercept efficiency	0.8	
Efficiency slope	13	$kJ/hr.m^2K$
Efficiency curvature	0.05	$kJ/hr.m^2K^2$
Optical mode 2	2	
1st-order IAM*	0.2	
2nd-order IAM*	0	

* Incident angle modifier

The efficiency parameters provided by the manufacturer are a function of the inlet temperature and therefore the efficiency mode is set to one. The total area of the solar collector array is taken from the supplied efficiency parameters (typically gross area and not net area) and the flow rate is per unit area at which the collector was tested in order to determine the collector efficiency parameters. Intercept efficiency, efficiency slope and efficiency curvature are a_0, a_1 and a_2 in efficiency equation (4 – 2), and are obtained from ASHRAE collector test. Optical mode 2 is a parameter that specifies the second-order ASHRAE incidence angle modifiers should be used. Collector tests are performed on clear days at normal incidence so that the transmittance-absorbance product is nearly the normal incidence value for the beam radiation.

The intercept efficiency is corrected for non-normal solar incidence using of a modifying factor of the form:

$$\text{Modifier} = 1 - b_0 \times S - b_1 \times S^2 \qquad (4-3)$$

where $S = \left(\frac{1}{\cos\text{(incidence angle)}} - 1\right)$, "1st-order IAM" parameter is b_0 and "2nd-order IAM" is b_1 in the above equation for incident angle modifier (IAM).

Table 4-10 shows the input parameters to the solar collector. The diverter module from the GHX loop feeds the temperature and flow rate to the collector, and the other parameters come from the weather data module.

Table 4-10: Solar collector input parameters

Input parameter	Data source
Inlet temperature	Diverter
Inlet flow rate	Diverter
Ambient temperature	Weather component
Incident radiation	Weather component
Total horizontal radiation	Weather component
Horizontal diffuse radiation	Weather component
Ground reflectance	Weather component
Incident angle	Weather component
Collector slope	Weather component

Table 4-11 shows the output parameters from the solar collector. The outlet temperature and flow rate are fed to the mixer and then to the ground loop exchanger after mixing with fluid from the heat pump.

Table 4-11: Solar collector output parameters

Output parameter	Data is sent to
Outlet temperature	Mixer
Outlet flow rate	Mixer
Useful energy gain	Plotter

4.2.5 Water Tank Model

A Type 4, Stratified Storage Tank with variable inlets and uniform losses was selected for this model. The thermal performance of a fluid-filled sensible energy storage tank is subject to a thermal stratification that can be modelled by considering that the tank consists of N (N = 6) fully-mixed equal volume segments, as per manufacturer information data. The value of N determines the degree of stratification. If N is equal to one, the storage tank is modelled as a fully-mixed tank and no stratification effects are possible. In this instance, Type 4 models a stratified tank having variable inlet positions such that the entering fluid may be added to the tank at a temperature as near to its own temperature as possible. Here the node sizes are equal (but they do not need to be). Temperature dead band on heater thermostats are available. This further assumes that the heat losses from each tank node are equal and does not compute losses through electric auxiliary heater.

The storage tank may operate in one of three modes in determining the inlet positions of the flow streams. Mode 2 is selected and it indicates that the heat source flow and the cold-side flow enter the tank in the nodes closest in temperature to the temperature of the respective flows. With a sufficient number of nodes, this permits a maximum degree of stratification. Table 4-12 shows the parameters and values selected for hot water storage tank.

Table 4-12: Hot water tank parameters

Tank volume	0.22 m^3
Fluid specific heat	4.19 kJ/kgK
Fluid density	1000 kg/m^3
Tank loss coefficient	3 kJ/hrm^2K
Number of temperature level (nodes)	6
Height of nodes (equal)	0.3 m
Number of heating element in tank	2, on top of the tank

Tank volume has been selected as 0.22 m^3 (60 gallons) with water density and specific heat. The specifications in Table 4-12 correspond to the equipment manufacturer, Rheem PRO620T.

The heat source for the tank is a water loop from the heat pump desuperheater. The inlet location for this hot-side fluid is the node closest in temperature to that of the hot-side flow.

Replacement fluid flowing into the storage tank is from the mixer that gets the return flow from the slab heating loop and the main cold water from the city that passes through the grey water heat recovery unit. The flow will enter the tank at the node which is closest in temperature to the cold-side flow at the bottom of tank. Table 4-13 shows the input parameters to the tank. The basement temperature would be the tank environment temperature and the controls of the electric auxiliary heater are set to the “On” position to supplement the heat needed for the set tank temperature of 60°C.

Table 4-13: Hot water tank input parameters

Input parameter	**Data source**
Hot side temperature	Heat pump desuperheater
Hot side flow rate	Heat pump desuperheater
Cols side temperature	Mixer
Cold side flow rate	Mixer
Environment temperature (basement)	19 °C
Control signal for element-1	On
Control signal for element-2	On

Table 4-14 shows the output from the hot water tank. The temperature and flow of the fluid flowing from the bottom of the storage tank are returned to the heat source (the bottom node temperature) or heat pump desuperheater. Flow from top of the tank is directed to a diverter for sending to the basement floor heating slab, as well as for domestic hot water use. Other out-put data is sent to the plotter and a file for further analysis.

Table 4-14: Hot water tank output parameters

Output parameter	**Data is sent to**
Temperature to heat source	Heat pump desuperheater
Flow rate to heat source	Heat pump desuperheater
Temperature to load	Diverter
Flow rate to load	Diverter
Thermal losses	Plotter
Energy rate to load	Plotter
Internal energy change	Plotter
Auxiliary heating rate	Plotter
Element 1 power	Plotter
Element 2 power	Plotter
Energy rate from heat source	Plotter
Average tank temperature	Plotter

4.2.6 In-Floor Radiant Heating Model

Type 653, Simple Floor Heating System/Radiant Floor is selected for the basement radiant slab heating. This component models a simple radiant slab system that operates under the assumption that the slab can be treated as a single lump of isothermal mass and that the fluid to slab energy transfer can be modelled using a heat exchanger effectiveness approach.

Table 4-15 shows the parameters selected for basement slab heating. Fluid running through the slab is the hot water from the hot water tank. Figure 4-3 shows the plan of the basement area covered by slab heating pipes.

Table 4-15: Radiant floor heating parameters

Capacitance of slab	15000 kJ/K
Specific heat of fluid	4.19 kJ/kgK
Initial slab temperature	35 °C

The capacitance of the massive slab for the floor heating system is a parameter for this module. The capacitance is calculated as follows:

The thermal properties of concrete slab:

$$C_p = 780 \frac{J}{kg.K} \quad , \quad \rho = 1860 \frac{kg}{m^3}$$

Considering 100 mm thickness of slab then,

Volume = 10.2 m^3 and thermal capacity would be about 15000 kJ/K.

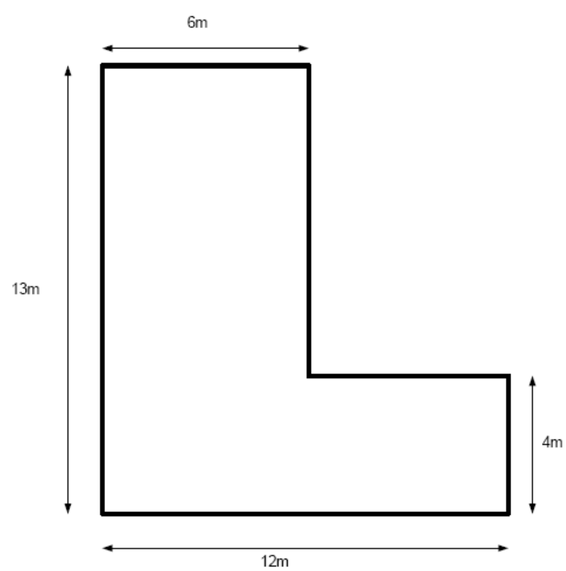

Figure 4-3: Basement floor slab coverage plan

Table 4-16 shows the input parameters and values to the radiant slab heating. The inlet flow and temperature come from the mixer, which is controlled from the return flow from the slab and hot water tank is set to 35°C. The basement air temperature has been set to 19°C, while the environmental loss, which in this study is heat loss to the soil, is set to zero with an assumption of insulated bottom. The heat transferred to the ambient through natural convection and radiation is negligible. For the zone floor surface, the heat transfer coefficient is calculated as follows [38]:

Surface heat transfer by free convection from surface of slab,

$$T_{surface} = 29\,°C\ ,\ T_{\infty}\ = 19°C\ \ \rightarrow T_{film} = \frac{19+29}{2} = 24°C\ \ or\ \ 297\,°K$$

The air properties are obtained from [38] as follows:

$$\nu = 15.67 \times 10^{-6}\ m^2/s\ \ ,\alpha = 22.3\ \times 10^{-6}\ m^2/s, k = 0.0263\ W/m.\text{K}\ , \beta = \frac{1}{T_f} =$$

$$0.00336\ K^{-1}, Pr = 0.706\ , L \equiv \frac{Surface\ of\ Area}{Perimeter\ of\ Area} = 2.04m \text{ (refer to Figure 4-3)}$$

The Rayleigh number is calculated as

$$Ra_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} = \frac{9.8 \times 0.00336 \times 10 \times 2.04^3}{15.67 \times 10^{-6} \times 22.3 \times 10^{-6}} = 8.0\ \times 10^9$$

Using a correlation from [38], the Nusselt number can be calculated as

$$Nu = 0.15 {Ra_L}^{\frac{1}{3}} = 300$$

Finally, the free convective heat transfer coefficient is obtained as follows:

$$h = \frac{k.Nu}{L} = 3.87\ \ {}^{W}/_{m^2.K}$$

Therefore heat transfer coefficient with area of 102 m^2 would be 3.87 × 102 = **395 W/K**

There is also Type 80a, a component module for calculating convective heat transfer coefficient. It was examined with similar results.

Table 4-16 shows the parameter input for the radiant floor heating module.

Table 4-16: Radiant floor heating input parameters

Input parameter	Data source
Fluid inlet temperature	Mixer
Fluid flow rate	Mixer
Zone air temperature	19 °C
Environmental temperature	10 °C
Slab to ambient loss coefficient	0
Slab to zone heat transfer coefficient	395 W/K
Heat exchanger effectiveness	0.6

Table 4-17 shows the output parameters from the radiant floor slab. The return flow of the heating liquid passes through the slab pump and then splits to two streams by diverter; one goes to the mixer for mixing with inlet flow from tank to a set temperature, and the other is directed back to the water heater tank. The basement heat transfer is directed to an equation module and from there combined with the other zone heat simulation result before sending to the house.

Table 4-17: Radiant floor heating output parameters

Output parameter	Data is sent to
Outlet fluid temperature	Pump/diverter
Outlet flow rate	Pump/diverter
Zone heat transfer	Equation module/house

4.2.7 Grey Water Heat Recovery Model

The grey water heat recovery system works on the principal of a gravity film exchanger. This takes advantage of the ultra-high rates and thermal conductive properties of water film and copper. This system has been installed to conduct the transfer of heat from the drainage water to the incoming cold city water. The model considers scheduled hot water draw. The preheated water is then supplied to the hot water tank for further heating. Incoming cold water can get as much as 85% of the waste water (grey water) heat energy [39]. Type 91, a Heat Exchanger with constant effectiveness is a simple choice from the TRNSYS modules to simulate grey water heat recovery component. In this module a zero capacitance sensible heat exchanger is modelled as a constant effectiveness device which is independent of the system configuration. For the constant effectiveness mode, the maximum possible heat transfer is calculated based on the minimum capacity rate fluid and the cold side and hot side fluid inlet temperatures. In this mode the effectiveness is input as a parameter and the concept of an overall heat transfer coefficient for the heat exchanger is not used.

Table 4-18 shows the parameters considered for this module. The effectiveness of the heat exchanger is considered as 0.85, as per “Power pipe” equipment manufacturer [39]. The effectiveness is a ratio of the actual heat exchanger heat transfer to the maximum possible heat transfer which could occur in the heat exchanger (Effectiveness = Q/Qmax). The specific heat of the fluid flowing through the hot-side and cold-side of the heat exchanger is set as water specific heat.

Table 4-18: Grey water heat recovery (heat exchanger) parameters

Heat exchanger effectiveness	0.85
Specific heat of hot side fluid	4.19 kJ/kgK
Specific heat of cold side fluid	4.19 kJ/kgK

Table 4-19 shows the input parameters to the heat recovery unit. The cold-side temperature is from the city water temperature profile (temperature forcing function module) and the flow rate is from the daily load equation module and diverter module. The hot-side temperature is estimated to be 37°C which represents the waste water temperature.

Table 4-19: Grey heat water heat recovery input parameters

Input parameter	**Data source**
Hot side inlet temperature	Equation hot water waste module
Hot side flow rate	Equation hot water waste module
Cold side inlet temperature	City cold water diverter
Cold side flow rate	City cold water diverter

The hot-side flow rate is calculated by an equation module as follow:

$$q_{system} = (T_{out} - T_{in}) \times 4.19 \times flowrate \quad (4-4)$$

where q_{system} is the heat delivered by the system to heat the domestic hot water, T_{out} is hot water temperature to the house, T_{in} is the city water temperature from the water temperature module and flow rate is the hot water flow rate. The hot water flow rate is the waste water flow rate which is calculated as follows:

$$Waste\ flow = \frac{q_{system}}{4.19 \times (T_{in\_Recovery} - T_{out\_recovery})} \quad (4-5)$$

where $T_{in\_Recovery}$ is estimated to be 37°C. As $T_{out\_recovery}$ cannot be less than city water temperature (Figure 4-6), it is assumed to be 12°C, considering the equipment effectiveness from the manufacturer and the monthly water temperature profile.

Table 4-20 shows the outputs from the grey water recovery heat exchanger that feed the temperature and flow rate to the hot water tank through the mixer.

Table 4-20: Grey water heat recovery output parameters

Output parameter	**Data is sent to**
Hot side outlet temperature	Mixer/ hot water tank
Hot side flow rate	Mixer/ hot water tank

4.2.8 Ventilation Model

Type 667b, Air-to-Air Heat Recovery is used for modelling ventilation to the house. In this model, the inputs are ambient temperature and relative humidity from the weather module, and the second floor temperature and flow rate are considered as return air characteristics. The outputs of the module are temperature (T_{HRV}) and relative humidity of the HRV. Section 4.2.1 presents information for this module and equipment.

4.2.9 Flow Control and Pump Component Model

Mixers, diverters and pumps are modelled using TRNSYS standard library component models and are explained in the following sections.

4.2.9.1 Control Flow Mixer

Type 11d, Controlled Flow Mixer is used in two places in the model: 1- for mixing return flows from the heat pump and solar panels, and 2- for mixing grey water exchanger cold-side output flow with part of the return flow from the radiant slab. The control flow mixer is used for mixing two stream flows with different percentage of flow in each stream. The flow rate and temperature of the two steams as well as the control signal are inputs to the module. The output would be the flow rate and temperature of mixture. Equation 4 – 6 shows the mathematical relation of the two flows:

$$\dot{m}\ (out) = \dot{m}1\ (in) \times (1 - y) + \ \dot{m}2\ (in) \times y \qquad (4-6)$$

where "$\dot{m}$" represent the flow rates and "y" is the fraction of flow $0 < y < 1$.

"y" is an important fraction for this study specially in solar collector-heat pump flow fractions. The default for this number is 0.1. This means that 10% of the fluid in GHX is from the solar panel and 90% is from the heat pump.

4.2.9.2 Control Flow Diverter

Type 11f functions as the control flow mixer but in the opposite direction. The control signal sets the position of a damper controlling the proportion of fluid to each exit.

$$\dot{m}_1 = \dot{m}_{in} \times (1\text{-y}) \qquad (4-7)$$

$$\dot{m}_2 = \dot{m}_{in} \times \text{y} \qquad (4-8)$$

This module has been used in two places: 1- splitting the flow between the solar panels and the heat pump, and 2- diverting the hot water tank flow to the floor slab and house.

4.2.9.3 Tee Piece

Tee piece is acting as a flow mixer without control. Module Type 11h is used in two locations in the model: 1- in the return slab flow and the hot water tank flow to slab, and 2- mixing the domestic cold water with the hot water from hot water tank.

4.2.9.4 Tempering Valve

Type 11b is an instance of the Type11 model that uses mode 4 or mode 5 to model a temperature controlled liquid flow diverter. In mode 4 the entire flow stream is sent through outlet 1 when T_h (heat source fluid temperature) is less than T_i (temperature of inlet fluid). In mode 5, the entire flow stream is sent through outlet 2 under these circumstances. This module is used in two places in mode 4: 1- to control the temperature of hot water sent to the house, and 2- to control the temperature of the hot water sent to the radiant floor slab.

4.2.9.5 Single Speed Pump

Type 114, a single (constant) speed pump is selected for this model. It works as integral part of the heat pump for sending and receiving exchanger loop liquid to/from the ground. It is able to maintain a constant fluid outlet mass flow rate. Pump starting and stopping characteristics are not modelled, nor are pressure drop effects. As with most pumps in TRNSYS, Type 114 takes mass flow rate as an input but ignores the value except to perform mass balance checks. Type 114 sets the downstream flow rate based on its rated flow rate parameter and the current value of its control signal input. In this study, the parameters of pump are set per manufacturer specifications for a rated flow rate of 1600 kg/hr and a power of 750 W capacity. Fluid properties would be the same as the ground loop fluid, an aqueous solution of 50% propylene glycol. The overall pump efficiency is 0.6, and that includes the inefficiencies due to the motor and shaft friction. Considering the pump and its motor efficiencies to be 0.85 and 0.70, respectively, the overall pump efficiency would be 0.6 ($0.85\times 0.70 = 0.6$).

4.2.10 Heat Pump Equipment Control and Scheduling

To control the heat pump ON/OFF position, a thermostat has been defined for commanding the heat pump to start or shut off when heating or cooling is demanded. By utilizing the cooling and heating season controls, plus forcing functions for heating set back, heat pump is switched from heating mode to cooling mode, and vice versa when necessary.

4.2.10.1 Thermostat

Type 698 is a five-stage multi zone room thermostat version. This ON/OFF differential device models a five stage room thermostat, which outputs five control signals that can be used to control an HVAC system having a three stage heating source and a two stage cooling source. This version of the model is designed to allow specifying multiple temperatures to be controlled by specific set points. For this module, three zones were defined with a temperature dead band of 2°C. This means thermostat is having hysteresis effects of 2°C, that above and below set points, the thermostat activates. The basement zone temperature is set to 19°C, where as the first and second floor temperature set points are 24°C and 21°C in cooling and heating modes, respectively.

The overall condition signal from the output parameters of the thermostat is sent to the heat pump to activate. This signal is ON when a zone commands for heating or cooling.

4.2.10.2 Heating Setback Forcing Function

To complement the function of the thermostat, there is a heating setback forcing function through the Type 14e module. Figure 4-4 shows the setback schedule. The heating set point with this forcing function falls from 21°C to 19°C at night time, defined as between 22:00 to 08:00 hr.

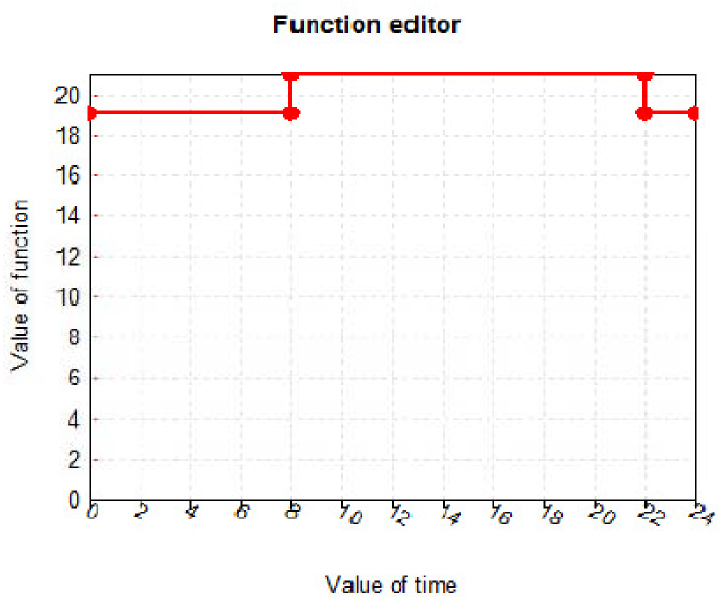

Figure 4-4: Heating set back temperature control in 24 hours

4.2.10.3 Season Heating and Cooling Forcing Function

The Type 14k module is selected for the heating forcing function and 14l selected for the cooling season cooling forcing function. Table 4-21 shows the values defined for these forcing functions. The output value, which is either 0 or 1, will be multiplied by the output value control of the thermostat through the equation module for final control to the heat pump.

Table 4-21: Cooling and heating season timing

	Time (hr)	Time (Month)
Cooling Season	2881 to 6552	1st May to 31st September
Heating Season	6552 to 2880	1st October to 30th April

4.2.11 Solar Thermal Equipment Controls and Scheduling

An equation module controls the solar collector's circulating flow loop, which gives the output of multiplying the control value of the heating season and forcing functions that become "on" when the temperature of the solar collector is greater than the output temperature. This means that the flow control diverter closes the flow to the solar panels in the cooling season at nights and on cloudy days when there is no solar radiation.

4.2.12 Domestic Cold and Hot Water Draw Model

Type 14b is used as a forcing function for cold water draw. Figure 4-5 shows typical water draw selected [40] for a typical house in Toronto.

By considering 225 litres/day of hot water consumption for a typical house with occupancy of two adults and two children 50% of time, the cold water draw profiles are multiplied by 225/100 as a percentage factor and simulate the timely need of hot water for the house.

The cold water temperature during a 24 hours period is also defined for Toronto [40] in a temperature forcing function as shown in Figure 4-6. The above temperatures, along with hot water demand are sent to a temperature control valve to control the hot water temperature to the house.

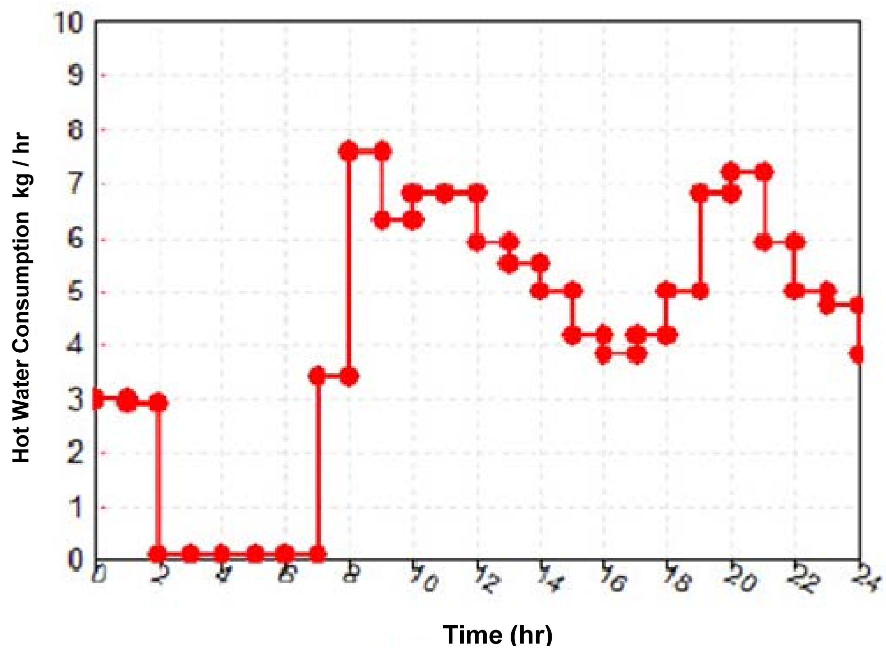

Figure 4-5: Hot water consumption in 24 hours vs. flow rate (kg/hr) [40]

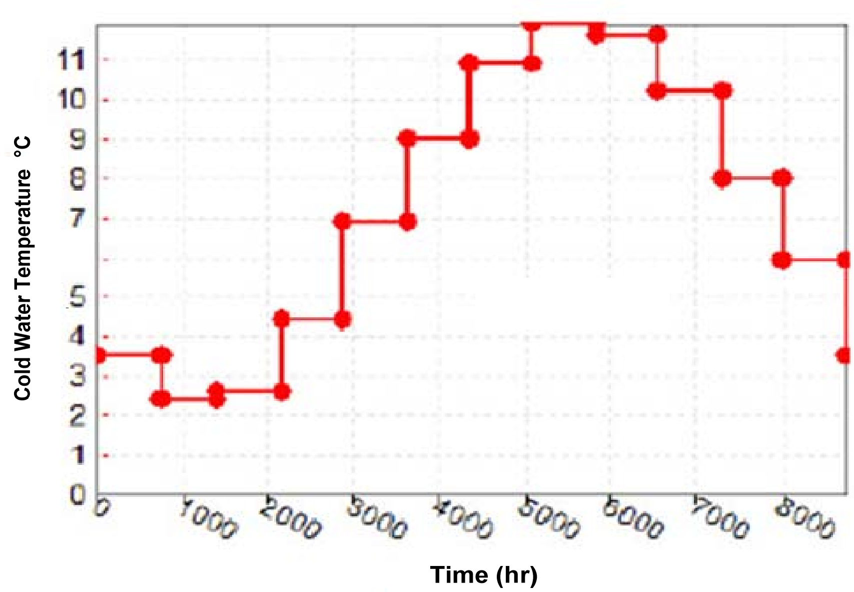

Figure 4-6: Cold water temperature (°C) during a year (monthly) [40]

4.3 System Layout in TRNSYS studio

Figure 4-7 shows the detail system layout as it looks in TRNSYS Studio. TRNSYS Studio is the main visual interface from which the project is being created. Appendix C shows generated input file through simulation studio.

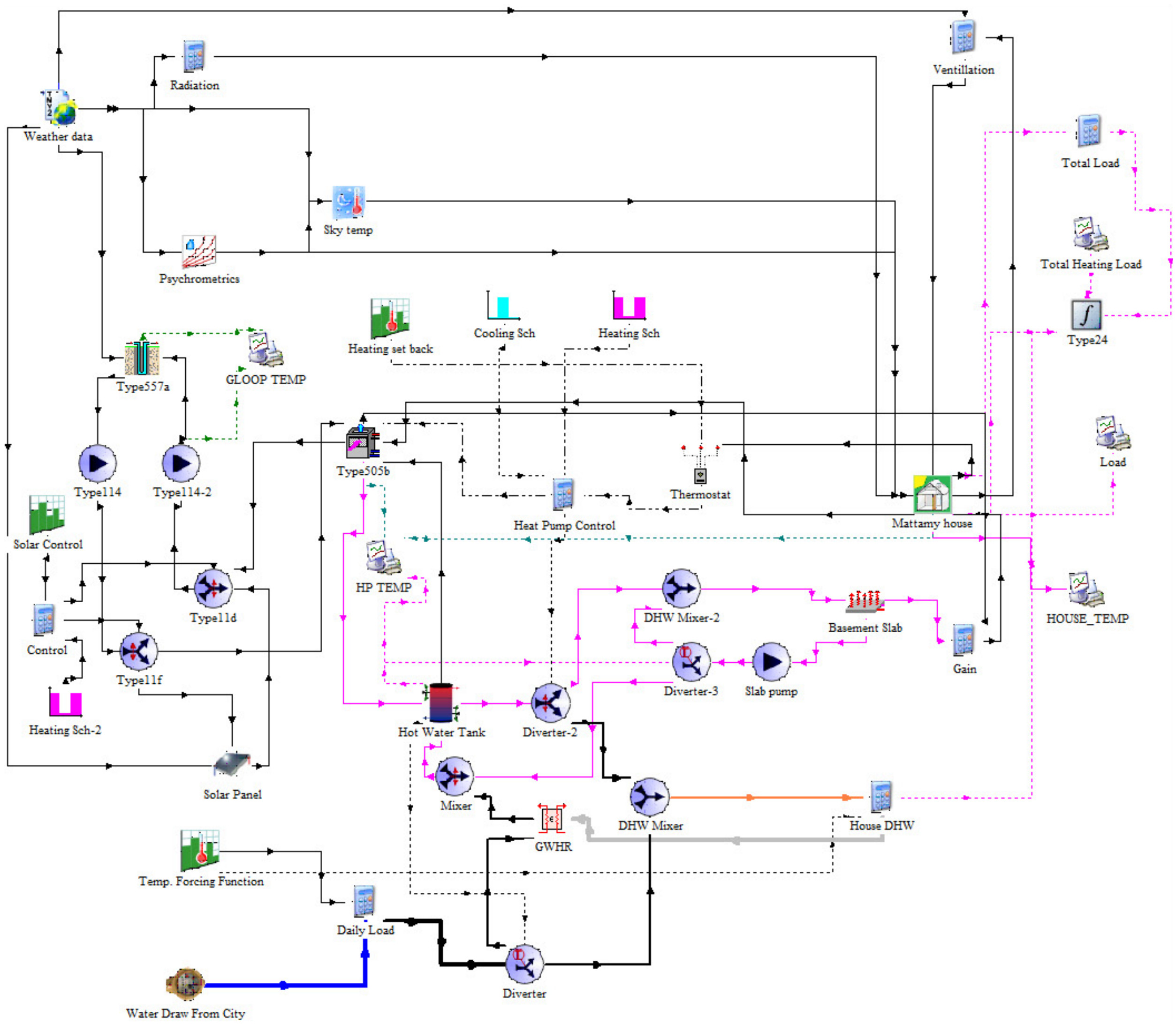

Figure 4-7: TRNSYS Model Schematic

Chapter 5
Ground Loop and Solar Thermal Collector Sizing

5.1 Unknowns of the As-Built House

In the as-built system model described in chapter four, there are two major unknown parameters:

1- Ground soil characteristic and thermal properties.
2- The solar collector fluid flow rate diverted from the ground loop.

The system is modelled and simulated with different soil conductivities first to examine the effect of this parameter. Then the model is tested with different solar collector flow rates with an estimated soil thermal conductivity to obtain the optimum solar collector flow rate.

5.1.1 Ground Soil Characteristic and Thermal Properties

According to Tarnawski and Leong [41], soils can be divided into three textural groups:

- sandy: sands
- loamy: loamy sands, sandy loams, loams
- Clayey: clay loams, silty clay loams, clays.

Natural soils are a mixture of sand, silt, and clay, and therefore, have intermediate structure and properties.

Soil heat capacity (specific heat) and thermal conductivity are two thermal properties needed for sizing the ground source heat pump (GSHP). Heat capacity indicates the ability of a substance to store thermal energy; the greater its heat capacity, the more heat it can gain (or lose) per unit rise (or fall) in temperature. The heat capacity of dry soil is about 0.836 kJ/kgK, which is only one-fifth of the heat capacity of water. Therefore, moist or saturated soils have greater heat capacity, typically in the range of 0.96 to 1.05 kJ/kgK [42]. For moderate soil moisture (30% mass) and a typical soil density of 1760 kg/m^3 in Toronto [41, 42], input for the TRNSYS ground heat storage capacity is estimated to be 1820 kJ/m^{3}K. Light, dry soils experience greater seasonal temperature swings at a given depth than wet soils. This is because their lower heat capacity causes their temperatures to rise or fall more than wet soils for a given amount of heat energy gained in the spring or lost in the fall. Thermal conductivity indicates the rate at which heat can be transferred between the ground loop and the surrounding soil for a given temperature gradient. The thermal conductivity of soil and rock is a critical value that determines the length of pipe required. This, in turn, affects the installation costs as well as the energy requirements for pumping working fluid through the ground loop. Table 5-1 indicates the thermal conductivity of different soil types. The heat transfer capability tends to increase as soil textures become increasingly fine, with loam mixtures having an intermediate value between sand and clay. Also shown in Table 5-1, the thermal conductivity of any soil greatly improves if the soil is saturated with water. This effect is much greater for sandy soils than for clay or silt, since coarse soils are more porous and therefore hold more water. Therefore, groundwater level is another important site factor in evaluating a potential GSHP project and optimizing the depth at which loops should be installed.

Table 5-1: Thermal conductivity of different soil types [42].

Soil Texture	**Thermal Conductivity**
Class	**(W/mK)**
Sand	0.76
Clay	1.11
Loam	0.90
Saturated sand	2.49
Saturated silt or clay	1.66

For the as-built condition of the system, the borehole length is 55 m. Examining the model with different soil thermal conductivities and a fixed entering fluid flow rate to the heat pump of 1273 kg/hr (5.8 USGPM), results in different heat pump (HP) entering fluid temperatures (EFT). Figures 5-1(a) to 5-1(d) show the entering fluid temperatures to the heat pump for four different selected soil thermal conductivities. For soil thermal conductivities less than 0.85 W/mK the peak EFT to the heat pump falls way below 0°C in heating mode and simulation stops (the EFT to the heat pump is the same as the exiting fluid temperature from the ground loop). The peak EFT to the heat pump is one of the most important and critical parameters in sizing a GSHP system [43].

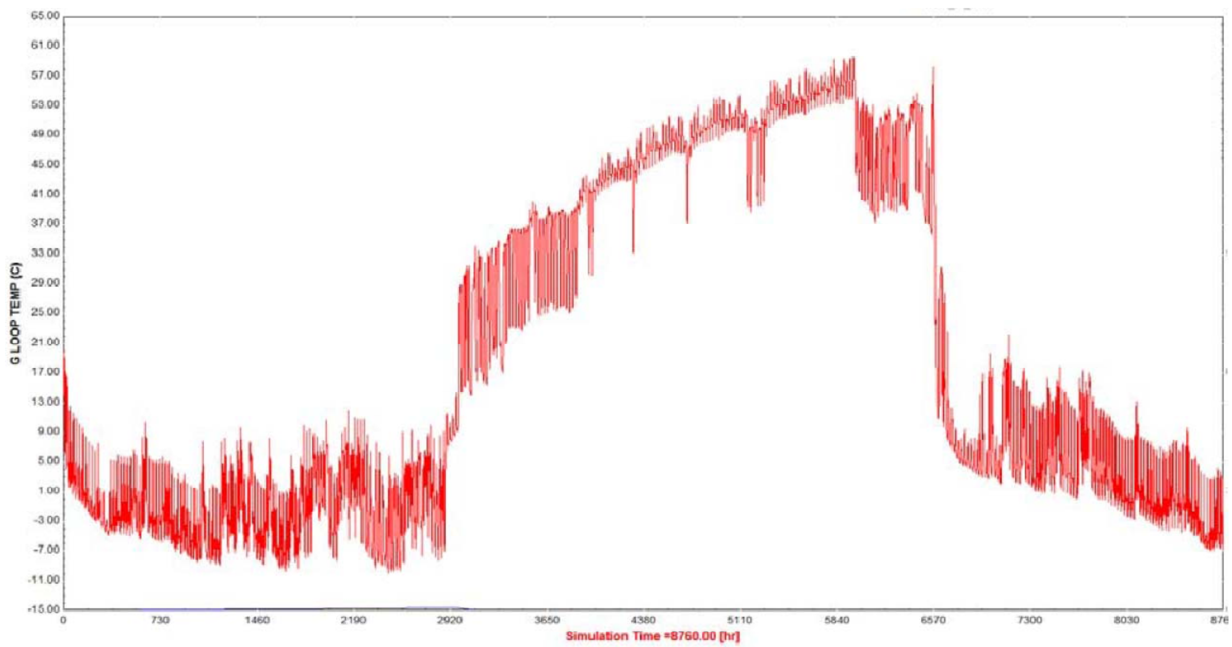

Figure 5-1 (a): EFTs to HP for a soil thermal conductivity of 0.85 W/mK

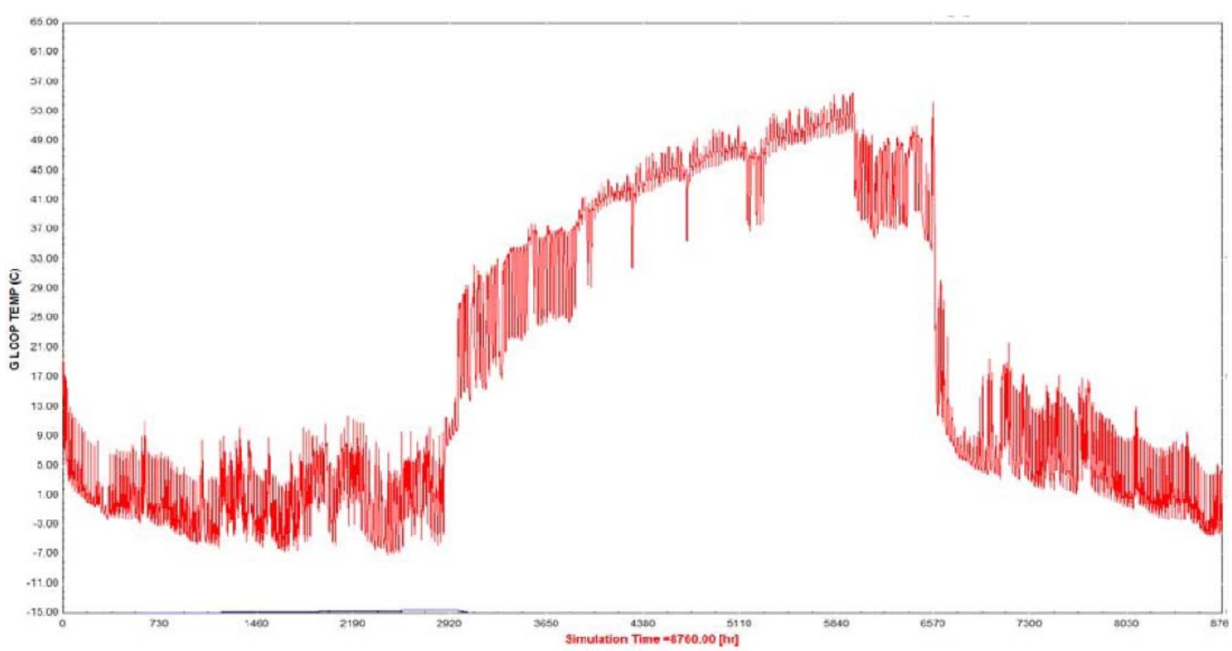

Figure 5-1 (b): EFTs to HP for a soil thermal conductivity of 1 W/mK

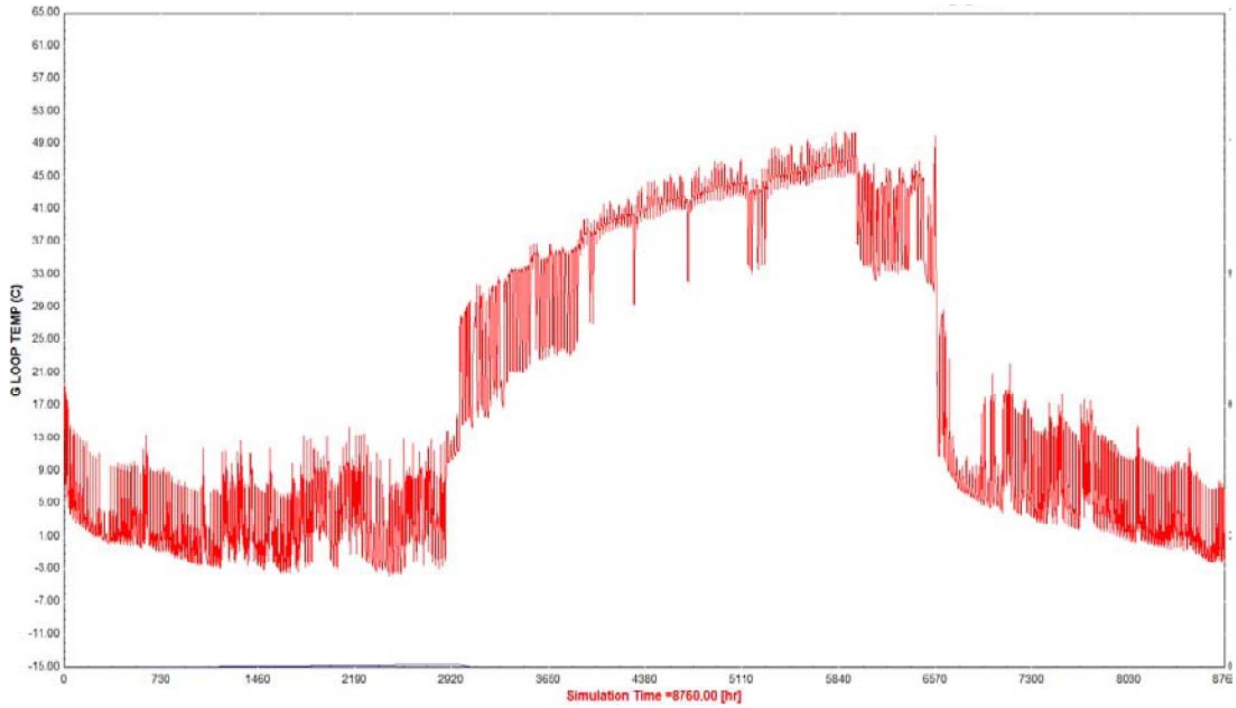

Figure 5-1 (c) EFTs to HP for a soil thermal conductivity of 1.5 W/mK

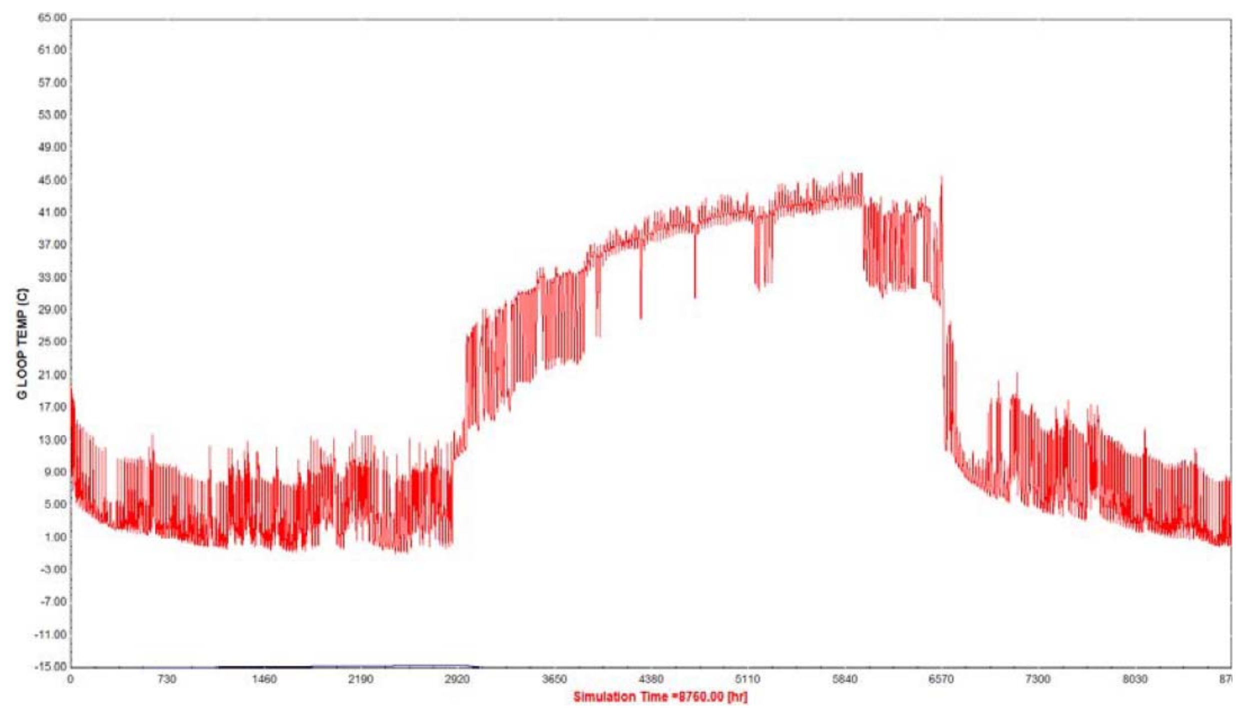

Figure 5-1 (d): EFTs to HP for a soil thermal conductivity of 2 W/mK

As per ASHRAE recommendation[21], selecting peak EFT to be 11 to 17°C higher than temperature of undisturbed soil in cooling, and 6 to 11°C lower than the temperature of undisturbed soil in heating is a good compromise between initial cost and efficiency. Considering the soil temperature in the Toronto region [44] to be an average of 10°C (283 K), as shown in Figure 5-2, the minimum and maximum (peak) design entering fluid temperatures are estimated to be:

$$EFT_{min} = T_{ground} - 11°C \rightarrow EFT_{min} \approx 0°C \quad (5\text{-}1)$$

$$EFT_{max} = T_{ground} + 17°C \rightarrow EFT_{min} \approx 27°C \quad (5\text{-}2)$$

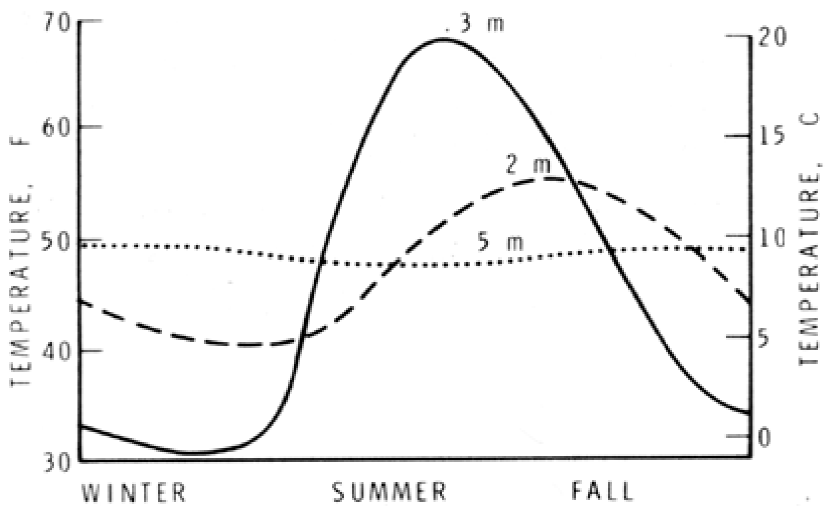

Figure 5-2: Annual variation of soil temperatures at three different depths – Toronto [44]

According to the International Ground Source Heat Pump Association (IGSHPA) who establishes the design and installation standard for geothermal heat pump systems, for closed-loop systems the EFTs to the heat pump are rated at 0°C for heating and 25°C for cooling. These are a good match with the estimated values [45]. Accordingly, selecting soil thermal conductivity is restricted to be greater than 2 W/mK with defined closed loop lengths and characteristics.

5.1.2 Solar Collector Fluid Flow Rate

The percentage of the ground loop flow rate to solar collectors is controlled by the Diverter and Mixer control signal through separate control equations in the model. By setting the control signal from 0.1 to 0.9, there would be 10 to 90% of ground loop flow rate directed to the solar collectors, with the rest to the heat pump. In this study, five different controls are examined, and the results compared to the base case.

5.1.2.1 Base Case

For this case, the ground loop heat exchanger is used without solar thermal collectors; the Diverter and Mixer control signal is set to "0". The simulation is run for one year and the results for ground loop fluid temperatures and heat pump energy consumptions are shown in Table 5-2. For comparison, the heating and cooling demand of the house was estimated to be 95 GJ and 19 GJ, respectively (Chapter 3).

Table 5-2: HP annual energy consumption and peak ground loop temperatures for base case

HEAT PUMP					
Heating Mode			Cooling Mode		
Min. Fluid Temperature (°C)		Total Energy Consumption (MJ)	Max. Fluid Temperature (°C)		Total Energy Consumption (MJ)
IN	OUT		IN	OUT	
0	-7	44,793	32	40	6,434

5.1.2.2 As-Built Solar Collector Case

As mentioned in Section 4.2.4 of Chapter 4, the as-built solar collectors are manufactured by Enerworks [26]. According to equipment data the maximum fluid flow rate that could be run through the three panels of the solar collector is 0.54 USGPM (120 kg/hr), considering the total flow rate through the ground loop to be 5.8 USGPM (1293 kg/hr). The maximum flow through the solar collectors would be less than 10% of the total ground loop flow rate. The model is examined with two different solar collector flow rates along with the base case, and their results are shown in Table 5-3.

The results from Table 5-3 show that in heating mode, increasing the fluid flow to the solar collector favours system performance and reduces the total energy consumption of the heat pump. However, in cooling mode, this goes against system performance, and would increase the energy consumption of the heat pump. Also shown in heating mode, the minimum fluid temperature to the heat pump is in the range of the designed temperature, whereas in cooling mode, the maximum temperature exceeds the suggested design temperature. This results in a lower heat pump performance in cooling season.

In conclusion, in the as-built case, a thermal conductivity of soil of 2 W/mK and 10% fluid rate to the solar collectors would be the optimum and feasible.

Table 5-3: Heat pump annual energy consumption with different solar collector flow rate

	HEAT PUMP			
	Heating Mode		**Cooling Mode**	
% of Flow to Solar Collector	Min. Fluid Temp. IN (°C)	Total Annual Energy (MJ)	Max. Fluid Temp. IN (°C)	Total Annual Energy (MJ)
0%	0	44,793	32	6,434
5%	1	44,581	33	6,945
10%	2	44,274	35	6,950

Figure 5-3 shows the simulation result of the heat pump fluid entering temperature and accumulative energy consumption of the heat pump for the optimum case.

5.2 Controls on Fluid Flow to the Solar Collectors

In order to stop circulating fluid flow through solar collectors at nights or on cloudy days when there is not solar energy available, the model uses a control to check the solar collector inlet and outlet fluid temperature. There would be no solar energy if the outlet temperature of the solar collectors is detected as being lower or equal to the inlet temperature. In this instance, the flow diverter control signal changes to zero to stop flow circulating to the solar collectors.

In the cooling season, by stopping the circulating fluid flow to the solar collectors at nights, the sky cooling effect would be ignored. Figure 5-4 shows that when there is a continuous fluid flow through solar collectors during the nights, the EFT to the heat pump can be reduced by 1°C to 1.5°C. Therefore, having continuous fluid circulation to the solar collectors favours the system performance. Although it is interesting to know that night-time cooling at the solar collectors can improve ground source heat pump performance in the cooling season, it will not be further investigated, because it is not a focus in the thesis.

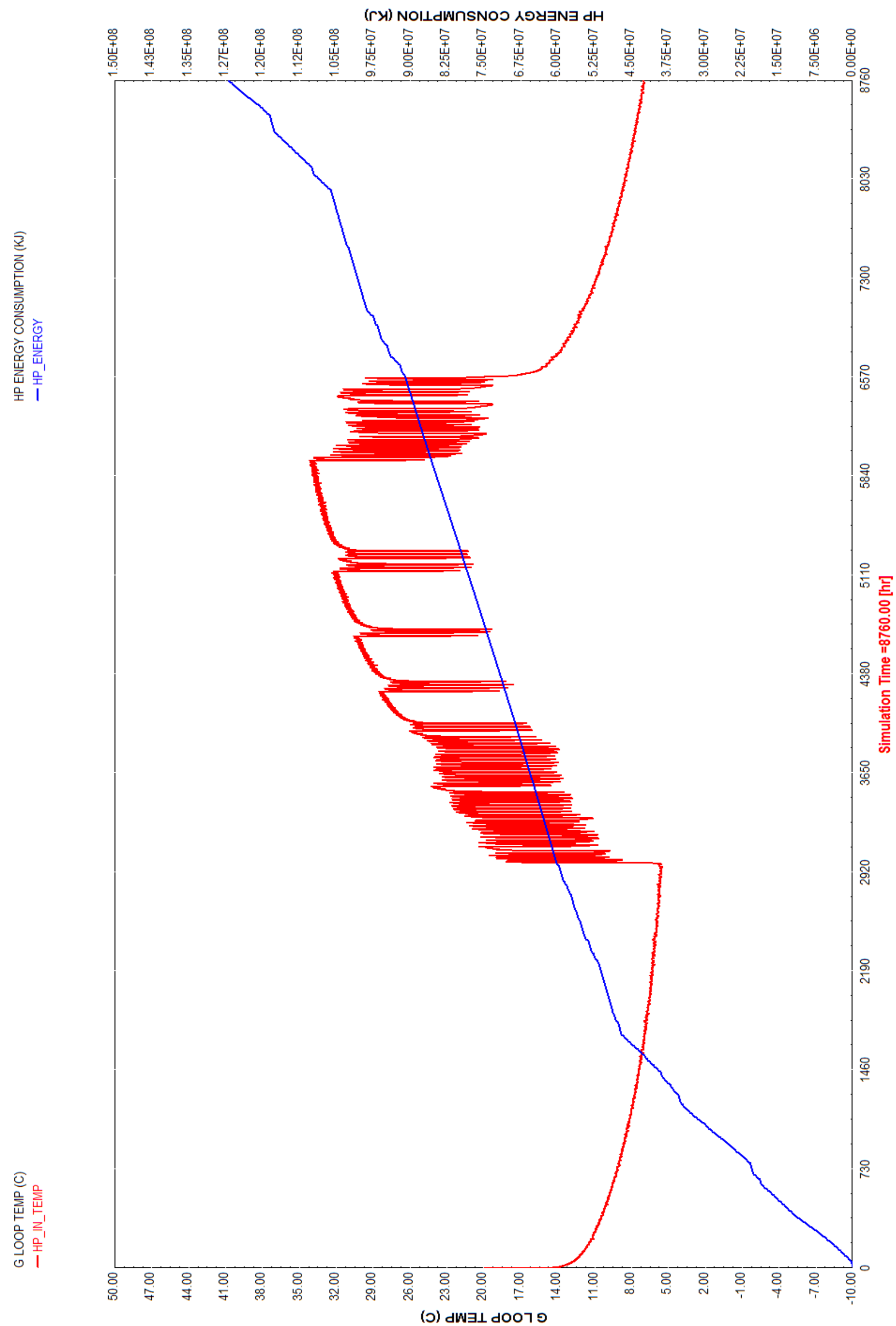

Figure 5-3: As-built heat pump energy consumption and entering fluid temperature (one year)

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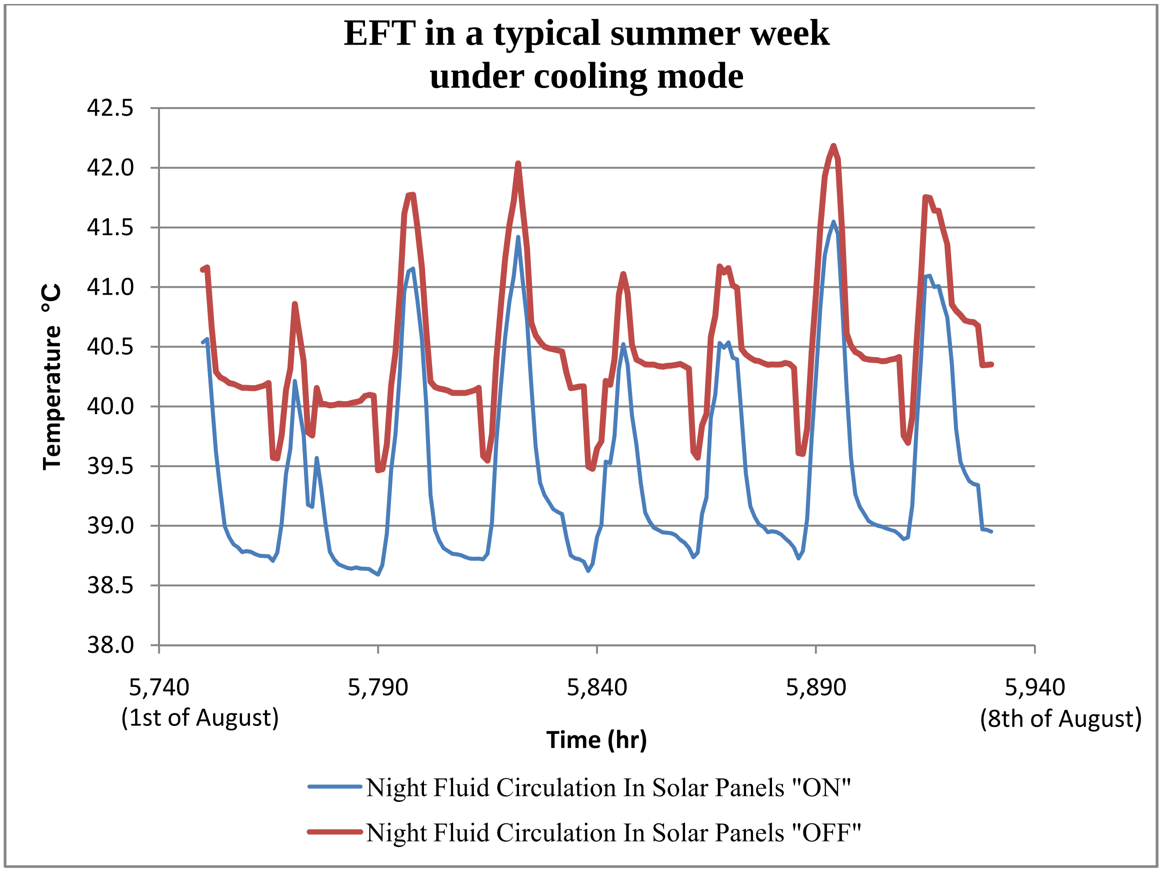

Figure 5-4: Heat pump EFT in the cooling mode in a typical summer week.

(with and without night time fluid circulation in solar collectors)

Chapter 6

Analysis of System Performance and Sensitivity Analysis

6-1 Field Testing and Verification of Hybrid Solar-GSHP System

The house selected and modelled for the purpose of this study was equipped with metering and measuring sensor devices in different locations of the house and its HVAC system. The data was recorded for more than a year mostly in year 2007. The metering sensors of interest for this study were located in the heat pump. They could measure the IN and OUT temperatures of the ground loop fluid to the heat pump, as well as metering the electricity consumption of the heat pump and its auxiliary heater. Due to some error in registering data, the following readings could only be extracted for the study:

1- Fluid temperature IN to heat pump from the ground loop for the period May to December 12, 2007.
2- Fluid temperature OUT from heat pump to the ground loop for the period May to December 12, 2007.
3- Heat pump electricity consumption for the month of August, 20 days; November, 30 days and December, 12 days.
4- Heat pump auxiliary heater electricity consumption for the month of August, 20 days; November, 30 days and December, 12 days.

Table 6-1 shows the minimum and maximum actual data recorded for the IN and OUT fluid temperatures to the heat pump, along with the corresponding simulated data for comparison.

Table 6-1: Actual versus simulated data for heat pump IN and OUT fluid temperature

	Actual		**Simulated**	
Months	**HP Entering Fluid Temp**		**HP Entering Fluid Temp**	
Year 2007	**Min (°C)**	**Max (°C)**	**Min (°C)**	**Max (°C)**
MAY	17.0	34.0	11.5	31.0
JUN	10.0	38.0	9.8	34.4
JUL	9.0	38.0	13.5	37.3
AUG	9.0	36.0	14.6	38.8
SEP	8.0	35.0	13.5	39.1
OCT	5.0	35.0	5.2	35.6
NOV	2.0	15.0	3.4	8.0
DEC	0.3	12.5	2.3	6.3

Figure 6-1(a) shows the actual maximum entering fluid temperature (EFT) to the heat pump (HP) versus the simulated data in the cooling season and Figure 6-1(b) shows the actual minimum EFT to the heat pump versus the simulated data in heating season.

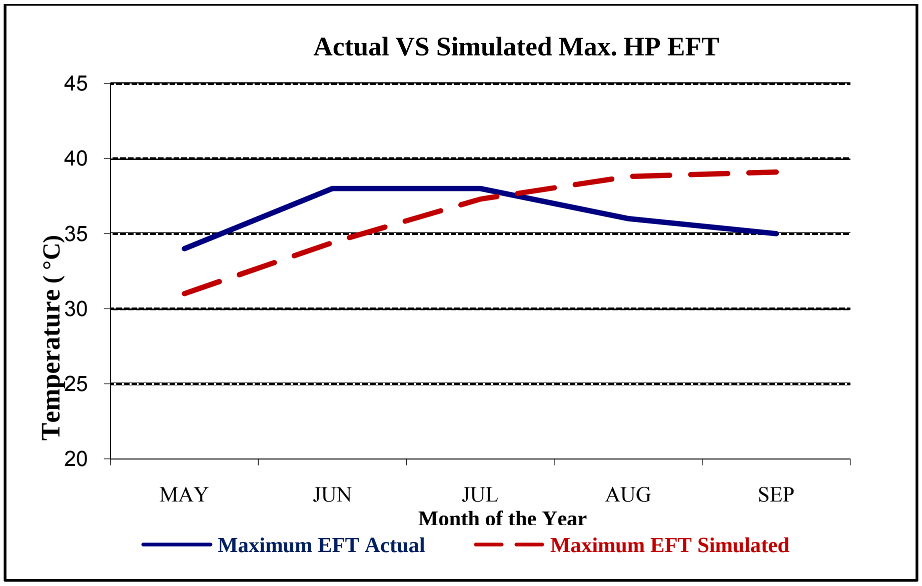

Figure 6-1(a): Actual versus simulated maximum EFT to the HP – Cooling Season

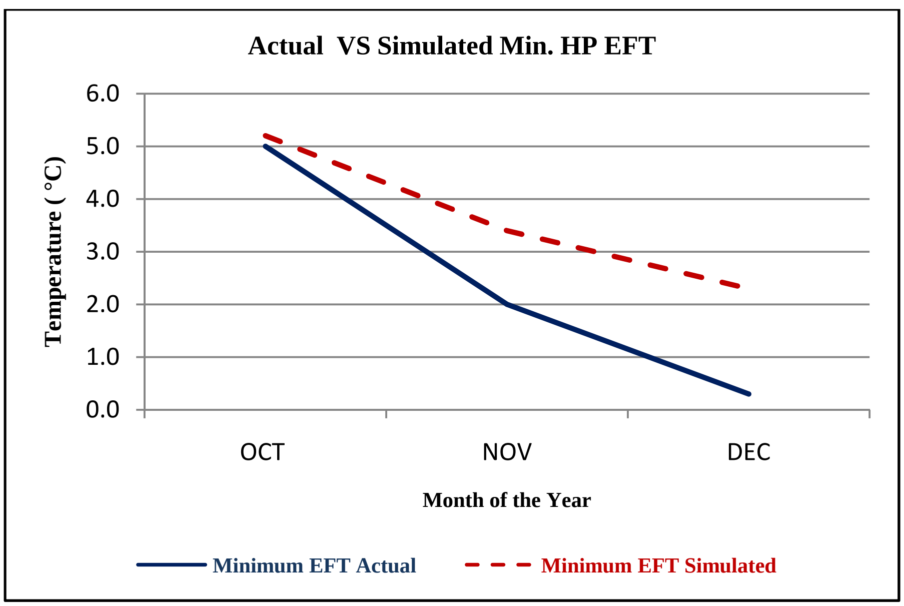

Figure 6-1(b): Actual versus simulated minimum EFT to the HP – Heating Season

From Figures 6-1(a) and 6-1(b), it can be seen that the actual fluid temperature entering the heat pump in the heating and cooling seasons almost matches the simulated data. From Figure 6-1(a), it can also be seen that in months of July to September, the actual heat pump entering fluid temperatures fall below the simulated data. This was because the heat pump was shut off during this period. The simulated data for the cooling season is obtained by selecting another heat pump data, rather than the actual installed heat pump data. As the capacity of the selected heat pump in cooling season is restricted to maximum 35 °C, the selected heat pump would not be able to work efficiently with an EFT greater than 25 °C, as its COP would fall below three, and by having an entering temperature above 35 °C, the heat pump would stop functioning. Appendix D shows the specification data for the heat pump installed in the house.

By studying the simulation results, Figure 6-2 shows that the EFT would be above 35 °C in certain periods of the cooling season. This is mentioned as a "No performance period" where the heat pump stops functioning. This occurs between 4400 to 6570 hour, which is the beginning of June and the end of August.

By disconnecting the solar thermal panels from the system, the simulation results show that the EFT will not pass 35°C. They also show that the heat pump functions well in cooling season, even though there would be a time when the heat pump would work in a lower COP. Figure 6-3 shows the entering heat pump fluid temperature limits in the same system without solar panels. One reported problem from the house was malfunctioning of the system during the cooling season. Based on the above discussions, for this system in cooling season, it is suggested that the fluid flow from the solar thermal panels should not be sent to the ground in the "No performance period". Alternatively in the existing case, a higher cooling capacity heat pump should be sized and selected. Both solutions apply if the ground exchanger loop is kept in its existing condition.

Figures 6-4 and 6-5 show a typical one-week EFT to the heat pump in the cooling and the heating season, respectively. Both figures show the data for systems with three solar collectors and without solar collectors. The case with solar collectors always has higher EFT and can be up to about 2.5°C to 3.0°C higher than the case without solar collectors at some instances. It is evident that the solar collectors do devastate the performance of GSHP during the cooling season, but opposite is true for the heating season.

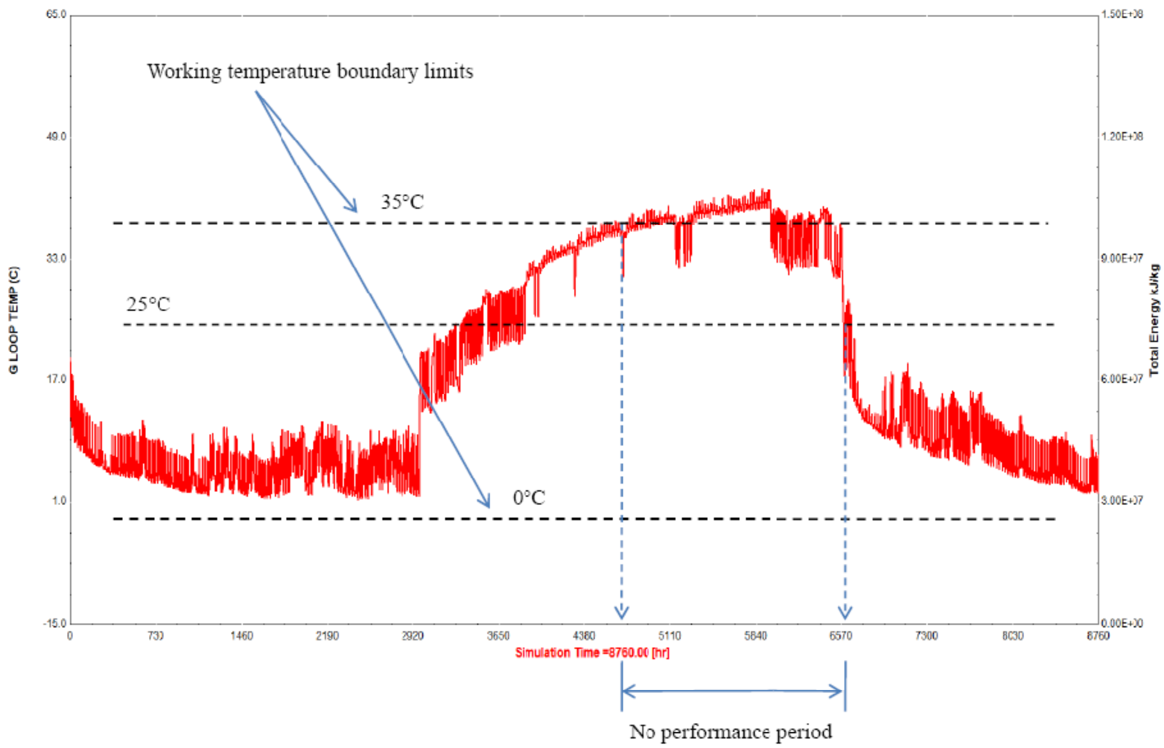

Figure 6-2: Existing heat pump EFT limits (system with three solar panels)

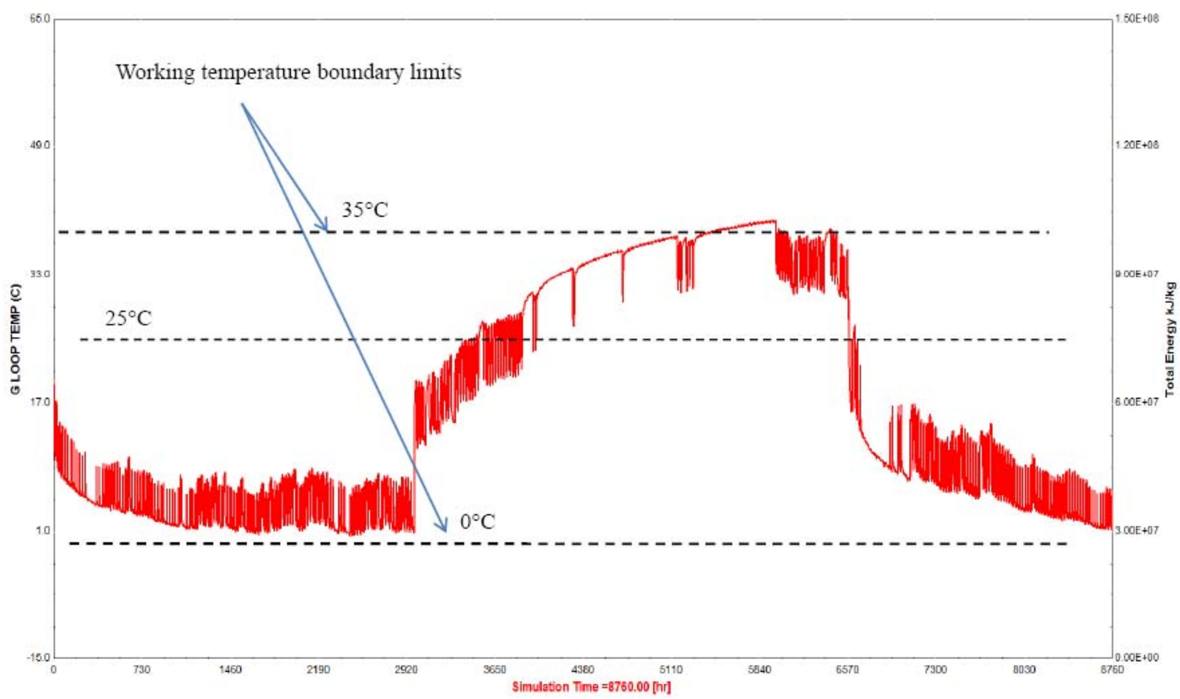

Figure 6-3: Existing heat pump EFT limits (system without solar panels)

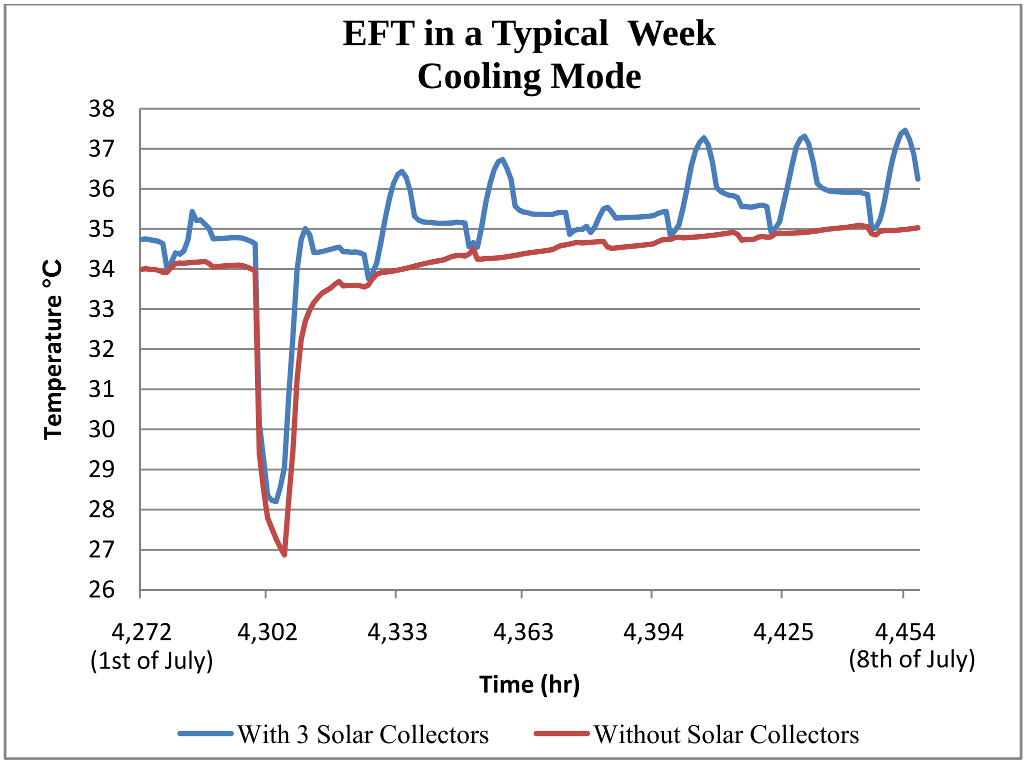

Figure 6-4: Heat pump EFT in a typical week of cooling season

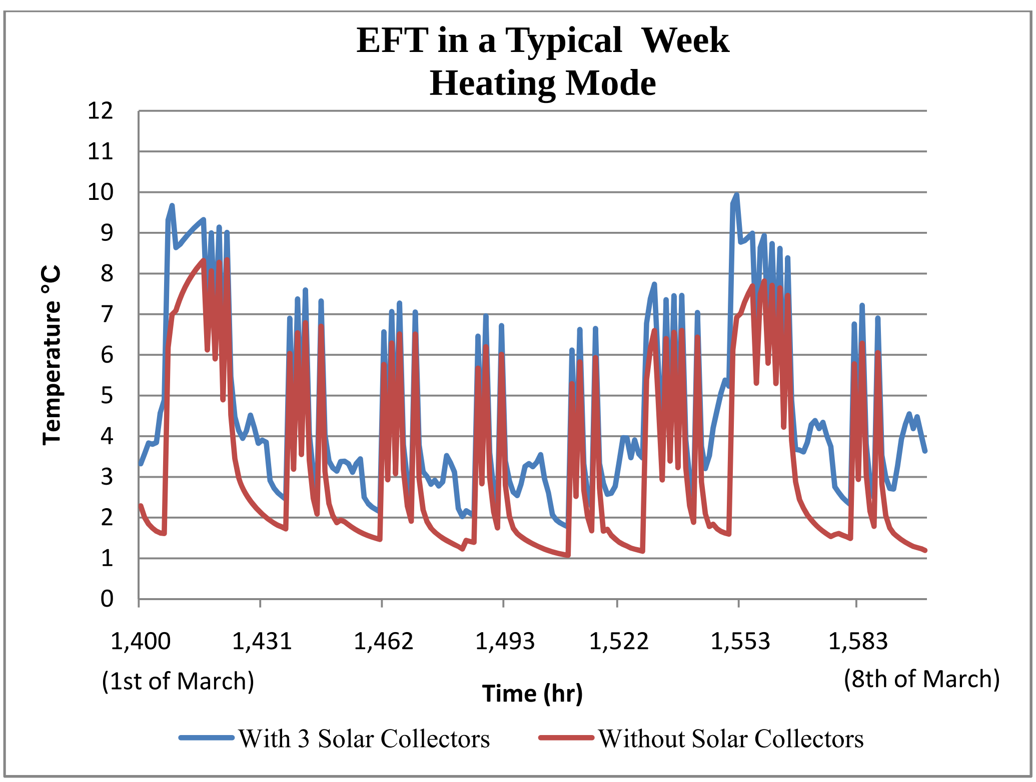

Figure 6-5: Heat pump EFT in a typical week of heating season

Table 6-2 shows the energy consumption of the heat pump in the months and dates available. N/A denotes that data in some of the actual readings were not available. There are only 20 days of data available in the cooling season in the month of the August. Here, the amount of energy consumed by the heat pump is unrealistic and shows that the heat pump is running with very low efficiency. It shows that if the heat pump was properly sized for cooling mode it would have consumed almost 72% less energy and system would have never failed and shut down.

Table 6-2: Actual and simulated heat pump energy consumption

Months	Number of	Actual (MJ)		Simulated (MJ)	
Year 2007	days	**HP**	**AUX**	**HP**	**AUX**
AUG	20 days	13,244	1,087	3,927	0
SEP	N/A	N/A	N/A	N/A	N/A
OCT	N/A	N/A	N/A	N/A	N/A
NOV	30 days	12,747	4,140	11,448	4,392
DEC	12 days	6,559	756	5,007	2,106

In the heating season, the situation is fine. Table 6-3 shows, the energy consumed by the heat pump matches the simulated data. In November, there is a 6% deviation between the actual data and simulated data, whereas December, this is about 2.7%. The deviation ranges are quite acceptable, and most likely originate from actual and simulated weather data. As mentioned before, the weather data used in simulations was the default TMY2 data in TRNSYS. Table 6-4 shows the actual degree days in the year 2007 as reported by Environment Canada to compare with the default TRNSYS degree days for the City of Toronto [46].

Table 6-3: Actual versus simulated heat pump energy consumption in heating mode

Months	Number of	Total System Energy		Deviation %
Year 2007	days	Actual (MJ)	Simulated (MJ)	Actual vs. Simulated
NOV	30 days	16887	15840	6.0
DEC	12 days	7315	7113	2.7

Table 6-4 shows that the heating degree days in TRNSYS were 108.8% of heating degree days in 2007, and the cooling degree days in TRNSYS were 44.3% of the cooling degree days in 2007. In the heating season, the less actual degree days justifies the 6% deviation of actual and simulated data, and higher actual degree days is against the system in cooling season. Table 6-5 shows the adjusted deviation percentage presented in Table 6-3. From these, it is concluded that the simulated model is within 0.01% to 2.7% of the actual model by considering the actual weather data in adjusting the simulation results. These small deviations could be the result of slight weather differences between Toronto and Milton, which is about 60 km west of Toronto. The hourly local weather data for Milton was not available at the time of this study. The approach of adjusting the simulation data follows the PRISM method [47]. PRISM is a statistical procedure that uses heating and cooling degree days to produce a weather-adjusted index of the energy consumption of a house or building. This finding shows that it is important to simulate using actual yearly weather data which corresponds to the year of actual field readings if excellent agreement between actual and simulated data is required; otherwise, differences within 10% can be expected when the default TMY2 data in TRNSYS is used.

Table 6-4: Actual year 2007 degree days versus TRNSYS (TMY2) weather data

Month	YEAR 2007 Degree Days		TRNSYS TMY2 Degree Days		Percentage of 2007	
	Heating	Cooling	Heating	Cooling	Heating	Cooling
JAN	647.1	0.0	745.7	0.0	115.2	0.0
FEB	740.1	0.0	671.8	0.0	90.8	0.0
MAR	546.7	0.0	568.3	0.0	104.0	0.0
APR	356.4	0.0	360.7	0.0	101.2	0.0
MAY	136.4	22.4	168.7	0.9	123.7	4.0
JUN	16.5	99.2	48.5	33.2	294.2	33.4
JLY	3.2	106.1	3.9	90.9	123.5	85.7
AUG	5.2	141.0	8.2	59.6	159.3	42.3
SEP	36.9	47.5	106.1	8.4	287.4	17.7
OCT	137.7	19.8	288.1	0.0	209.2	0.0
NOV	462.5	0.0	440.7	0.0	95.3	0.0
DEC	630.7	0.0	636.7	0.0	101.0	0.0
Total	**3,719.4**	**436.0**	**4048.0**	**193.0**	**108.8**	**44.3**

Table 6-5: Adjusted deviation between actual and simulated heat pump energy consumption

Months Year 2007	Number of days	Total system Energy Actual (MJ)	 Simulated(MJ)	Adjusted Simulated(MJ)	Deviation% Actual vs. Simulated	Adjusted Deviation %
NOV	30 days	16,887	15,840	16,650	6.0	0.01
DEC	12 days	7,315	7,113	7,113	2.7	2.7

6-2 Solar Collector Area and Ground Loop Length Relations

One of the most important measures of solar assisted ground source heat pump (SAGSHP) systems is the length of the ground loop heat exchanger offset by the area of the solar collectors. For this purpose a sensitivity analysis was conducted by varying the solar collector area to assess changes in borehole length. The study was conducted in five different solar collector areas that would be of the capacity of a typical residential house.

By increasing the total solar collector area, more fluid flow needs to be diverted to panels from ground loop fluid flow. As the flow rate of the heat pump is kept constant (1173 kg/hr), the ground loop flow and control flow diverter are adjusted in such a way as to meet the capacities of both the heat pump and solar collectors. Table 6-6 shows the relationship between the parameters mentioned.

Table 6-6: System components fluid flow rates and controls in different scenario

Solar Collector		**System Flow (kg/hr)**			
No. of Panels	Area (m^2)	HP	Solar	Ground Loop	% Control
0	0	1173	0	1173	0
3	6.81	1173	120	1293	10
6	13.62	1173	240	1413	17
9	20.43	1173	360	1533	23.5
12	27.24	1173	480	1653	29

The house with as-built borehole length and layout, as shown in Figure 4-1, is set to be the base case scenario and the total system energy consumptions is recorded. By considering the base case energy consumption as a benchmark, the following steps are considered for the sensitivity analysis;

1- Four scenarios are defined based on system with different solar panel collector areas.

2- In each scenario the simulation is run with a different ground loop heat exchange length until the energy consumption of the system reaches the same value as its corresponding base case system.

With the above steps and scenarios different simulations were run and the results are summarized in Table 6-7. EFT is also an important parameter needing to be controlled in order to avoid falling below heat-pump operating limits (i.e. 0°C).

Table 6-7: Ground loop heat exchanger length with different solar collector area

Solar Collector		**Ground Loop Heat Exchanger**			**Annual System Energy Consumption**	
No. of Panels	Area (m^2)	Total Length (m)	Borehole	Min. EFT (°C)	**Space Heating and Cooling (MJ)**	
					Heating	Cooling
0	0	220	4 × 55(m)	5	44,793	6,434
3	6.81	188	4×47(m)	0	44,749	6,931
6	13.62	172.8	4×43.25(m)	1	44,041	7,446
9	20.43	150	3×50(m)	0	44,126	7,967
12	27.24	135	3×45(m)	-1	44,070	8,124

The total ground loop heat exchanger (GLHE) parameters recorded in Table 6-7 are the minimum GLHE that the system could have in order to maintain the minimum EFT to the heat-pump in heating mode.

Table 6-8 shows the length of GLHE offset by the solar collector area. Figures 6-5 and 6-6 show these relations graphically.

Table 6-8: GLHE length reduction and its corresponding solar panel area

Solar Collector		**GLHE**		**Reduction**	
No. of Panels	Area (m^2)	Total Length (m)	Borehole	Loop Length (m)	m/m^2
0	0	220	4×55(m)	0	0
3	6.81	188	4×47(m)	32	4.70
6	13.62	172.8	4×43.25(m)	47.2	3.47
9	20.43	150	3×50(m)	70	3.43
12	27.24	135	3×45(m)	85	3.12

The greatest length of GLHE replaced by an area of the solar collector was observed for three solar panels scenario at 4.7 m/m^2, and the least was observed for the twelve solar panels scenario at 3.12m/m^2. This shows that the optimum number of solar panels for the system would be three (6.81m^2).

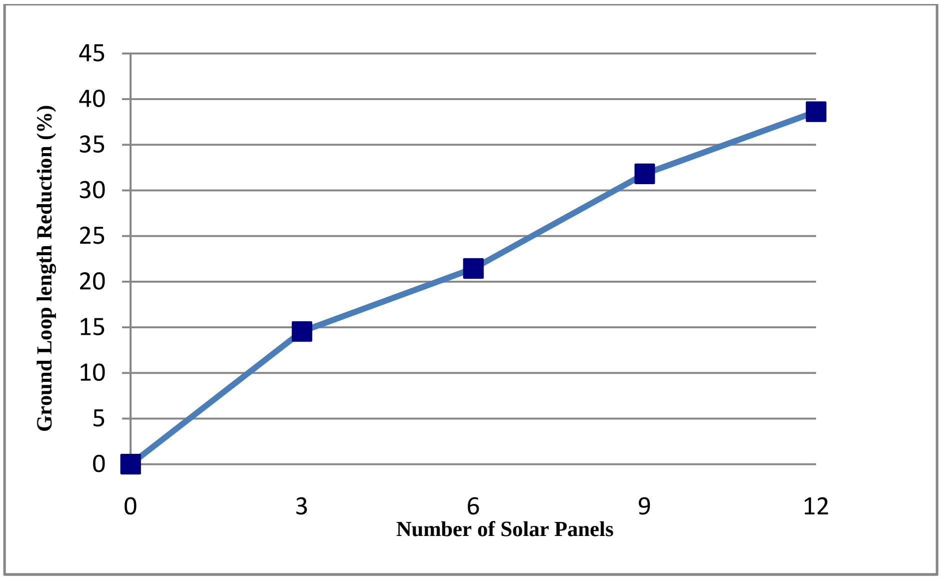

Figure 6-6: Ground loop length reduction percentage versus number of solar panels

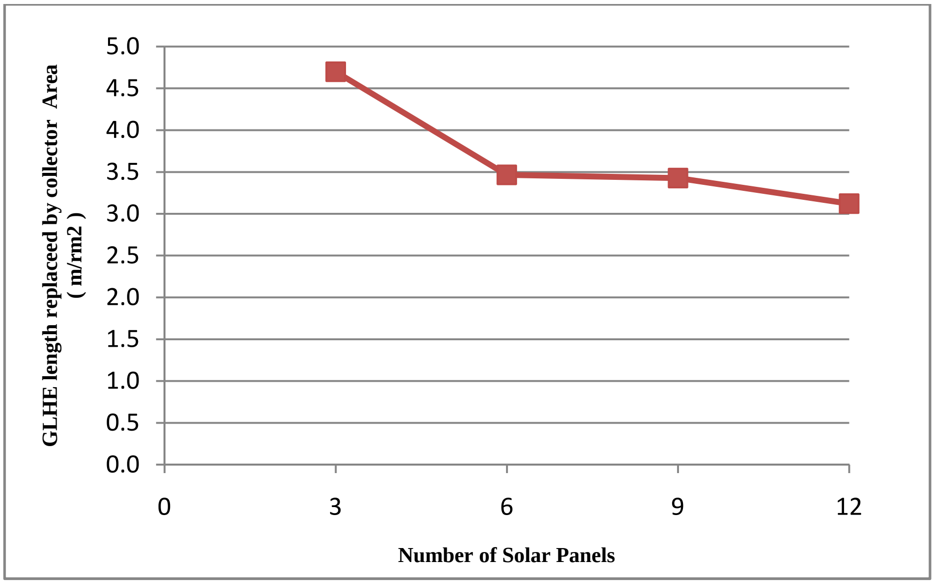

Figure 6-7: Ground loop length replaced by solar collector area

6-3 Life-Cycle Cost Analysis

To evaluate the economics of various cases, a 20-year life-cycle cost analysis was performed. A present value approach was selected to compare the alternatives. The options utilized in cost analysis are:

1- Ground loop heat exchanger installation cost are expressed per meter of vertical borehole and include all labor and materials for drilling, grouting, horizontal trenching and headering, and building penetrations. Cost ranges are from $29/m to $39/m of borehole. In this study, $33/m is considered to be the GLHE cost [48].
2- Heat pump costs including material and labor for installing are $6,500 [25].
3- Solar collector cost is $125/m^2 which includes all material and labor for installing the collector array, controls and all associated plumbing [26].
4- Electricity rate cost is $0.10 per kWh for the Toronto area including delivey and tax charges [49].
5- Interest rate is 6% compounded annually over the 20-year period [50].

The results of the economic analysis are summarized in Table 6-9.

Table 6-9: Net present value of hybrid solar-ground source heat pump system

Solar Collector		**GLHE**	**Cost Analysis**				
	Area	Total Length	Initial Cost		Operation Cost		**Net Present Value**
No. of Panels	(m^2)	(m)	Solar Cost	GLHE and HP Cost	Annual Cost	Present Value	
0	0	380	$0	$19,040	$2,050	$23,514	**$42,554**
0	0	220	$0	$13,760	$2,330	$26,721	**$40,481**
3	6.81	188	$851	$12,704	$2,330	$26,723	**$40,278***
6	13.62	172.8	$1,703	$12,202	$2,334	$26,776	**$40,681**
9	20.43	150	$2,554	$11,450	$2,337	$26,804	**$40,807**
12	27.24	135	$3,405	$10,955	$2,335	$26,786	**$41,146**

*Optimum balance between the GLHE size and solar collector size

The first row of Table 6-9 is the base case considered for the financial analysis. This is the case of the house with a 380 m borehole length, which would have been designed if the house were only equipped with a GSHP system. The second row is the as-built house data that has been simulated without solar collectors.

The net present value calculation uses the discount rate and the time cost occurred to establish the present value of the cost in the base year of the study period. Since most initial expenses occur about the same time, initial expenses are considered to occur during the base year of the study period. Thus, there is no need to calculate the present value of these initial expenses because their present value is equal to their actual cost. Future cost is inccured every year between Year 1 and Year 20. In this case, future cost will be the operational cost and is only restricted to energy costs as there would be no or very minor maintenance cost. The operational cost is a recurring cost that occurs every year over the span of the 20 years. Table 6-9 shows that there is an economic benefit of $2,276 (5.3%) in using the system with three solar panels while the benefit is less for the system with more than three panels. However the economic benefit also depends on the interest rate. The higher the rate, the better is the benefit; for example, the benefit increases to $3,100 (8.5%) if the interest rate is 10%. This is due to the fact that the saving of initial cost in the ground loop heat exchanger installation cost for the system with more than three solar panels is not significant. In all cases the system would also be economically viable if GLHE cost fell into the higher range of drilling costs (i.e. $39/m). Table 6-10 shows the net present value of the systems with minimum and maximum bore hole costs.

Table 6-10: Net present value of systems with minimum and maximum bore hole cost

Solar Collector		**GLHE**	**System Cost**			
No. of Panels	**Area**	**Total Length**	**Initial Cost**		**Net Present Value**	
	(m^2)	**(m)**	**$29.00/m**	**$39.00/m**	**$29.00/m**	**$39.00/m**
0	0	380	$17,520	$21,320	$41,034	$44,834
0	0	220	$12,880	$15,080	$39,601	$41,801
3	6.81	188	$12,803	$14,683	$39,526	$41,406
6	13.62	172.8	$13,214	$14,942	$39,990	$41,718
9	20.43	150	$13,404	$14,904	$40,207	$41,707
12	27.24	135	$13,820	$15,170	$40,606	$41,956

One aspect needing to be considered in system cost analyses is the comparison of the GSHP and the SAGSHP total system energy consumptions in 20 years. The total annual energy consumption of the system in its life span varies from year to year. In the GSHP system, depending on the soil conditions, the annual minimum heat pump EFTs reduce from year to year whereas in the SAGSHP, the minimum heat pump EFTs are almost constant. This results in higher operating costs over the system life span for the GSHP system, making the SAGSHP more beneficial. However, the exact yearly cost analysis for the two systems is beyond the scope of this study. Figure 6-8 shows the EFTs to the heat pump for both the SAGSHP and GSHP systems. Due to the limitation of the graph generator tool in Excel this figure is generated in 32,000 hours (3.6 years). Over the first three years, the minimum EFTs drop about 2°C for the SAGSHP system, whereas for the GSHP system the drop is as much as 3°C. From Figure 6-8 and the 20-year simulation analysis, it is concluded that the yearly drop in minimum EFT in the GSHP is much higher than for the SAGSHP.

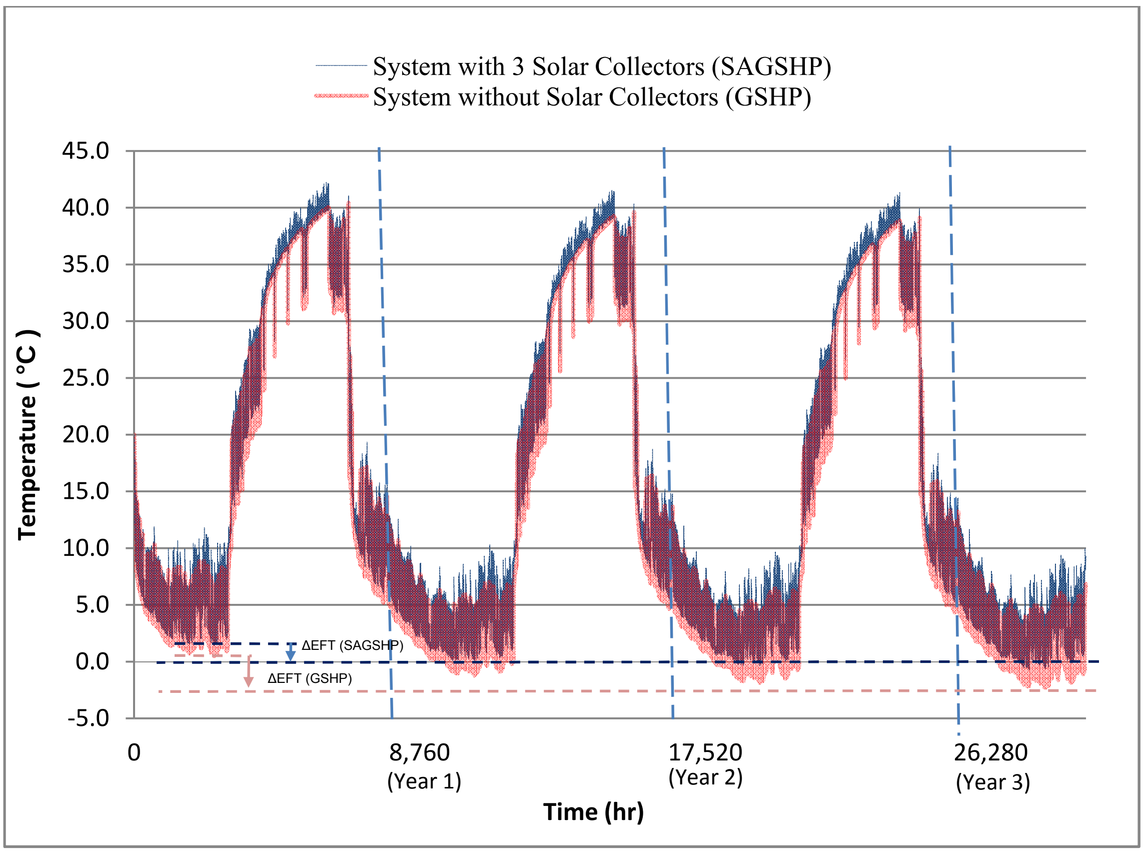

Figure 6-8: Annual EFT to the HP for SAGSHP and GSHP systems

6-4 System Performance in Different Cities of Canada

For investigating the performance of the system with different climatic and enviromental charactristics, simulations were run in five cities other than Toronto: Halifax, Nova Scotia; Montreal, Quebec; Ottawa, Ontario; Edmonton, Alberta; and Vancouver, British Columbia. In different cities, the house would have varying heating and cooling loads. A relative measure of heating dominance of the house of each city is expessed as the ratio of annual heating load to the annual cooling load for the base-case house (the house using only GHX as an energy source or sink) is tabulated in Table 6-11.

Table 6-11 shows that the least heating dominated case is Vancouver, and the most is Edmonton. Running simulations for all mentioned cities with the base-case system and with three solar panels, the results are recorded in Table 6-12. Table 6-12 shows that the house in Vancouver with lowest annual heating load to annual cooling load (1.54), has the highest reduced GHX loop length to solar collector area ratio (of 7.64 m/m^2). Whereas the house in Edmonton with highest annual heating load to annual cooling load ratio (3.80) has the lowest ratio of reduced GHX loop length to solar collector area (2.93 m/m^2). It is concluded that the house in cities with a smaller annual heating load to annual cooling load ratio shows better reduced GHX loop length to collector area ratio.

Table 6-11: Annual heating load to annual cooling load ratio of the house in different cities

City	Degree Days *		HDD/CDD	House Energy Demand (MJ)		Annual heating load / Annual cooling load
	Heating	Cooling		Heating	Cooling	
Vancouver	2926	44	66.5	49,794	32,392	**1.54**
Toronto	4066	252	16.1	93,608	40,150	**2.33**
Montreal	4575	235	19.5	106,606	43,799	**2.43**
Ottawa	4620	229	20.2	109,079	40,323	**2.71**
Halifax	4367	104	42.0	83,831	25,018	**3.35**
Edmonton	5708	28	203.9	133,121	35,019	**3.80**

* Environment Canada Average Annual Totals, 1971-2000

Table 6-12: System performance in different cities

City	Solar Collector		GHX Loop			Annual System Energy Space Heating and Cooling (MJ)		Reduced GHX length/Collector Area
	No. of Panels	Area (m^2)	Total Length (m)	Borehole	Min. EFT (°C)	Heating	Cooling	m/m^2
Vancouver								
	0	0	220	4×55(m)	1	46,305	5,364	(52m)
	3	6.81	168	4×42(m)	0	46,119	5,623	**7.64**
Toronto								
	0	0	220	4×55(m)	1	44,793	6,434	(40m)
	3	6.81	180	4×45(m)	0	44,749	6,631	**5.9**
Montreal								
	0	0	220	4×55(m)	0	46,766	6,989	(36m)
	3	6.81	184	4×46(m)	0	46,779	7,174	**5.28**
Ottawa								
	0	0	220	4×55(m)	0	46,327	6,150	(32m)
	3	6.81	188	4×47(m)	0	46,445	6,331	**4.7**
Halifax								
	0	0	220	4×55(m)	0	49,566	5,015	(24m)
	3	6.81	196	4×49(m)	0	49,301	5,268	**3.52**
Edmonton								
	0	0	220	4×55(m)	0	51,979	5,935	(20m)
	3	6.81	200	4×50(m)	0	52,052	6,076	**2.93**

6-5 Sizing Suggestions for the House System

As mentioned earlier, in the cooling season the house energy simulation with the current system specification including solar panels was not possible. In this case the heat pump capacity in the cooling season was increased in order to run the analysis in cooling mode. Existing heat pump specifications (Appendix D) show that the cooling capacity of the heat pump is between 11 and 16.7kW, and the heating capacity is between 1.5 and 20.6 kW. Exact heat pump capacity depends on the EFT. In the existing case, the house peak cooling and heating demands are 9.5kW and 11.5kW, respectively. The selected heat pump capacities for meeting these demands should be fine if the EFT falls below 25 °C. EFTs greater than 25°C reduces the heat pump cooling capacity to less than 9.5kW where the heat pump will not functioning properly. In order to avoid this problem following suggestions are made:

1- Select a heat pump which is still functional and has higher performance when the EFTs are greater than 35°C.
2- Increase the total borehole length.
3- Shut down the solar collectors and isolate them from the system in summer.

Table 6-13 shows two proposed systems to compare with the existing house system. For the existing system, stopping the flow stream to the solar panels in summer is the easiest and most economical way. But in this case the occupants would have to endure thermal discomfort in the cooling season. As an alternative and more costly solution, the heat pump performance data file is substituted by another heat pump, i.e. WaterFurnace Model Synergy3D [51], with the same capacity but a better heat pump cooling performance at higher EFTs. However, for a new system, designing with a proper borehole length and heat pump size is essential. Table 6-13 shows that for the existing heat pump capacity the borehole length should be increased to 85 m from the existing 55 m. This highlights the importance of proper design of a SAGSHP system with appropriate length of ground loop; besides functioning well in the cooling season with lower maximum EFT, a substantial energy savings (14.4 GJ) for heating season is also achieved.

Table 6-13: Suggestions for improvement of the existing as-built system performance

		Heat pump system			**Annual System Energy Consumptions (MJ)**	
Hybrid System	No. of Panels	Total Loop length (m)	Min. EFT (°C)	Max. EFT (°C)	Heating	Cooling
Existing	3	220	0	40	44,749	N/A
Higher heat pump performance	3	220	0	40	44,749	6,631
Longer ground loop exchanger	3	340	6	32	30,314	5,842

Chapter 7
Conclusions and Recommendations

To assess the viability of hybrid ground source heat pump systems (GSHP) with solar thermal collectors, a system simulation approach was presented. An actual house located in Milton Ontario was modelled using TRNbuild and TRNSYS. The house was energy efficient, and equipped with a similar system to the subject of this study. The house also had sensors and a data acquisition system in order to read and save temperatures, flow rates, and electricity consumption of mechanical equipments in different locations of the system.

There was a complaint by the owner about the house system operation as it was not functioning in the cooling season. There was no information for the system design from the design consultant.

In this study, the overall system viability was evaluated and existing system problems were detected through dedicated modelling and simulation of the installed system. Some specific conclusions of this study are outlined in the following sections:

7.1 TRNSYS versus HOT2000

HOT2000 is widely used by builders in North America, as reported by Natural Resourses Canada [24]. The design heating and cooling loads, as well as the annual energy demands of the house were simulated using HOT2000 and TRNbuild, a module of TRNSYS. The purpose of this study was to verify the TRNbuild model of the house. The results show that both the HOT2000 and TRNbuild models are in good agreement in terms of overall annual energy demands. The TRNSYS results for annual heating and cooling demand of the house are almost 3% higher than the HOT2000 results. This deviation is acceptable considering the different calculation methods used in the two softwares. HOT2000 uses a bin method whereas TRNbuild uses a more accurate time step transfer function method. After the TRNbuild model of the house was verified, further studies with a hybrid GSHP system could be carried out with confidence.

7.2 Optimum Flow to Solar Thermal Collectors

In the as-built system, the percentage of the ground loop flow rate diverted to the solar collectors was studied using three different flows. From the equipment manufacturer, the maximum acceptable flow rates to the heat pump and the three solar panels were determined to be 1173 kg/hr and 120 kg/hr, respectively. This means that the total maximum flow rate in the ground loop exchanger was the sum of the two, i.e., 1293 kg/hr. The maximum flow diversion from the ground loop was determined to be 10% of the total flow. This study showed that by increasing the fluid flow to the solar panels from zero to 10% of the heat pump flow rate, the overall system energy consumption in the heating mode decreases, whereas, in the cooling mode the system energy consumption increases. This trend is in favour of the system performance in the heating season and against in the cooling season. This indicates that for Toronto weather conditions, a residential house with a hybrid GSHP system can benefit from higher flow diversion to solar thermal collectors in the heating season; however, the reverse is true in the cooling season.

7.3 Sensitivity Analysis of the Ground Thermal Conductivity

Thermal conductivity is one of the physical properties needed for sizing GSHP. As the exact soil thermal conductivity for the site of the house was unknown, the house was modelled with different soil thermal conductivities and the effects recorded. Changing the soil thermal conductivity leads to a change in the entering fluid temperature (EFT) to the heat pump. This is a very important parameter for the efficiency of the heat pump. The heat pump of the house is designed to work between 0°C and 35°C. Analysis was carried out with four different soil types in the range of 0.85 W/mK to 2.5 W/mK. The result showed that in the heating season, the lower thermal conductivity leads to a lower EFT to the heat pump. Soil types with a thermal conductivity lower than 2 W/mK lead to an EFT lower than 0°C and cause a malfunction of the heat pump. On the other hand, a higher soil thermal conductivity leads to a higher EFT in the heating season and more efficient heat pump operation. In conclusion, based on overall regional soil type, soil with 2 W/mK is a reasonable selection , and this was the value used in the rest of the studies. Having better heat transfer in the vicinity of the ground heat exchanger loop is ideal for the system, whereas having lower thermal conductivity in the backfill volume would be good for overall thermal storage.

7.4 Solar Collector Area and Ground Loop Heat Exchanger Length Relation

Finding the relationship between solar collector area and ground loop length was one of the important aspects of this study. In the heating season, the results of this study showed that for this specific house located in Toronto region, three solar panels in the system helped to reduce the total ground loop heat exchanger (GLHE) length by 15% compared to the system that only has a heat pump. Increasing the number of solar panels from three to six does not double the GLHE length reduction, whereas its trend would be in the range of 8% to 13% after that. An optimum relationship of the two mentioned parameters would be a system with three solar panels and a reduced ground loop heat exchanger length of 15%. In the cooling season, adding solar panels to the system would have a negative impact on the system performance and an increase in the heat pump energy consumption; therefore, in heating dominated places, where the cooling season is short, this increment of energy consumption in the cooling season would not be significant compared to savings in heating season.

7.5 System Cost Analysis

A 20-year life-cycle analysis of the system showed a small economic benefit for the hybrid system compared to the system with only GSHP. This was due to the low borehole drilling cost of $33/m. At the time of study, the borehole drilling costs were determined to be in the range of $29/m to $39/m for different ground conditions. However, for the case of higher drilling costs the economic benefits would be considerable, because of the 15% reduction of GLHE length due to the three solar collectors. During the system life cycle, the SAGSHP system energy consumptions increase slightly, corresponding to a reduction of 2°C in minimum EFT to the heat pump from year to year. However, in the GSHP system without solar collectors there would be more energy consumption due to an almost 4°C reduction of minimum EFT to the heat pump from year to year.

7.6 Field Study and Verification

For this study there was limited field data available to validate the simulation results. For heat pump energy consumption there were only 42 days of data in heating season and no considerable data in cooling season; whereas for the EFT to the heat pump there were almost eight months of data available in 2007. The comparison of the simulation results with the field data showed a 2.7% to 6% deviation in energy consumptions. The source of this deviation was found to be the weather data used in the simulation. By adjusting the simulation results with the actual weather data for 2007 for Toronto, this deviation was reduced to 0.01 to 2.7%. The approach of adjusting the simulation data follows the PRISM method [47]. PRISM is a statistical procedure that uses heating and cooling degree days to produce a weather-adjusted index of the energy consumption of a house or building. The study shows that it is important to simulate using actual yearly weather data which corresponds to the year of actual field readings if excellent agreement between actual and simulated data is required; otherwise, differences within 10% can be expected when the default TMY2 data in TRNSYS is used.

This verification exercise is a means to confirm the TRNSYS simulation model of the hybrid GSHP system and the suitability of using TRNSYS in this study.

7.7 Solutions to the Problem of the As-built System

The existing system had problems in functioning properly in the cooling season. The study results showed that the system was not properly sized for the cooling season as the EFTs to the heat pump were exceeding the allowable EFT defined by the manufacturer. This happened from June to August, almost the whole cooling season. Simulated solutions include: (a) stopping the flow to the solar panel in cooling season; (b) selecting a heat pump with a modified cooling capacity and specification; and (c) increasing the GLHE length. All three solutions are applicable with case (a) being the simplest and least cost to implement. This problem could have been preventable if the borehole lengths were increased by 35%. This solution could be justified as the system would perform better in the heating season in spite of the extra borehole cost.

7.8 System Viability in Different Cities of Canada

By considering the same house characteristics, the effects of different climates in Canada were investigated. For this purpose, six Canadian cities in different regions were studied. The results showed that, in different cities, in general, as the ratio of annual heating load to annual cooling load of the house increased, the reduced ground loop heat exchanger length to solar collector area ratio decreased. This ratio was 7.64 m/m^2 for Vancouver, with an annual heating to annual cooling load ratio of 1.54. For Edmonton, the annual heating to cooling load ratio was 3.8, having reduced ground loop heat exchanger length to solar collector area ratio of 2.93 m/m^2. A higher ratio, such as for Vancouver, indicates better viability of the hybrid GSHP system. This would not be an absolute conclusion as other parameters, such as ratio of heating degree days to cooling degree days in each city also affects the conclusion.

7.9 Viability of System

The result of this study have shown that the hybrid GSHP system combined with solar thermal collectors is a feasible choice for space conditioning for heating-dominated houses. For the house in this study, the seasonal solar thermal energy storage in the ground in the hybrid system was sufficient enough to offset large amount of ground loop heat exchanger length that would have been required in conventional GSHP systems. The economic benefit of such a system depends on climate as well as borehole drilling cost.

7-10 System Simulation Approach

This study demonstrates the value in utilizing a system simulation approach to evaluating alternatives in complex systems. The hourly time step simulation for the implementation of complex control and operation strategies enabled the assessment of transient system responses. This study can be continued with examining and analysing different controls and configurations, and the interaction of different components as well as study in broader geographical areas.

7-10 Future Research Recommendations

Some specific recommendations for further study and research arising from this study are:

- Implementing an optimization routine into the system simulation would be useful in order to obtain the optimum values of desired parameters. In particular, minimizing the system life-cycle cost by optimizing the size of ground loop exchanger versus the area of solar collectors.
- Further research in the system controls and configurations to increase the system performance. This could be diverting the extra energy harvested by the solar collectors during the cooling season for an independent DHW system.
- Using more efficient solar thermal collectors in the model. In particular, using vacuum tube solar thermal collectors with reduced initial and maintenance cost.

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Appendix - A

Floor plans of the house

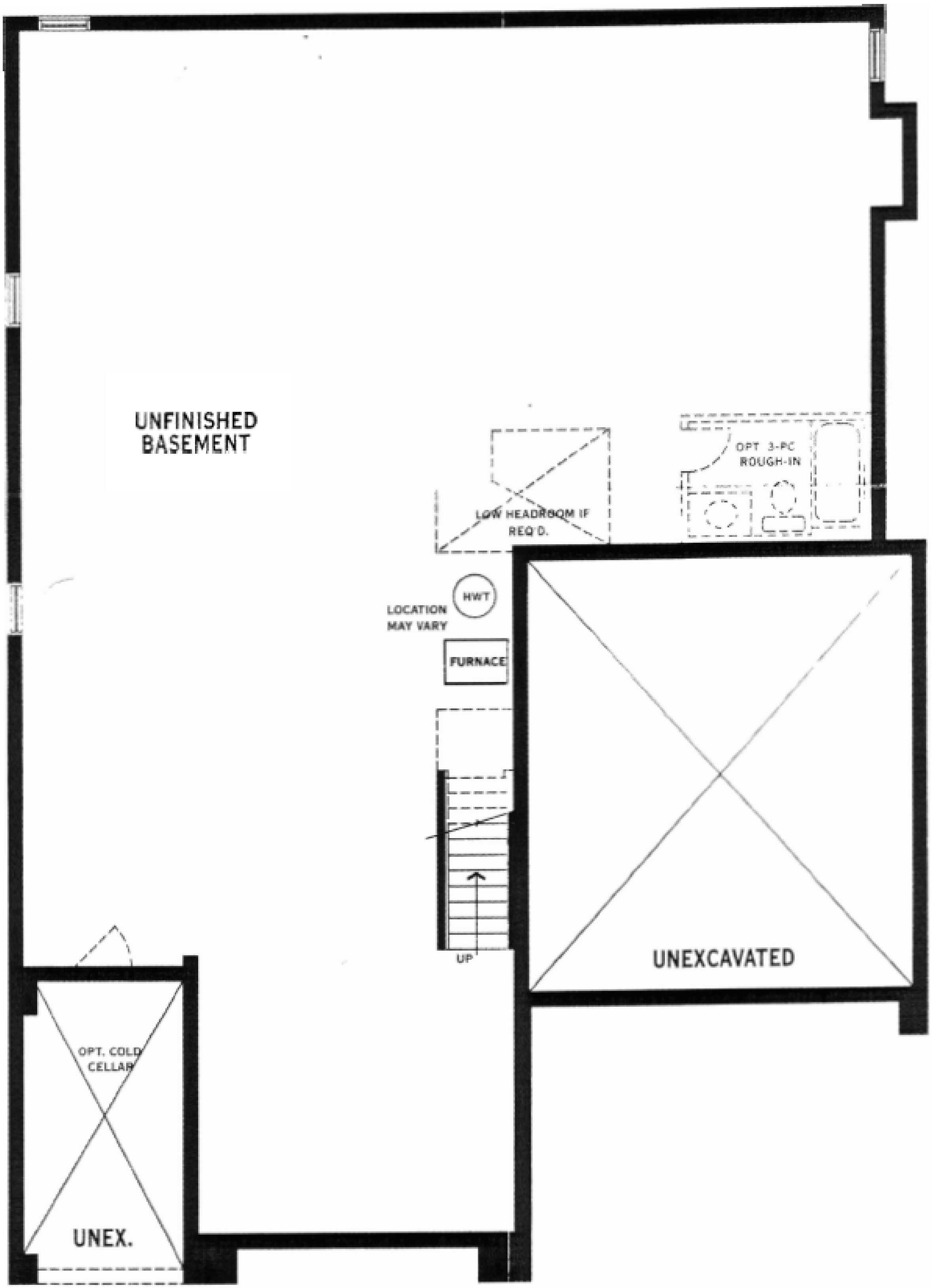

Figure A-1: Basement Floor plan

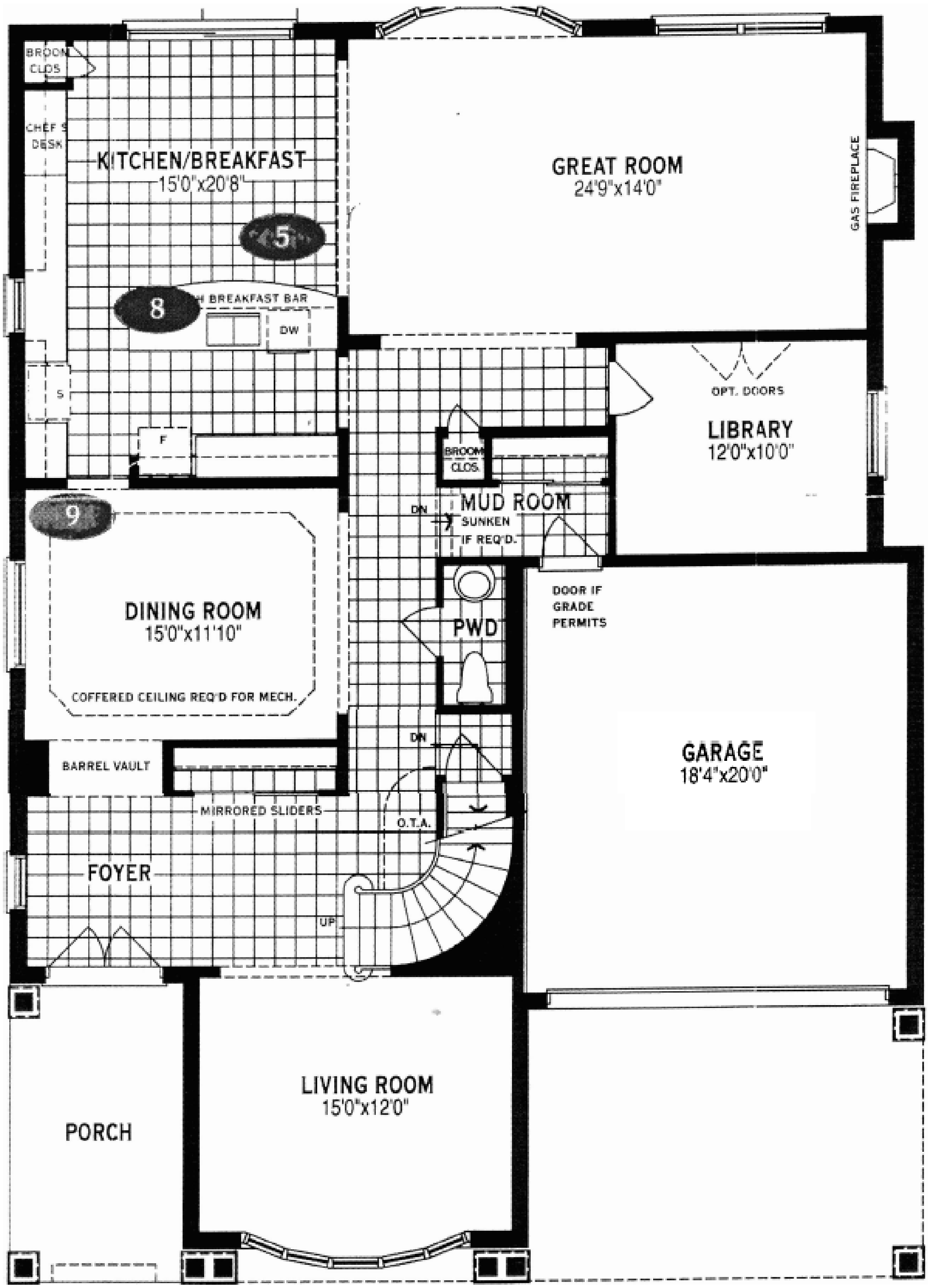

Figure A-2: Ground (First) Floor plan

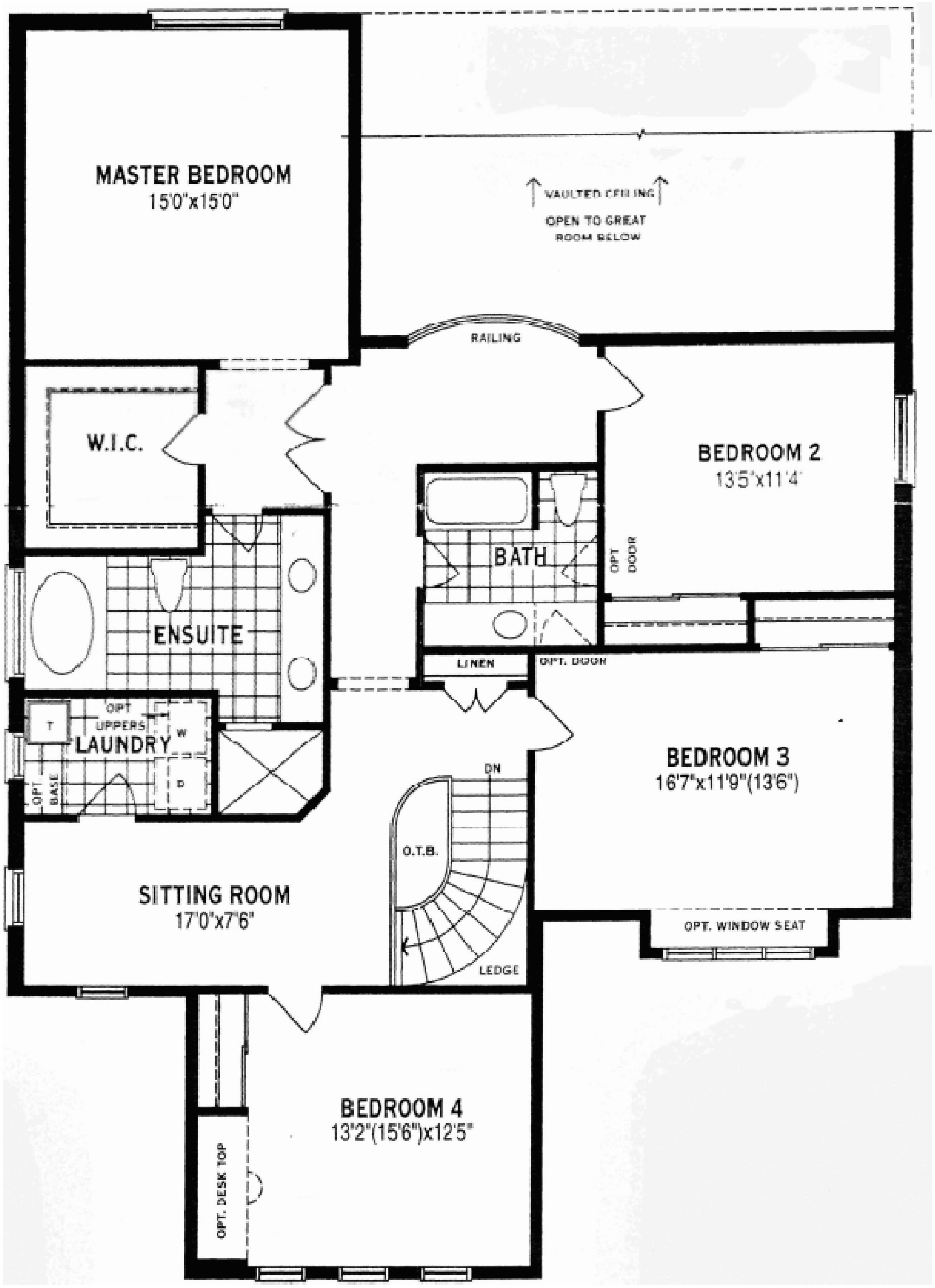

Figure A-3: Second Floor plan

Appendix - B

HOT2000 output report for the house

HOT2000
Natural Resources CANADA
Version 9.33

File:	Mattamy 04060-HV5018GH-C-CORNER AS BUILT (EDIT)_Thesis_Used.HSE
Application Type:	General

Weather Data for TORONTO, ONTARIO

Builder Code:

Data Entry by: Farzin Rad
Date of entry: 21/01/2007
Company: Ryerson University

Client name: Homes, Mattamy
Street address: Lot 213

City:	Milton	**Region:**	Ontario
Postal code:		**Telephone:**	

GENERAL HOUSE CHARACTERISTICS

House type:	Single Detached		
Number of storeys:	Two storeys		
Plan shape:	Other, 11 or more corners		
Front orientation:	South		
Year House Built:	2005		
Wall colour:	Default	**Absorptivity:**	0.40
Roof colour:	Medium brown	**Absorptivity:**	0.84
Soil Condition:	Normal conductivity (dry sand, loam, clay)		
Water Table Level:	Normal (7-10m/23-33ft)		

House Thermal Mass Level: (A) Light, wood frame

Effective mass fraction 1.000

Occupants :
2 Adults for 50.0% of the time
2 Children for 50.0% of the time
0 Infants for 0.0% of the time

Sensible Internal Heat Gain From Occupants: 2.40 kWh/day

HOUSE TEMPERATURES

Heating Temperatures

Main Floor:	21.1 °C
Basement:	20.0 °C
TEMP. Rise from 21.1 °C:	2.8 °C
Cooling Temperature: Main Floor :	23.89 °C

Basement is- Heated: YES **Cooled:** NO **Separate T/S:** NO
Fraction of internal gains released in basement : 0.150

Indoor design temperatures for equipment sizing

Heating:	22.2 °C
Cooling:	23.9 °C

WINDOW CHARACTERISTICS

Label	Location	#	Overhang Width (m)	Header Height (m)	Tilt deg	Curtain Factor	Shutter (RSI)
South							
door window	fr / ext	1	5.49	0.91	90.0	1.00	0.00
door window copy	fr / ext 2	1	5.49	0.91	90.0	1.00	0.00
front 1	1st Flr. Stone	1	5.55	0.46	90.0	0.00	0.00
front 1	2nd Flr. Siding	1	0.40	0.15	90.0	0.00	0.00
front 2	1st Flr. Stone	2	1.77	0.15	90.0	0.00	0.00
front 2	2nd Flr. Siding	2	0.24	0.15	90.0	0.00	0.00
front 3	2nd Flr. Siding	1	0.24	0.15	90.0	0.00	0.00
front 4	2nd Flr. Siding	3	0.40	0.15	90.0	0.00	0.00
East							
right 1	1st Flr. Siding	1	0.40	4.72	90.0	0.00	0.00
right 1	2nd Flr. Siding	1	0.40	1.62	90.0	0.00	0.00
right basement	Basement	1	0.40	3.20	90.0	0.00	0.00
North							
back 1	1st Flr. Siding	3	0.40	0.51	90.0	0.00	0.00
back 1	2nd Flr. Siding	2	0.40	0.15	90.0	0.00	0.00
back 2	1st Flr. Siding	5	0.40	0.30	90.0	0.00	0.00
back 3	1st Flr. Siding	1	0.40	3.20	90.0	0.00	0.00
back basement	Basement	1	0.40	3.20	90.0	0.00	0.00
West							
left 1	1st Flr. Stone	2	3.66	0.46	90.0	0.00	0.00
left 1	1st Flr. Siding	2	0.40	3.23	90.0	0.00	0.00
left 1	2nd Flr. Siding	2	0.40	0.15	90.0	0.00	0.00
left 2	1st Flr. Siding	2	0.24	0.15	90.0	0.00	0.00
left 2	2nd Flr. Siding	5	0.40	0.15	90.0	0.00	0.00
left 3	1st Flr. Siding	1	0.24	0.15	90.0	0.00	0.00
left 4	1st Flr. Siding	2	0.40	0.46	90.0	0.00	0.00
left basement 1	Basement	1	0.40	6.04	90.0	0.00	0.00
left basement 2	Basement	1	0.40	2.96	90.0	0.00	0.00

Label	Type	#	Window Width (m)	Window Height (m)	Total Area (m^2)	Window RSI	SHGC
South							
door window	18 W	1	0.61	1.07	0.65	0.506	0.3205
door window copy	18 W	1	0.61	1.07	0.65	0.506	0.3205
front 1	18 W	1	1.73	0.30	0.53	0.460	0.2528
front 1	18 W	1	0.63	1.09	0.69	0.510	0.3256
front 2	18 W	2	1.24	1.75	4.36	0.570	0.3969
front 2	18 W	2	0.79	1.75	2.76	0.546	0.3698
front 3	18 W	1	1.14	1.75	2.00	0.566	0.3928
front 4	18 W	3	0.63	1.75	3.34	0.531	0.3522
East							
right 1	18 W	1	1.24	1.75	2.18	0.570	0.3969
right 1	18 W	1	1.24	1.55	1.93	0.564	0.3903
right basement	18 W	1	0.76	0.30	0.23	0.443	0.2140
North							
back 1	18 W	3	0.79	1.75	4.14	0.546	0.3698
back 1	18 W	2	0.79	1.45	2.28	0.537	0.3601
back 2	18 W	5	0.53	1.75	4.67	0.517	0.3348
back 3	18 W	1	2.44	2.39	5.82	0.610	0.4342
back basement	18 W	1	0.76	0.30	0.23	0.443	0.2140
West							
left 1	18 W	2	0.63	1.75	2.23	0.531	0.3522
left 1	18 W	2	0.79	1.75	2.76	0.546	0.3698
left 1	18 W	2	0.79	1.75	2.76	0.546	0.3698
left 2	18 W	2	0.53	1.75	1.87	0.517	0.3348
left 2	18 W	5	0.63	1.75	5.56	0.531	0.3522
left 3	18 W	1	1.22	1.75	2.14	0.569	0.3959
left 4	18 W	2	0.63	1.75	2.23	0.531	0.3522
left basement 1	18 W	1	0.76	0.30	0.23	0.443	0.2140
left basement 2	18 W	1	0.76	0.30	0.23	0.443	0.2140

WINDOW CODE SCHEDULE

Name	Internal Code	Description (Glazings, Coatings, Fill, Spacer, Type, Frame)
18 W	213224	Double/double with 1 coat, Low-E .04 (soft), 13 mm Argon, Insulating, Slider with sash, Vinyl, ER* = -13.90, Eff. RSI= 0.38

* Window Standard Energy Rating estimated for assumed dimensions, and Air tightness type: CSA - A1; Leakage rate = 2.790 m^3/hr/m

BUILDING PARAMETER DETAILS

CEILING COMPONENTS

	Construction Type	Code Type	Roof Slope	Heel Ht.(m)	Section Area (m^2)	R. Value (RSI)
1st Flr. Alcoves	Attic/hip	18 Ceil	6.0/12	0.24	1.67	7.33
2nd Floor Flat	Attic/gable	18 Ceil	8.0/12	0.24	146.17	7.07
Bdrm 4 Cathdral	Cathedral	18 Cath	8.0/12	0.24	3.02	5.95
Greatroom Cathdr	Cathedral	18 Cath	7.6/12	0.24	40.03	6.48

MAIN WALL COMPONENTS

Label	Lintel Type	Fac. Dir	Number of Corn.	Number of Inter.	Height (m)	Perim. (m)	Area (m^2)	R. Value (RSI)
1st Flr. Siding Type: 18Wall	101	N/A	17	2	3.02	33.43	101.09	3.43
1st Flr. Stone Type: 18Wall	101	N/A	5	0	3.02	15.40	46.58	3.55
2nd Flr. Siding Type: 18Wall	101	N/A	15	6	2.77	53.14	147.06	3.65
2nd Flr.to Attic Type: 18Wall	101	N/A	4	0	2.67	7.62	20.32	3.85
Garage Wall Type: 18Wall	N/A	N/A	1	2	3.02	11.13	33.64	3.90
F. H. 1st Siding Type: 18002C0020	000	N/A	4	4	0.23	26.17	5.98	3.18
F. H. 1st Stone Type: 18002C0070	000	N/A	4	4	0.23	22.67	5.18	3.32
F. H. 2nd Siding Type: 18002C0020	000	N/A	4	4	0.23	53.14	12.15	3.18
F. H. 2nd Siding Type: 18002C0000	000	N/A	4	4	0.23	7.62	1.74	3.06

WALL CODE SCHEDULE

Name	Internal Code	Description (Structure, typ/size, Spacing, Insull, 2, Int., Sheathing, Exterior, Studs)
18002C0020	18002C0020	Floor header, N/A, N/A, RSI 2.1 (R 12) batt, N/A, None, None, Hollow metal/vinyl cladding, 2 studs
18002C0070	18002C0070	Floor header, N/A, N/A, RSI 2.1 (R 12) batt, N/A, None, None, Stone, 2 studs
18002C0000	18002C0000	Floor header, N/A, N/A, RSI 2.1 (R 12) batt, N/A, None, None, None, 2 studs

EXPOSED FLOORS

Label	Floor Code Type	Area (m^2)	R. Value (RSI)
Bdrm 4 Window	18 ExFlr	1.53	5.59
Over Garage	18 ExFlr	24.08	5.55

EXPOSED FLOOR SCHEDULE

Name	Internal Code	Description (Structure, typ/size, Spacing, Insull, 2, Int., Sheathing, Exterior, Studs)
18 ExFlr		N/A, N/A, N/A, N/A, N/A, N/A, N/A, N/A, N/A

DOORS

Label	Type	Height (m)	Width (m)	Gross Area (m^2)	R. Value (RSI)
fr / ext **Loc: 1st Flr. Stone**	Steel polystyrene core	2.03	0.86	1.75	0.98
fr / ext 2 **Loc: 1st Flr. Stone**	Steel polystyrene core	2.03	0.86	1.75	0.98
garage / foyer **Loc: Garage Wall**	Steel polystyrene core	2.03	0.81	1.65	0.98

USER-DEFINED STRUCTURE CODES SCHEDULE

Name	Description
1118Wall	
2118 Ceil	
2118 Cath	
3118 ExFlr	

FOUNDATIONS

Foundation Name: Basement
Foundation Type: Basement
Data Type: Library

Volume: 402.5 m^3
Opening to Main Floor: 1.56 m^2

Total Wall Height: 2.59 m
Depth Below Grade: 1.98 m

Non-Rectangular
Floor Perimeter: 61.30 m
Floor Area: 155.36 m^2

Interior wall type: 18 BWall — **R-value:** 2.22 RSI
Exterior wall type: 64 mm (2.5 in) XTPS IV — **R-Value:** 2.22 RSI
Number of corners : 19
Lintel type: N/A
Added to slab type : User specified — **R-Value:** 2.22 RSI
Floors Above Found.: 4221000240 — **R-Value:** 0.60 RSI

Exposed areas for: Basement
Exposed Perimeter: 61.30m

Configuration: BCCB_4
- concrete walls and floor
- interior surface of wall insulated over full-height
- exterior surface of wall insulated over full-height
- sub-surface of floor slab fully insulated but no insulation under footings
- thermal-break between walls and floor slab
- any first storey construction type

FOUNDATION CODE SCHEDULE

Added To Slab

Name	Code	Description (Framing, Spacing, Insulation, Int., Sheathing)
64 mm XTPS IV (2	00B00	None, 305 mm (12 in), N/A, None, None

Floors Above Foundation

Name	Internal Code	Description (Structure, typ/size, Spacing, Insul1, 2, Int., Sheathing, Exterior, Drop Framing)
4221000240	4221000240	Wood frame, 38x184 (2x8), 400 mm (16 in), None, None, None, Waferboard/OSB 11.1 mm (7/16 in), Tile-linoleum, No

ROOF CAVITY INPUTS

Gable Ends		**Total Area:**	32.50 m^2
Sheathing Material	Plywood/Part. bd 9.5 mm (3/8 in)		0.08 RSI
Exterior Material:	Hollow metal/vinyl cladding		0.11 RSI
Sloped Roof		**Total Area:**	177.58 m^2
Sheathing Material	Plywood/Part. bd 12.7 mm (1/2 in)		0.11 RSI
Exterior Material:	Asphalt shingles		0.08 RSI
Total Cavity Volume:	240.8 m^3	**Ventilation Rate:**	0.50 ACH/hr

BUILDING ASSEMBLY DETAILS

Label	Construction Code	Nominal (RSI)	System (RSI)	Effective (RSI)
CEILING COMPONENTS				
1st Flr. Alcoves	18 Ceil	7.05	7.04	7.33
2nd Floor Flat	18 Ceil	7.05	7.06	7.07
Bdrm 4 Cathdral	18 Cath	7.14	5.95	5.95
Greatroom Cathdr	18 Cath	7.14	6.48	6.48
MAIN WALL COMPONENTS				
1st Flr. Siding	18Wall	4.38	3.43	3.43
1st Flr. Stone	18Wall	4.38	3.55	3.55
2nd Flr. Siding	18Wall	4.38	3.65	3.65
2nd Flr.to Attic	18Wall	4.38	3.85	3.85
Garage Wall	18Wall	4.38	3.90	3.90
F. H. 1st Siding	18002C0020	2.80	3.18	3.18
F. H. 1st Stone	18002C0070	2.80	3.32	3.32
F. H. 2nd Siding	18002C0020	2.80	3.18	3.18
F. H. 2nd Siding	18002C0000	2.80	3.06	3.06
FLOORS ABOVE BASEMENTS				
Basement	4221000240	0.00	0.60	0.60

BUILDING PARAMETERS SUMMARY

ZONE 1 : Above Grade

Component	Area m^2 Gross	Area m^2 Net	Effective (RSI)	Heat Loss MJ	% Annual Heat Loss
Ceiling	190.90	190.90	6.92	9604.64	6.82
Main Walls	373.74	314.33	3.58	35913.80	25.50
Doors	5.16	3.86	0.98	1729.17	1.23
Exposed floors	25.61	25.61	5.55	1859.09	1.32
South Windows	14.99	14.99	0.54	12128.10	8.61
East Windows	4.11	4.11	0.57	3183.34	2.26
North Windows	16.92	16.92	0.56	13364.10	9.49
West Windows	19.54	19.54	0.54	15969.16	11.34
		ZONE 1 Totals:		**93751.41**	**66.55**

INTER-ZONE Heat Transfer : Floors Above Basement

	Area m^2 Gross	Area m^2 Net	Effective (RSI)	Heat Loss MJ
	155.36	155.36	0.597	10515.30

ZONE 2 : Basement

Component	Area m^2 Gross	Area m^2 Net	Effective (RSI)	Heat Loss MJ	% Annual Heat Loss
Walls above grade	37.37	36.44	-	5216.37	3.70
East windows	0.23	0.23	0.44	213.54	0.15
North windows	0.23	0.23	0.44	213.54	0.15
West windows	0.46	0.46	0.44	427.08	0.30

Below grade foundation	276.80	276.80	-	14189.35	10.07
		ZONE 2 Totals:		**20259.87**	**14.38**

Ventilation

House Volume	Air Change	Heat Loss MJ	% Annual Heat Loss
1323.30 m^3	0.378 ACH	26852.834	19.06

AIR LEAKAGE AND VENTILATION

Building Envelope Surface Area: 904.42 m^2

Air Leakage Test Results at 50 Pa.(0.2 in H_2O) = 1.41 ACH

Equivalent Leakage Area @ 10 Pa = 696.69 cm2

Terrain Description	**Height**	**m**
@ Weather Station : Open flat terrain, grass	Anemometer	10.0
@ Building site : Suburban, forest	Bldg. Eaves	6.4

Local Shielding:	**Walls:**	Light
	Flue :	None

Leakage Fractions- **Ceiling:** 0.200 **Walls:** 0.650 **Floors:** 0.150

Normalized Leakage Area @ 10 Pa:	0.7703 cm2/m2
Estimated Airflow to cause a 5 Pa Pressure Difference:	111 L/s
Estimated Airflow to cause a 10 Pa Pressure Difference:	174 L/s

F326 VENTILATION REQUIREMENTS

Kitchen, Living Room, Dining Room	3 rooms @ 5.0 L/s: 15.0 L/s
Utility Room	1 rooms @ 5.0 L/s: 5.0 L/s
Bedroom	1 rooms @ 10.0 L/s: 10.0 L/s
Bedroom	2 rooms @ 5.0 L/s: 10.0 L/s
Bathroom	2 rooms @ 5.0 L/s: 10.0 L/s
Basement Rooms	: 10.0 L/s

CENTRAL VENTILATION SYSTEM

System Type:	HRV
Manufacturer:	VanEE
Model Number:	2001 HRV (Gold Series)

Fan and Preheater Power at 0.0 °C:	124 Watts
Fan and Preheater Power at -25.0 °C:	114 Watts
Preheater Capacity:	0 Watts
Sensible Heat Recovery Efficiency at 0.0 °C	80%
Sensible Heat Recovery Efficiency at -25.0 °C	80%
Total Heat Recovery Efficency in Cooling Mode	25%
Low Temperature Ventilation Reduction:	0%
Low Temperature Ventilation Reduction: Airflow Adjustment	(0%)

Vented combustion appliance depressurization limit: 5.00 Pa.

Ventilation Supply Duct

Location:	Main floor	**Type:**	Flexible
Length:	1.5 m	**Diameter:**	152.4 mm

Insulation:	0.7 RSI	**Sealing Characteristics:**	Sealed

Ventilation Exhaust Duct

Location:	Main floor	**Type:**	Flexible
Length:	1.5 m	**Diameter:**	152.4 mm
Insulation:	0.7 RSI	**Sealing Characteristics:**	Sealed

SECONDARY FANS & OTHER EXHAUST APPLIANCES

	Control	Supply (L/s)	Exhaust (L/s)
Dryer	Continuous	-	1.20

Dryer is vented outdoors

AIR LEAKAGE AND VENTILATION SUMMARY

F326 Required continous ventilation:	60.000 L/s (0.16 ACH)
Central Ventilation Supply Rate ():	110.908 L/s (0.30 ACH)
Total house ventilation is Balanced	
Gross Air Leakage and Ventilation Energy Load:	73105.164 MJ
Seasonal Heat Recovery Ventilator Efficiency:	79.436 %
Estimated Ventilation Electrical Load: Heating Hours:	3533.697 MJ
Estimated Ventilation Electrical Load: Non-Heating Hours:	373.219 MJ
Net Air Leakage and Ventilation Load:	28619.682 MJ

SPACE HEATING SYSTEM

Primary Space Heating Fuel:	Natural Gas
Space Heating Equipment:	Ground Source Heat Pump
Manufacturer:	Atlas
Model:	ATO60
Capacity at XT3 °C:	0.00 kW
COP at XT3 °C:	3.82
Crankcase Heater Power:	60.00 watts
Heat Pump Temperature Cut-Off:	Balance point

SPACE HEATING SYSTEM

Secondary Heating Fuel:	Electricity
Equipment:	Baseboard/Hydronic/Plenum(duct) htrs.
Manufacturer:	
Model:	
Calculated* Output Capacity:	18.00 kW

* Design Heat loss X 1.00 + 0.5 kW

Steady State Efficiency:	50.00 %
Fan Mode:	Auto
Low Speed Fan Power:	0 watts
High Speed Fan Power:	791 watts

AIR CONDITIONING SYSTEM

System Type:	Conventional A/C		
Manufacturer:			
Model:			
Capacity:	10776 Watts		
SEER	14.70	**Rated COP**	3.1
Sensible Heat Ratio:	0.76		
Indoor Fan Flow Rate:	600.69 L/s	**Fan Power (watts)**	465.54
Ventilator Flow Rate:	0.00 L/s	**Crankcase Heater Power (watts):**	60.00
Fraction of windows Openable	0.00		
Economizer control:	N/A	**Indoor Fan Operation:**	Continuous

Air Conditioner is integrated with the Heating System

DOMESTIC WATER HEATING SYSTEM

Primary Water Heating Fuel:	Solar
Water Heating Equipment:	Solar collector system
Manufactuer:	Enerworks
Model:	EWRA2
CSIA Solar Collector Rating:	10400.00 MJ/Year

Secondary Water Heating Fuel:	Solar
Water Heating Equipment:	B-Medium, Wood frame
Manufactuer:	Enerworks
Model:	EWRA2
CSIA Solar Collector Rating:	MJ/Year

ANNUAL SPACE HEATING SUMMARY

Design Heat Loss at -17.20 °C (13.43 Watts / m3):	17774.13 Watts
Including credit for HRV (0.00 Watts / m3):	0.00
Gross Space Heat Loss:	140864.11 MJ
Gross Space Heating Load:	139450.69 MJ
Usable Internal Gains:	24173.33 MJ
Usable Internal Gains Fraction:	17.16 %
Usable Solar Gains:	24260.95 MJ
Usable Solar Gains Fraction:	17.22 %
Auxilary Energy Required:	91016.44 MJ
Space Heating System Load:	91016.41 MJ
Heat Pump and Furnace Annual COP:	2.94
Heat Pump Annual Energy Consumption:	27269.14 MJ
Furnace/Boiler Annual Energy Consumption:	1694.82 MJ
Annual Space Heating Energy Consumption:	28963.96 MJ

ANNUAL SPACE COOLING SUMMARY

Design Cooling Load for July at 31.00 °C:	10727.38 Watts
Design Sensible Heat Ratio:	0.77
Estimated Annual Space Cooling Energy:	1654.89
Seasonal COP (May to October):	3.45

ANNUAL DOMESTIC WATER HEATING SUMMARY

Daily Hot Water Consumption:	225.00 Litres
Hot Water Temperature:	55.00 °C
Estimated Domestic Water Heating Load:	15341.32 MJ
Solar Domestic Water Heating System Contribution:	8755.98 MJ
Domestic Water Heating Energy Consumption:	7621.24 MJ
System Seasonal Efficiency:	Secondary 86.41

BASE LOADS SUMMARY

	kwh/day	**Annual kWh**
Interior Lighting	1.00	365.00
Appliances	14.00	5110.00

Other	3.00	1095.00
Exterior Use	4.00	1460.00
HVAC Fans		
HRV/Exhaust	2.97	1085.25
Space Heating	1.50	547.56
Space Cooling	3.42	1249.88
Total Average Electrical Load	29.90	10912.69

FAN OPERATION SUMMARY (kWh)

Hours	**HRV/Exhaust Fans**	**Space Heating**	**Space Cooling**
Heating	981.58	547.56	0.00
Neither	0.00	0.00	1023.36
Cooling	103.67	0.00	226.51
Total	1085.25	547.56	1249.88

ENERGY CONSUMPTION SUMMARY REPORT

Estimated Annual Space Heating Energy Consumption	= 37395.54 MJ	= 10387.65 kWh
Ventilator Electrical Consumption: Heating Hours	= 3533.70 MJ	= 981.58 kWh
Estimated Annual DHW Heating Energy Consumption	= 7621.24 MJ	= 2117.01 kWh
ESTIMATED ANNUAL SPACE + DHW ENERGY CONSUMPTION	= 48550.48 MJ	= 13486.24 kWh

Estimated Greenhouse Gas Emissions 12.47 tonnes/year

ESTIMATED ANNUAL FUEL CONSUMPTION SUMMARY

Fuel	Space Heating	Space Cooling	DHW Heating	Appliance	Total
Natural Gas (m3)	173.39	0.00	0.00	0.00	173.39
Electricity (kWh)	9574.68	1654.89	2117.01	9053.36	22399.95

ESTIMATED ANNUAL FUEL CONSUMPTION COSTS

Fuel Costs Library = C:\PROGRA~1\H2KEGH~1\Stdlibs\FuelLib.FLC

RATE	Electricity (Ottawa97)	Natural Gas (Ottawa97)	Oil (Ottawa97)	Propane (Ottawa97)	Wood (Sth Ont)	Total
$	1781.58	135.62	0.00	0.00	0.00	1917.20

MONTHLY ENERGY PROFILE

Month	Energy Load (MJ)	Internal Gains (MJ)	Solar Gains (MJ)	Aux. Energy (MJ)	HRV Eff. %
Jan	24332.2	2296.4	2613.1	19422.8	79.4
Feb	21310.6	2067.8	3049.3	16193.4	79.4
Mar	19092.6	2296.8	3751.8	13044.0	79.4
Apr	12490.5	2241.9	3210.5	7038.2	79.4
May	7493.9	2343.3	2860.4	2290.2	79.4
Jun	2397.6	1700.0	697.6	0.0	79.5
Jul	819.0	794.1	25.0	0.0	79.5
Aug	1284.1	1168.1	116.0	0.0	79.5
Sep	4525.5	2312.2	1837.8	375.6	79.5
Oct	9755.4	2369.8	2549.9	4835.8	79.4
Nov	14622.3	2267.2	1583.4	10771.7	79.4
Dec	21326.9	2315.9	1966.2	17044.8	79.4
Ann	139450.7	24173.3	24260.9	91016.4	79.4

FOUNDATION ENERGY PROFILE

	Heat Loss (MJ)				
Month	Crawl Space	Slab	Basement	Walkout	Total
Jan	0.0	0.0	1240.5	0.0	1240.5
Feb	0.0	0.0	1034.1	0.0	1034.1
Mar	0.0	0.0	832.9	0.0	832.9
Apr	0.0	0.0	449.4	0.0	449.4
May	0.0	0.0	146.2	0.0	146.2
Jun	0.0	0.0	0.0	0.0	0.0
Jul	0.0	0.0	0.0	0.0	0.0
Aug	0.0	0.0	0.0	0.0	0.0
Sep	0.0	0.0	24.0	0.0	24.0
Oct	0.0	0.0	308.8	0.0	308.8
Nov	0.0	0.0	687.8	0.0	687.8
Dec	0.0	0.0	1088.4	0.0	1088.4
Ann	0.0	0.0	5812.1	0.0	5812.1

FOUNDATION TEMPERATURES & VENTILATION PROFILE

	Temperature (Deg °C)			Air Change Rate		Heat Loss
Month	Crawl Space	Basement	Walkout	Natural	Total	(MJ
Jan	0.0	20.0	0.0	0.112	0.417	5463.8
Feb	0.0	19.9	0.0	0.108	0.413	4694.9
Mar	0.0	19.8	0.0	0.098	0.403	3949.1
Apr	0.0	19.9	0.0	0.082	0.387	2273.0
May	0.0	20.1	0.0	0.061	0.366	1072.0
Jun	0.0	20.5	0.0	0.045	0.350	171.9
Jul	0.0	21.3	0.0	0.038	0.343	-97.5

Aug	0.0	21.2	0.0	0.038	0.343	-11.9
Sep	0.0	20.6	0.0	0.048	0.353	494.1
Oct	0.0	20.4	0.0	0.065	0.370	1555.9
Nov	0.0	20.3	0.0	0.085	0.390	2754.6
Dec	0.0	20.1	0.0	0.101	0.406	4532.9
Ann	0.0	20.3	0.0	0.073	0.378	26852.8

SPACE HEATING SYSTEM PERFORMANCE

Month	Space Heating Load (MJ)	Furnace Input (MJ)	Pilot Light (MJ)	Indoor Fans (MJ)	Heat Pump Input (MJ)	Total Input (MJ)	System Cop
Jan	19422.8	676.1	0.0	431.6	5725.8	6833.5	2.8
Feb	16193.4	420.8	0.0	386.2	4998.0	5805.0	2.8
Mar	13043.9	109.3	0.0	314.9	4174.5	4598.7	2.8
Apr	7038.2	67.7	0.0	161.0	2252.6	2481.4	2.8
May	2290.2	35.7	0.0	47.6	729.2	812.5	2.8
Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	375.6	6.7	0.0	6.4	140.4	153.5	2.4
Oct	4835.8	55.1	0.0	83.6	1348.6	1487.4	3.3
Nov	10771.7	78.3	0.0	197.3	3025.4	3301.0	3.3
Dec	17044.8	245.0	0.0	342.7	4874.5	5462.2	3.1
Ann	91016.4	1694.8	27269.1	1971.2	0.0	30935.2	2.9

AIR CONDITIONING SYSTEM PERFORMANCE

Month	Sensible	Latent	AirCond	Fan	Ventilator	Total	COP	Av.RH
Jan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Apr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
May	796.6	149.0	66.1	287.7	0.0	146.1	3.4	35.1
Jun	2810.4	867.0	254.1	1206.7	0.0	599.2	3.3	42.3
Jul	5191.3	1918.2	474.3	1246.9	0.0	823.7	3.5	45.7
Aug	4184.7	1650.5	392.6	1246.9	0.0	744.8	3.5	46.7
Sep	1114.9	395.7	105.8	451.3	0.0	231.2	3.4	44.0
Oct	137.5	46.1	13.0	60.1	0.0	29.7	3.3	42.5
Nov	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dec	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ann	14235.4	5026.5	1305.9	4499.6	0.0	2574.6	3.4	44.2

MONTHLY ESTIMATED ENERGY CONSUMPTION BY DEVICE (MJ)

Month	Space Heating Primary	Space Heating Secondary	DHW Heating Primary	DHW Heating Secondary	Lights & Appliances	HRV & FANS	Air Conditioner
Jan	5725.8	1224.8	0.0	1242.0	2455.2	762.2	0.0
Feb	4998.0	916.4	0.0	954.8	2217.6	685.0	0.0
Mar	4174.5	658.0	0.0	867.7	2455.2	646.8	0.0
Apr	2252.6	598.7	0.0	434.5	2376.0	482.4	0.0
May	729.2	584.4	0.0	297.5	2455.2	667.4	238.1
Jun	0.0	531.0	0.0	85.3	2376.0	1528.1	950.5
Jul	0.0	548.7	0.0	88.2	2455.2	1579.0	1718.3
Aug	0.0	548.7	0.0	116.9	2455.2	1579.0	1434.3
Sep	140.4	537.7	0.0	398.9	2376.0	779.1	380.9
Oct	1348.6	603.8	0.0	792.3	2455.2	475.8	46.8
Nov	3025.4	609.3	0.0	1085.1	2376.0	518.7	0.0
Dec	4874.5	793.7	0.0	1258.1	2455.2	674.1	0.0
Ann	27269.1	8155.2	0.0	7621.2	28908.0	10377.7	4768.9

MONTHLY ESTIMATED SOLAR DHW CONTRIBUTION (MJ)

Month	DHW Heating Primary
Jan	300.1
Feb	459.4
Mar	675.0
Apr	996.9
May	1094.5
Jun	1178.2
Jul	1154.1
Aug	1102.1
Sep	801.8
Oct	512.3
Nov	261.4
Dec	220.3
Ann	8756.0

ESTIMATED FUEL COSTS (Dollars)

Month	Electricity	Natural Gas	Oil	Propane	Wood	Total
Jan	229.2	11.4	0.0	0.0	0.0	240.6
Feb	198.3	11.0	0.0	0.0	0.0	209.4
Mar	178.4	11.4	0.0	0.0	0.0	189.7
Apr	126.9	11.3	0.0	0.0	0.0	138.1
May	103.7	11.4	0.0	0.0	0.0	115.0
Jun	113.8	11.3	0.0	0.0	0.0	125.0
Jul	131.3	11.4	0.0	0.0	0.0	142.7
Aug	126.3	11.4	0.0	0.0	0.0	137.7
Sep	97.0	11.3	0.0	0.0	0.0	108.3

Oct	118.3	11.4	0.0	0.0	0.0	129.7
Nov	155.6	11.3	0.0	0.0	0.0	166.8
Dec	202.8	11.4	0.0	0.0	0.0	214.2
Ann	1781.6	135.6	0.0	0.0	0.0	1917.2

The calculated heat losses and energy consumptions are only estimates, based upon the data entered and assumptions within the program. Actual energy consumption and heat losses will be influenced by construction practices, localized weather, equipment characteristics and the lifestyle of the occupants.

Appendix - C

System Input File Generated by TRNSYS

```
VERSION 16
*******************************************************************************
*** TRNSYS input file (deck) generated by TrnsysStudio
*** on Monday, April 20, 2009 at 11:39
*** from TrnsysStudio project: M:\mattamy_27_Sep.TPF
***
*** If you edit this file, use the File/Import TRNSYS Input File function in
*** TrnsysStudio to update the project.
***
*** If you have problems, questions or suggestions please contact your local
*** TRNSYS distributor or mailto:iisibat@cstb.fr
***
*******************************************************************************


*******************************************************************************
*** Units
*******************************************************************************

*******************************************************************************
*** Control cards
*******************************************************************************
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=8760.000229455
STEP=1
* User defined CONSTANTS

SIMULATION     START  STOP     STEP    ! Start time       End time        Time step
TOLERANCES 0.001 0.001                          ! Integration      Convergence
LIMITS 60 30 30                        ! Max iterations   Max warnings    Trace limit
DFQ 1                                  ! TRNSYS numerical integration solver method
WIDTH 72                               ! TRNSYS output file width, number of characters
LIST                                   ! NOLIST statement
                                       ! MAP statement
SOLVER 0 1 1                           ! Solver statement         Minimum relaxation factor
        Maximum relaxation factor
NAN_CHECK 0                            ! Nan DEBUG statement
OVERWRITE_CHECK 0                      ! Overwrite DEBUG statement
EQSOLVER 0                             ! EQUATION SOLVER statement

* EQUATIONS "Radiation"
*
EQUATIONS 27
AISZ = [109,10]
AISA = [109,11]
IT_H = Max([109,12],0)
IB_H = Max([109,13],0)
ID_H = [109,14]
AI_H = [109,16]
IT_N = [109,18]
AI_N = [109,22]
IB_N = [109,19] * LT(AI_N,90)
IT_S = [109,24]
IB_S = [109,25]
```

```
AI_S = [109,28]
IT_E = [109,30]
IB_E = [109,31]
AI_E = [109,34]
IT_W = [109,36]
IB_W = [109,37]
AI_W = [109,40]
IT_SLOPE_E = [109,42]
IB_SLOPE_E = [109,43]
AI_SLOPE_E = [109,46]
IT_SLOPE_W = [109,48]
IB_SLOPE_W = [109,49]
AI_SLOPE_W = [109,52]
IT_SLOPE_S = [109,54]
IB_SLOPE_S = [109,55]
AI_SLOPE_S = [109,58]
*$UNIT_NAME Radiation
*$LAYER Main
*$POSITION 196 125

*------------------------------------------------------------------------------


* Model "Weather data" (Type 109)
*

UNIT 109 TYPE 109	 Weather data
*$UNIT_NAME Weather data
*$MODEL .\Weather Data Reading and Processing\Standard Format\TMY2\Type109-TMY2.tmf
*$POSITION 57 178
*$LAYER Main #
PARAMETERS 4
2		! 1 Data Reader Mode
30		! 2 Logical unit
4		! 3 Sky model for diffuse radiation
1		! 4 Tracking mode
INPUTS 17
0,0		! [unconnected] Ground reflectance
0,0		! [unconnected] Slope of surface-1
0,0		! [unconnected] Azimuth of surface-1
0,0		! [unconnected] Slope of surface-2
0,0		! [unconnected] Azimuth of surface-2
0,0		! [unconnected] Slope of surface-3
0,0		! [unconnected] Azimuth of surface-3
0,0		! [unconnected] Slope of surface-4
0,0		! [unconnected] Azimuth of surface-4
0,0		! [unconnected] Slope of surface-5
0,0		! [unconnected] Azimuth of surface-5
0,0		! [unconnected] Slope of surface-6
0,0		! [unconnected] Azimuth of surface-6
0,0		! [unconnected] Slope of surface-7
0,0		! [unconnected] Azimuth of surface-7
0,0		! [unconnected] Slope of surface-8
0,0		! [unconnected] Azimuth of surface-8
*** INITIAL INPUT VALUES
0.2 90 0 90 90 90 180 90 270 45 90 45 270 45 180 45 0
```

```
*** External files
ASSIGN "SUI Transys\CA-ON-Toronto-716240.tm2" 30
*|? Weather data file |1000
*------------------------------------------------------------------------------

* Model "Psychrometrics" (Type 33)
*

UNIT 331 TYPE 33	 Psychrometrics
*$UNIT_NAME Psychrometrics
*$MODEL .\Physical Phenomena\Thermodynamic Properties\Psychrometrics\Dry Bulb and Relative Humidity Known\Type33e.tmf
*$POSITION 200 325
*$LAYER Main #
PARAMETERS 3
2		! 1 Psychrometrics mode
1		! 2 Wet bulb mode
1		! 3 Error mode
INPUTS 3
109,1		! Weather data:Ambient temperature ->Dry bulb temp.
109,2		! Weather data:relative humidity ->Percent relative humidity
0,0		! [unconnected] Pressure
*** INITIAL INPUT VALUES
20 50 1
*------------------------------------------------------------------------------

* Model "Sky temp" (Type 69)
*

UNIT 69 TYPE 69	 Sky temp
*$UNIT_NAME Sky temp
*$MODEL .\Physical Phenomena\Sky Temperature\read in cloudiness factor\Type69a.tmf
*$POSITION 353 273
*$LAYER Main # #
PARAMETERS 2
1		! 1 mode for cloudiness factor
0		! 2 height over sea level
INPUTS 5
331,7		! Psychrometrics:Dry bulb temperature ->Ambient temperature
331,8		! Psychrometrics:Dew point temperature. ->Dew point temperature at ambient conditions
109,13		! Weather data:beam radiation on horitonzal ->Beam radiation on the horizontal
109,14		! Weather data:sky diffuse radiation on horizontal ->Diffuse radiation on the horizontal
0,0		! [unconnected] Cloudiness factor -  sky
*** INITIAL INPUT VALUES
0 0 0 0 0
*------------------------------------------------------------------------------

* Model "Mattamy house" (Type 56)
*

UNIT 56 TYPE 56	 Mattamy house
*$UNIT_NAME Mattamy house
*$MODEL .\Loads and Structures\Multi-Zone Building\With Standard Output Files\Type56a.tmf
*$POSITION 948 573
*$LAYER Main # #
*$#
```

PARAMETERS 6
31 ! 1 Logical unit for building description file (.bui)
1 ! 2 Star network calculation switch
0.5 ! 3 Weighting factor for operative temperature
32 ! 4 Logical unit for monthly summary
33 ! 5 Logical unit for hourly temperatures
34 ! 6 Logical unit for hourly loads
INPUTS 36
331,7 ! Psychrometrics:Dry bulb temperature -> 1- TAMB (AMBIENT TEMPERATURE)
331,6 ! Psychrometrics:Percent relative humidity -> 2- ARELHUM (RELATIVE AMBIENT HUMIDITY)
69,1 ! Sky temp:Fictive sky temperature -> 3- TSKY (FIKTIVE SKY TEMPERATURE)
IT_N ! Radiation:IT_N -> 4- ITNORTH (INCIDENT RADIATION FOR ORIENTATION NORTH)
IT_S ! Radiation:IT_S -> 5- ITSOUTH (INCIDENT RADIATION FOR ORIENTATION SOUTH)
IT_E ! Radiation:IT_E -> 6- ITEAST (INCIDENT RADIATION FOR ORIENTATION EAST)
IT_W ! Radiation:IT_W -> 7- ITWEST (INCIDENT RADIATION FOR ORIENTATION WEST)
IT_H ! Radiation:IT_H -> 8- ITHORIZONT (INCIDENT RADIATION FOR ORIENTATION HORIZONTAL)
IT_SLOPE_E ! Radiation:IT_SLOPE_E -> 9- ITESLOPE (INCIDENT RADIATION FOR ORIENTATION ESLOPE)
IT_SLOPE_W ! Radiation:IT_SLOPE_W -> 10- ITWSLOPE (INCIDENT RADIATION FOR ORIENTATION WSLOPE)
IT_SLOPE_S ! Radiation:IT_SLOPE_S -> 11- ITSOUTHSLO (INCIDENT RADIATION FOR ORIENTATION SOUTHSLOPE)
IB_N ! Radiation:IB_N -> 12- IBNORTH (INCIDENT BEAM RADIATION FOR ORIENTATION NORTH)
IB_S ! Radiation:IB_S -> 13- IBSOUTH (INCIDENT BEAM RADIATION FOR ORIENTATION SOUTH)
IB_E ! Radiation:IB_E -> 14- IBEAST (INCIDENT BEAM RADIATION FOR ORIENTATION EAST)
IB_W ! Radiation:IB_W -> 15- IBWEST (INCIDENT BEAM RADIATION FOR ORIENTATION WEST)
IB_H ! Radiation:IB_H -> 16- IBHORIZONT (INCIDENT BEAM RADIATION FOR ORIENTATION HORIZONTAL)
IB_SLOPE_E ! Radiation:IB_SLOPE_E -> 17- IBESLOPE (INCIDENT BEAM RADIATION FOR ORIENTATION ESLOPE)
IB_SLOPE_W ! Radiation:IB_SLOPE_W -> 18- IBWSLOPE (INCIDENT BEAM RADIATION FOR ORIENTATION WSLOPE)
IB_SLOPE_S ! Radiation:IB_SLOPE_S -> 19- IBSOUTHSLO (INCIDENT BEAM RADIATION FOR ORIENTATION SOUTHSLOPE)
AI_N ! Radiation:AI_N -> 20- AINORTH (ANGLE OF INCIDENCE FOR ORIENTATION NORTH)
AI_S ! Radiation:AI_S -> 21- AISOUTH (ANGLE OF INCIDENCE FOR ORIENTATION SOUTH)
AI_E ! Radiation:AI_E -> 22- AIEAST (ANGLE OF INCIDENCE FOR ORIENTATION EAST)
AI_W ! Radiation:AI_W -> 23- AIWEST (ANGLE OF INCIDENCE FOR ORIENTATION WEST)
AI_H ! Radiation:AI_H -> 24- AIHORIZONT (ANGLE OF INCIDENCE FOR ORIENTATION HORIZONTAL)
AI_SLOPE_E ! Radiation:AI_SLOPE_E -> 25- AIESLOPE (ANGLE OF INCIDENCE FOR ORIENTATION ESLOPE)
AI_SLOPE_W ! Radiation:AI_SLOPE_W -> 26- AIWSLOPE (ANGLE OF INCIDENCE FOR ORIENTATION WSLOPE)
AI_SLOPE_S ! Radiation:AI_SLOPE_S -> 27- AISOUTHSLO (ANGLE OF INCIDENCE FOR ORIENTATION SOUTHSLOPE)

```
Basement_Heat              ! Gain:Basement_Heat ->   28- HEATER_SLA  (INPUT)
64,8                 ! HRV:Fresh air %RH ->   29- RH_HVAC  (INPUT)
64,6                 ! HRV:Fresh air temperature ->   30- T_HVAC  (INPUT)
Heat_1stFLR                ! Gain:Heat_1stFLR ->   31- HEATER1  (INPUT)
Heat_2ndFLR                ! Gain:Heat_2ndFLR ->   32- HEATER2  (INPUT)
0,0                  ! [unconnected]    33- COOLING  (INPUT)
Cooling_1stFLR             ! Gain:Cooling_1stFLR ->   34- COOLING1  (INPUT)
cooling_2ndFLR             ! Gain:cooling_2ndFLR ->   35- COOLING2  (INPUT)
30,1                 ! Heating Sch:Heating enable signal ->   36- HEATING_SC  (INPUT)
*** INITIAL INPUT VALUES
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
*** External files
ASSIGN "Mattamy\mattamy TRANSBUILD\Mattamy Home Transbuild 14 june.bui" 31
*|? Building description file (*.bui) |1000
ASSIGN "T56_std-Output.sum" 32
*|? Monthly Summary File |1000
ASSIGN "T56_std-temp.prn" 33
*|? Hourly Temperatures |1000
ASSIGN "T56_std-q.prn" 34
*|? Hourly Loads |1000
*------------------------------------------------------------------------------

* Model "Type505b" (Type 505)
*

UNIT 14 TYPE 505          Type505b
*$UNIT_NAME Type505b
*$MODEL .\HVAC Library (TESS)\Water Loop Heat Pump\Relative Humidity\Type505b.tmf
*$POSITION 368 519
*$LAYER Main #
*$# The value for power in the catalog data files for both heating and cooling mode should include the
*$# indoor fan.
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
*$#
PARAMETERS 21
2                    ! 1 Humidity mode
39                   ! 2 Logical unit for cooling data
40                   ! 3 Logical unit for heating data
```

```
41                  ! 4 Logical unit number for cooling correction data
42                  ! 5 Logical unit number for heating correction data
3                   ! 6 Number of water flow steps
4                   ! 7 Number of water temps. - cooling
4                   ! 8 Number of water temps. - heating
6                   ! 9 Number of wet bulb steps
4                   ! 10 Number of dry bulb steps - cooling
6                   ! 11 Number of dry bulb steps - heating
2                   ! 12 Number of airflow steps - cooling
2                   ! 13 Number of airflow steps - heating
1036                ! 14 Density of liquid stream
3.6                 ! 15 Specific heat of liquid stream
4.18                ! 16 Specific heat of DHW fluid
671.101145                  ! 17 Blower power
35.999997                   ! 18 Controller power
8999.999334                 ! 19 Capacity of stage-1 auxiliary
0                   ! 20 Capacity of stage-2 auxiliary
943.899617                  ! 21 Total air flow rate
INPUTS 29
22,1                ! Type11f:Temperature at outlet 1 ->Inlet liquid temperature
0,0                 ! [unconnected] Inlet liquid flow rate
56,3                ! Mattamy house:    3- (air temperature of zone)  TAIR   3 ->Return air temperature
0,0                 ! [unconnected] Not used
0,0                 ! [unconnected] Return air %RH
0,0                 ! [unconnected] Return air pressure
0,0                 ! [unconnected] Return air damper pressure drop
0,0                 ! [unconnected] Fresh air temperature
0,0                 ! [unconnected] Not used
0,0                 ! [unconnected] Fresh air %RH
0,0                 ! [unconnected] Fresh air pressure
0,0                 ! [unconnected] Fresh air damper pressure drop
27,1                ! Hot Water Tank:Temperature to heat source ->Inlet DHW temperature
27,2                ! Hot Water Tank:Flowrate to heat source ->Inlet DHW flow rate
HP_COOLING                  ! Heat Pump Control:HP_COOLING ->Cooling control signal
HP                  ! Heat Pump Control:HP ->Heating control signal
HP                  ! Heat Pump Control:HP ->Stage 1 auxiliary signal
HP                  ! Heat Pump Control:HP ->Stage 2 auxiliary signal
Fan_signal                  ! Heat Pump Control:Fan_signal ->Fan control signal
0,0                 ! [unconnected] Fraction of outside air
0,0                 ! [unconnected] Cooling desuperheater temperature
0,0                 ! [unconnected] Heating desuperheater temperature
0,0                 ! [unconnected] Desuperheater UA - cooling
0,0                 ! [unconnected] Desuperheater UA - heating
0,0                 ! [unconnected] Fraction of rated cooling power
0,0                 ! [unconnected] Fraction of rated cooling capacity
0,0                 ! [unconnected] Fraction of rated heating power
0,0                 ! [unconnected] Fraction of rated heating capacity
0,0                 ! [unconnected] Pressure rise through heat pump
*** INITIAL INPUT VALUES
5 1173 20.0 0.008 50.0 1.0 0 15 0.008 50. 1.0 0 12 500 0 0 0 0 0 0 60.0 55.0 1500.0
1500.0 1.0 1.0 1 1 0.0
*** External files
ASSIGN "Atlas60_C.dat" 39
*|? Which file contains the heat pump cooling performance data? |1000
ASSIGN "Atlas60_Heating.txt" 40
*|? Which file contains the heat pump heating performance data? |1000
```

```
ASSIGN "C:\Program Files\Trnsys16\Tess Models\SampleCatalogData\GeothermalHeatPump\Samp_CT.DAT"
41
*|? Which file contains the heat pump cooling correction factor data? |1000
ASSIGN "C:\Program Files\Trnsys16\Tess Models\SampleCatalogData\GeothermalHeatPump\Samp_HT.DAT"
42
*|? Which file contains the heat pump heating correction factor data? |1000
*------------------------------------------------------------------------------

* Model "Solar Panel" (Type 1)
*

UNIT 15 TYPE 1 Solar Panel
*$UNIT_NAME Solar Panel
*$MODEL .\Solar Thermal Collectors\Quadratic Efficiency Collector\2nd-Order Incidence Angle
Modifiers\Type1b.tmf
*$POSITION 232 850
*$LAYER Main #
PARAMETERS 11
3               ! 1 Number in series
6.81            ! 2 Collector area
3.6             ! 3 Fluid specific heat
1               ! 4 Efficiency mode
40.0            ! 5 Tested flow rate
0.80            ! 6 Intercept efficiency
13.0            ! 7 Efficiency slope
0.05            ! 8 Efficiency curvature
2               ! 9 Optical mode 2
0.2             ! 10 1st-order IAM
0.0             ! 11 2nd-order IAM
INPUTS 9
22,3            ! Type11f:Temperature at outlet 2 ->Inlet temperature
22,4            ! Type11f:Flow rate at outlet 2 ->Inlet flowrate
109,1           ! Weather data:Ambient temperature ->Ambient temperature
109,60          ! Weather data:total radiation on tilted surface-8 ->Incident radiation
109,12          ! Weather data:total radiation on horizontal ->Total horizontal radiation
109,14          ! Weather data:sky diffuse radiation on horizontal ->Horizontal diffuse radiation
0,0             ! [unconnected] Ground reflectance
109,64          ! Weather data:angle of incidence for tilted surface -8 ->Incidence angle
0,0             ! [unconnected] Collector slope
*** INITIAL INPUT VALUES
5 0 10.0 0. 0.0 0.0 0.2 45.0 45
*------------------------------------------------------------------------------

* Model "Type557a" (Type 557)
*

UNIT 18 TYPE 557        Type557a
*$UNIT_NAME Type557a
*$MODEL .\GHP Library (TESS)\Ground Heat Exchangers\Vertical U-Tubes\Standard\Type557a.tmf
*$POSITION 143 433
*$LAYER Main #
PARAMETERS 44
1293            ! 1 Storage volume
55              ! 2 Borehole depth
1.8             ! 3 Header depth
4               ! 4 Number of boreholes
```

```
0.1                     ! 5 Borehole radius
1                       ! 6 No. of boreholes in series
1                       ! 7 Number of radial regions
10                      ! 8 Number of vertical regions
7.2                     ! 9 Storage thermal conductivity
1820                    ! 10 Storage heat capacity
-1                      ! 11 Negative of u-tubes/bore
0.01664                 ! 12 Outer radius of u-tube pipe
0.01372                 ! 13 Inner radius of u-tube pipe
0.0254                  ! 14 Center-to-center half distance
3.6                     ! 15 Fill thermal conductivity
1.512202                        ! 16 Pipe thermal conductivity
6.000001                        ! 17 Gap thermal conductivity
0.0                     ! 18 Gap thickness
350                     ! 19 Reference borehole flow rate
10                      ! 20 Reference temperature
-1                      ! 21 Pipe to pipe heat transfer
3.6                     ! 22 Fluid specific heat
1036                    ! 23 Fluid density
0                       ! 24 Insulation indicator
0                       ! 25 Insulation height fraction
0                       ! 26 Insulation thickness
0                       ! 27 Insulation thermal conductivity
1                       ! 28 Number of simulation years
100.0                   ! 29 Maximum storage temperature
20.0                    ! 30 Initial surface temperature
0.0                     ! 31 Initial thermal gradient
0                       ! 32 Number of preheating years
30.0                    ! 33 Maximum preheat temperature
10.0                    ! 34 Minimum preheat temperature
90                      ! 35 Preheat phase delay
20.0                    ! 36 Average air temperature
15.0                    ! 37 Amplitude of air temperature
240                     ! 38 Air temperature phase delay
1                       ! 39 Number of ground layers
7.2                     ! 40 Thermal conductivity of layer
2016.0                  ! 41 Heat capacity of layer
1000.0                  ! 42 Thickness of layer
0                       ! 43 Not used (printing 1)
0                       ! 44 Not used (printing 2)
INPUTS 5
21,1                    ! Type114-2:Outlet fluid temperature ->Inlet fluid temperature
21,2                    ! Type114-2:Outlet flow rate ->Inlet flowrate (total)
109,1                   ! Weather data:Ambient temperature ->Temperature on top of storage
109,1                   ! Weather data:Ambient temperature ->Air temperature
0,0                     ! [unconnected] Circulation switch
*** INITIAL INPUT VALUES
0 1533 0 0 1
*------------------------------------------------------------------------------

* Model "Type11f" (Type 11)
*

UNIT 22 TYPE 11         Type11f
*$UNIT_NAME Type11f
*$MODEL .\Hydronics\Flow Diverter\Other Fluids\Type11f.tmf
```

```
*$POSITION 139 733
*$LAYER Water Loop #
PARAMETERS 1
2                    ! 1 Controlled flow diverter mode
INPUTS 3
20,1                 ! Type114:Outlet fluid temperature ->Inlet temperature
20,2                 ! Type114:Outlet flow rate ->Inlet flow rate
Solar_Loop                     !  Control:Solar_Loop ->Control signal
*** INITIAL INPUT VALUES
5 0 1
*------------------------------------------------------------------------------

* Model "Type11h-2" (Type 11)
*

UNIT 23 TYPE 11            Type11h-2
*$UNIT_NAME Type11h-2
*$MODEL .\Hydronics\Tee-Piece\Other Fluids\Type11h.tmf
*$POSITION 215 669
*$LAYER Water Loop #
PARAMETERS 1
1                    ! 1 Tee piece mode
INPUTS 4
14,1                 ! Type505b:Exiting fluid temperature ->Temperature at inlet 1
22,2                 ! Type11f:Flow rate at outlet 1 ->Flow rate at inlet 1
15,1                 ! Solar Panel:Outlet temperature ->Temperature at inlet 2
15,2                 ! Solar Panel:Outlet flowrate ->Flow rate at inlet 2
*** INITIAL INPUT VALUES
5 1173 20 120
*------------------------------------------------------------------------------

* Model "Type114" (Type 114)
*

UNIT 20 TYPE 114           Type114
*$UNIT_NAME Type114
*$MODEL .\Hydronics\Pumps\Single Speed\Type114.tmf
*$POSITION 97 541
*$LAYER Main #
*$# SINGLE-SPEED PUMP
PARAMETERS 4
1293                 ! 1 Rated flow rate
3.6                  ! 2 Fluid specific heat
2684.0001                      ! 3 Rated power
0.0                  ! 4 Motor heat loss fraction
INPUTS 5
18,1                 ! Type557a:Outlet temperature ->Inlet fluid temperature
18,2                 ! Type557a:Outlet flow rate (total) ->Inlet fluid flow rate
pump_sinal                     !  Control:pump_sinal ->Control signal
0,0                  ! [unconnected] Overall pump efficiency
0,0                  ! [unconnected] Motor efficiency
*** INITIAL INPUT VALUES
5 1293 1.0 0.6 0.9
*------------------------------------------------------------------------------

* Model "Type114-2" (Type 114)
```

```
*

UNIT 21 TYPE 114	 Type114-2
*$UNIT_NAME Type114-2
*$MODEL .\Hydronics\Pumps\Single Speed\Type114.tmf
*$POSITION 182 541
*$LAYER Main #
*$# SINGLE-SPEED PUMP
PARAMETERS 4
1293		! 1 Rated flow rate
3.6		! 2 Fluid specific heat
2684.0001		! 3 Rated power
0.0		! 4 Motor heat loss fraction
INPUTS 5
23,1		! Type11h-2:Outlet temperature ->Inlet fluid temperature
23,2		! Type11h-2:Outlet flow rate ->Inlet fluid flow rate
pump_sinal		!  Control:pump_sinal ->Control signal
0,0		! [unconnected] Overall pump efficiency
0,0		! [unconnected] Motor efficiency
*** INITIAL INPUT VALUES
20.0 1393 1.0 0.6 0.9
*------------------------------------------------------------------------------

* Model "Hot Water Tank" (Type 4)
*

UNIT 27 TYPE 4 Hot Water Tank
*$UNIT_NAME Hot Water Tank
*$MODEL .\Thermal Storage\Stratified Storage Tank\Variable Inlets\Uniform Losses\Type4c.tmf
*$POSITION 448 786
*$LAYER Water Loop #
PARAMETERS 25
2		! 1 Variable inlet positions
0.22		! 2 Tank volume
4.19		! 3 Fluid specific heat
1000		! 4 Fluid density
3		! 5 Tank loss coefficient
.3		! 6 Height of node-1
.3		! 7 Height of node-2
.3		! 8 Height of node-3
.3		! 9 Height of node-4
.3		! 10 Height of node-5
.3		! 11 Height of node-6
1		! 12 Auxiliary heater mode
1		! 13 Node containing heating element -1
1		! 14 Node containing thermostat -1
60.0		! 15 Set point temperature for element-1
5.0		! 16 Deadband for heating element-1
9000		! 17 Maximum heating rate of element -1
1		! 18 Node containing heating element -2
1		! 19 Node containing thermostat -2
60.0		! 20 Set point temperature for element-2
5.0		! 21 Deadband for heating element-2
8999.999334		! 22 Maximum heating rate of element -2
0.0		! 23 Not used (Flue UA)
20.0		! 24 Not used (Tflue)
```

```
100.0          ! 25 Boiling point
INPUTS 7
14,8           ! Type505b:Exiting DHW temperature ->Hot-side temperature
14,9           ! Type505b:Exiting DHW flow rate ->Hot-side flowrate
49,1           ! Mixer:Outlet temperature ->Cold-side temperature
49,2           ! Mixer:Outlet flow rate ->Cold-side flowrate
0,0            ! [unconnected] Environment temperature
0,0            ! [unconnected] Control signal for element-1
0,0            ! [unconnected] Control signal for element-2
*** INITIAL INPUT VALUES
45.0 1000 8 600 22 1 1
DERIVATIVES 6
0              ! 1 Initial temperature of node-1
0              ! 2 Initial temperature of node-2
0              ! 3 Initial temperature of node-3
0              ! 4 Initial temperature of node-4
0              ! 5 Initial temperature of node-5
0              ! 6 Initial temperature of node-6
*------------------------------------------------------------------------------

* Model "Heating set back" (Type 14)
*

UNIT 26 TYPE 14       Heating set back
*$UNIT_NAME Heating set back
*$MODEL .\Utility\Forcing Functions\Temperature\Type14e.tmf
*$POSITION 460 393
*$LAYER Main #
PARAMETERS 12
0              ! 1 Initial value of time
19             ! 2 Initial temperature
8              ! 3 Time at point-1
19             ! 4 Temperature at point -1
8              ! 5 Time at point-2
21             ! 6 Temperature at point -2
22             ! 7 Time at point-3
21             ! 8 Temperature at point -3
22             ! 9 Time at point-4
19             ! 10 Temperature at point -4
24             ! 11 Time at point-5
19             ! 12 Temperature at point -5
*------------------------------------------------------------------------------

* Model "Thermostat" (Type 698)
*

UNIT 28 TYPE 698      Thermostat
*$UNIT_NAME Thermostat
*$MODEL .\Controllers Library (TESS)\5-Stage Multi-Zone Thermostat\Type698.tmf
*$POSITION 713 542
*$LAYER Main #
PARAMETERS 7
3              ! 1 Number of zones to monitor
5              ! 2 # of oscillations permitted
1              ! 3 1st stage heating in 2nd stage?
1              ! 4 2nd stage heating in 3rd stage?
```

```
1                    ! 5 1st stage heating in 3rd stage?
1                    ! 6 1st stage cooling in 2nd stage?
2.0                  ! 7 Temperature dead band
INPUTS 8
26,2                 ! Heating set back:Instantaneous temperature ->1st stage heating setpoint temperature
0,0                  ! [unconnected] 2nd stage heating setpoint temperature
0,0                  ! [unconnected] 3rd stage heating setpoint temperature
0,0                  ! [unconnected] 1st stage cooling setpoint temperature
0,0                  ! [unconnected] 2nd stage cooling setpoint temperature
0,0                  ! [unconnected] Temperature of zone-1
56,2                 ! Mattamy house:    2- (air temperature of zone)  TAIR   2 ->Temperature of zone-2
56,3                 ! Mattamy house:    3- (air temperature of zone)  TAIR   3 ->Temperature of zone-3
*** INITIAL INPUT VALUES
21 15 15 24 24 20.0 20.0 20.0
*------------------------------------------------------------------------------

* EQUATIONS "Heat Pump Control"
*
EQUATIONS 4
HP = [28,19]*[30,1]
HP_COOLING = [28,19]*[53,1]
Ground_Loop = 0.7*[30,1]
Fan_signal = HP+HP_COOLING
*$UNIT_NAME Heat Pump Control
*$LAYER Main
*$POSITION 573 574

*------------------------------------------------------------------------------


* Model "Heating Sch" (Type 14)
*

UNIT 30 TYPE 14          Heating Sch
*$UNIT_NAME Heating Sch
*$MODEL .\Utility Library (TESS)\Forcing Functions\Heating Season (Annual)\Type14k.tmf
*$POSITION 683 380
*$LAYER Main #
PARAMETERS 12
0.0                  ! 1 Start of the year
1                    ! 2 Control signal-1
2880                 ! 3 End of heating season
1                    ! 4 Control signal-2
2880                 ! 5 End of heating season again
0                    ! 6 Control signal-3
6552                 ! 7 Begin of heating season
0                    ! 8 Control signal-4
6552                 ! 9 Begin of heating season again
1                    ! 10 Control signal-5
8760.0               ! 11 End of year
1                    ! 12 Control signal-6
*------------------------------------------------------------------------------

* Model "Basement Slab" (Type 653)
*
```

```
UNIT 33 TYPE 653	Basement Slab
*$UNIT_NAME Basement Slab
*$MODEL .\Ground Coupling Library (TESS)\Slab Heating and Radiant Floors\Simple 1-Node
Model\Type653.tmf
*$POSITION 881 680
*$LAYER Main #
*$# FLOOR HEATING / HEATED SLAB / RADIANT SLAB
PARAMETERS 3
20000		! 1 Capacitance of slab
4.190		! 2 Specific heat of fluid
35		! 3 Initial slab temperature
INPUTS 7
50,1		! DHW Mixer-2:Outlet temperature ->Fluid inlet temperature
50,2		! DHW Mixer-2:Outlet flow rate ->Fluid flow rate
0,0		! [unconnected] Zone air temperature
0,0		! [unconnected] Environment temperature
0,0		! [unconnected] Slab-to-ambient loss coefficient
0,0		! [unconnected] Slab-to-zone heat transfer coefficient
0,0		! [unconnected] Heat exchanger effectiveness
*** INITIAL INPUT VALUES
35 500 19 10.0 0 1367.999964 0.6
*------------------------------------------------------------------------------

* EQUATIONS "Gain"
*
EQUATIONS 6
Heat_1stFLR = .6*[14,10]*[54,1]
Heat_2ndFLR = .4*[14,10]*[54,1]
Basement_Heat = [33,5]*[54,1]
cooling_2ndFLR = -0.5*[14,10]*[59,1]
Cooling_1stFLR = -0.5*[14,10]*[59,1]
total_Air_heat = [14,10]
*$UNIT_NAME Gain
*$LAYER Main
*$POSITION 986 722

*------------------------------------------------------------------------------


* Model "Slab pump" (Type 114)
*

UNIT 35 TYPE 114	Slab pump
*$UNIT_NAME Slab pump
*$MODEL .\Hydronics\Pumps\Single Speed\Type114.tmf
*$POSITION 785 744
*$LAYER Main #
*$# SINGLE-SPEED PUMP
PARAMETERS 4
1000.0		! 1 Rated flow rate
4.19		! 2 Fluid specific heat
2684.0		! 3 Rated power
0.0		! 4 Motor heat loss fraction
INPUTS 5
33,1		! Basement Slab:Outlet fluid temperature ->Inlet fluid temperature
33,2		! Basement Slab:Outlet flow rate ->Inlet fluid flow rate
```

```
0,0                    ! [unconnected] Control signal
0,0                    ! [unconnected] Overall pump efficiency
0,0                    ! [unconnected] Motor efficiency
*** INITIAL INPUT VALUES
20.0 500 1.0 0.6 0.9
*------------------------------------------------------------------------------

* Model "GLOOP TEMP" (Type 65)
*

UNIT 36 TYPE 65             GLOOP TEMP
*$UNIT_NAME GLOOP TEMP
*$MODEL .\Output\Online Plotter\Online Plotter With File\TRNSYS-Supplied Units\Type65a.tmf
*$POSITION 273 424
*$LAYER Main #
PARAMETERS 12
3                      ! 1 Nb. of left-axis variables
6                      ! 2 Nb. of right-axis variables
-15                    ! 3 Left axis minimum
65                     ! 4 Left axis maximum
0                      ! 5 Right axis minimum
150000000                        ! 6 Right axis maximum
1                      ! 7 Number of plots per simulation
12                     ! 8 X-axis gridpoints
0                      ! 9 Shut off Online w/o removing
53                     ! 10 Logical Unit for output file
2                      ! 11 Output file units
0                      ! 12 Output file delimiter
INPUTS 9
18,1                   ! Type557a:Outlet temperature ->Left axis variable-1
21,1                   ! Type114-2:Outlet fluid temperature ->Left axis variable-2
14,17                  ! Type505b:C.O.P. ->Left axis variable-3
61,1                   ! Type24-2:Result of integration-1 ->Right axis variable-1
61,2                   ! Type24-2:Result of integration-2 ->Right axis variable-2
61,5                   ! Type24-2:Result of integration-5 ->Right axis variable-3
61,6                   ! Type24-2:Result of integration-6 ->Right axis variable-4
61,3                   ! Type24-2:Result of integration-3 ->Right axis variable-5
61,4                   ! Type24-2:Result of integration-4 ->Right axis variable-6
*** INITIAL INPUT VALUES
HP_IN_TEMP HP_OUT_TEMP HP_COP Total_HP_Energy Total_HP_AUX_ Heat
Heat_to_Water Heat_to_DHW Heat_to_air_S Heat_to_air_L
LABELS  3
"G LOOP TEMP (C)"
"Total Energy kJ/kg"
"G_LOOP TEMP"
*** External files
ASSIGN "LOOP_TEMP.xls" 53
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "HP TEMP" (Type 65)
*

UNIT 39 TYPE 65             HP TEMP
*$UNIT_NAME HP TEMP
*$MODEL .\Output\Online Plotter\Online Plotter With File\TRNSYS-Supplied Units\Type65a.tmf
```

```
*$POSITION 389 638
*$LAYER Main #
PARAMETERS 12
4                    ! 1 Nb. of left-axis variables
0                    ! 2 Nb. of right-axis variables
0                    ! 3 Left axis minimum
80                   ! 4 Left axis maximum
0                    ! 5 Right axis minimum
20                   ! 6 Right axis maximum
1                    ! 7 Number of plots per simulation
12                   ! 8 X-axis gridpoints
0                    ! 9 Shut off Online w/o removing
45                   ! 10 Logical Unit for output file
2                    ! 11 Output file units
0                    ! 12 Output file delimiter
INPUTS 4
14,3                 ! Type505b:Outlet air temperature ->Left axis variable-1
56,3                 ! Mattamy house:    3- (air temperature of zone)  TAIR   3 ->Left axis variable-2
27,1                 ! Hot Water Tank:Temperature to heat source ->Left axis variable-3
14,8                 ! Type505b:Exiting DHW temperature ->Left axis variable-4
*** INITIAL INPUT VALUES
SUPLY_AIR RETURN_AIR HP_DHW_IN HP_DHW_OUT
LABELS  3
"HP-SPPLY_TEMP"
""
"HP_SUPPLY_TEMP"
*** External files
ASSIGN "TEMP" 45
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* EQUATIONS "Daily Load"
*
EQUATIONS 2
outflow = [43,1] * 225 / 100
temperature = [42,1]
*$UNIT_NAME Daily Load
*$LAYER Main
*$POSITION 370 989

*------------------------------------------------------------------------------


* Model "Temp. Forcing Function" (Type 14)
*

UNIT 42 TYPE 14          Temp. Forcing Function
*$UNIT_NAME Temp. Forcing Function
*$MODEL .\Utility\Forcing Functions\Temperature\Type14e.tmf
*$POSITION 202 937
*$LAYER Main #
PARAMETERS 50
0                    ! 1 Initial value of time
3.5                  ! 2 Initial temperature
743.999974                ! 3 Time at point-1
3.5                  ! 4 Temperature at point -1
```

```
743.999974                    ! 5 Time at point-2
2.4               ! 6 Temperature at point -2
1415.999946                   ! 7 Time at point-3
2.4               ! 8 Temperature at point -3
1415.999946                   ! 9 Time at point-4
2.6               ! 10 Temperature at point -4
2160.000057                   ! 11 Time at point-5
2.6               ! 12 Temperature at point -5
2160.000057                   ! 13 Time at point-6
4.4               ! 14 Temperature at point -6
2880.000075                   ! 15 Time at point-7
4.4               ! 16 Temperature at point -7
2880.000075                   ! 17 Time at point-8
6.9               ! 18 Temperature at point -8
3624.000095                   ! 19 Time at point-9
6.9               ! 20 Temperature at point -9
3624.000095                   ! 21 Time at point-10
9                 ! 22 Temperature at point -10
4344.000114                   ! 23 Time at point-11
9                 ! 24 Temperature at point -11
4344.000114                   ! 25 Time at point-12
10.9              ! 26 Temperature at point -12
5088.000133                   ! 27 Time at point-13
10.9              ! 28 Temperature at point -13
5088.000133                   ! 29 Time at point-14
11.9              ! 30 Temperature at point -14
5832.000153                   ! 31 Time at point-15
11.9              ! 32 Temperature at point -15
5832.000153                   ! 33 Time at point-16
11.6              ! 34 Temperature at point -16
6552.000172                   ! 35 Time at point-17
11.6              ! 36 Temperature at point -17
6552.000172                   ! 37 Time at point-18
10.2              ! 38 Temperature at point -18
7296.000191                   ! 39 Time at point-19
10.2              ! 40 Temperature at point -19
7296.000191                   ! 41 Time at point-20
8                 ! 42 Temperature at point -20
8016.00021                    ! 43 Time at point-21
8                 ! 44 Temperature at point -21
8016.00021                    ! 45 Time at point-22
5.9               ! 46 Temperature at point -22
8760.000229                   ! 47 Time at point-23
5.9               ! 48 Temperature at point -23
8760.000229                   ! 49 Time at point-24
3.5               ! 50 Temperature at point -24
*------------------------------------------------------------------------------

* Model "Water Draw From City" (Type 14)
*

UNIT 43 TYPE 14          Water Draw From City
*$UNIT_NAME Water Draw From City
*$MODEL .\Utility\Forcing Functions\Water Draw\Type14b.tmf
*$POSITION 187 1074
*$LAYER Main #
```

PARAMETERS 98

0	! 1 Initial value of time
3	! 2 Initial value of function
1	! 3 Time at point-1
3	! 4 Water draw at point -1
1	! 5 Time at point-2
2.9	! 6 Water draw at point -2
2	! 7 Time at point-3
2.9	! 8 Water draw at point -3
2	! 9 Time at point-4
0.1	! 10 Water draw at point -4
3	! 11 Time at point-5
0.1	! 12 Water draw at point -5
3	! 13 Time at point-6
0.1	! 14 Water draw at point -6
4	! 15 Time at point-7
0.1	! 16 Water draw at point -7
4	! 17 Time at point-8
0.1	! 18 Water draw at point -8
5	! 19 Time at point-9
0.1	! 20 Water draw at point -9
5	! 21 Time at point-10
0.1	! 22 Water draw at point -10
6	! 23 Time at point-11
0.1	! 24 Water draw at point -11
6	! 25 Time at point-12
0.1	! 26 Water draw at point -12
7	! 27 Time at point-13
0.1	! 28 Water draw at point -13
7	! 29 Time at point-14
3.4	! 30 Water draw at point -14
8	! 31 Time at point-15
3.4	! 32 Water draw at point -15
8	! 33 Time at point-16
7.6	! 34 Water draw at point -16
9	! 35 Time at point-17
7.6	! 36 Water draw at point -17
9	! 37 Time at point-18
6.3	! 38 Water draw at point -18
10	! 39 Time at point-19
6.3	! 40 Water draw at point -19
10	! 41 Time at point-20
6.8	! 42 Water draw at point -20
11	! 43 Time at point-21
6.8	! 44 Water draw at point -21
11	! 45 Time at point-22
6.8	! 46 Water draw at point -22
12	! 47 Time at point-23
6.8	! 48 Water draw at point -23
12	! 49 Time at point-24
5.9	! 50 Water draw at point -24
13	! 51 Time at point-25
5.9	! 52 Water draw at point -25
13	! 53 Time at point-26
5.5	! 54 Water draw at point -26
14	! 55 Time at point-27

```
5.5            ! 56 Water draw at point -27
14             ! 57 Time at point-28
5              ! 58 Water draw at point -28
15             ! 59 Time at point-29
5              ! 60 Water draw at point -29
15             ! 61 Time at point-30
4.2            ! 62 Water draw at point -30
16             ! 63 Time at point-31
4.2            ! 64 Water draw at point -31
16             ! 65 Time at point-32
3.8            ! 66 Water draw at point -32
17             ! 67 Time at point-33
3.8            ! 68 Water draw at point -33
17             ! 69 Time at point-34
4.2            ! 70 Water draw at point -34
18             ! 71 Time at point-35
4.2            ! 72 Water draw at point -35
18             ! 73 Time at point-36
5              ! 74 Water draw at point -36
19             ! 75 Time at point-37
5              ! 76 Water draw at point -37
19             ! 77 Time at point-38
6.8            ! 78 Water draw at point -38
20             ! 79 Time at point-39
6.8            ! 80 Water draw at point -39
20             ! 81 Time at point-40
7.2            ! 82 Water draw at point -40
21             ! 83 Time at point-41
7.2            ! 84 Water draw at point -41
21             ! 85 Time at point-42
5.9            ! 86 Water draw at point -42
22             ! 87 Time at point-43
5.9            ! 88 Water draw at point -43
22             ! 89 Time at point-44
5              ! 90 Water draw at point -44
23             ! 91 Time at point-45
5              ! 92 Water draw at point -45
23             ! 93 Time at point-46
4.7            ! 94 Water draw at point -46
24             ! 95 Time at point-47
4.7            ! 96 Water draw at point -47
24             ! 97 Time at point-48
3.8            ! 98 Water draw at point -48
*------------------------------------------------------------------------------

* Model "Diverter" (Type 11)
*

UNIT 31 TYPE 11     Diverter
*$UNIT_NAME Diverter
*$MODEL .\Hydronics\Tempering Valve\Other Fluids\Type11b.tmf
*$POSITION 533 1053
*$LAYER Main #
PARAMETERS 2
4              ! 1 Tempering valve mode
7              ! 2 Nb. of oscillations allowed
```

```
INPUTS 4
temperature             ! Daily Load:temperature ->Inlet temperature
outflow         ! Daily Load:outflow ->Inlet flow rate
27,3            ! Hot Water Tank:Temperature to load ->Heat source temperature
0,0             ! [unconnected] Set point temperature
*** INITIAL INPUT VALUES
5 0 55 45
*------------------------------------------------------------------------------

* Model "GWHR" (Type 91)
*

UNIT 44 TYPE 91      GWHR
*$UNIT_NAME GWHR
*$MODEL .\Heat Exchangers\Constant Effectiveness\Type91.tmf
*$POSITION 563 904
*$LAYER Main #
PARAMETERS 3
.85             ! 1 Heat exchanger effectiveness
4.19            ! 2 Specific heat of hot side fluid
4.19            ! 3 Specific heat of cold side fluid
INPUTS 4
waste_temp              ! House DHW:waste_temp ->Hot side inlet temperature
waste_flow              ! House DHW:waste_flow ->Hot side flow rate
31,1            ! Diverter:Temperature at outlet 1 ->Cold side inlet temperature
31,2            ! Diverter:Flowrate at outlet 1 ->Cold side flow rate
*** INITIAL INPUT VALUES
20.0 200 20.0 100
*------------------------------------------------------------------------------

* Model "DHW Mixer" (Type 11)
*

UNIT 32 TYPE 11      DHW Mixer
*$UNIT_NAME DHW Mixer
*$MODEL .\Hydronics\Tee-Piece\Other Fluids\Type11h.tmf
*$POSITION 661 882
*$LAYER Main #
PARAMETERS 1
1               ! 1 Tee piece mode
INPUTS 4
48,1            ! Diverter-2:Temperature at outlet 1 ->Temperature at inlet 1
48,2            ! Diverter-2:Flow rate at outlet 1 ->Flow rate at inlet 1
31,3            ! Diverter:Temperature at outlet 2 ->Temperature at inlet 2
31,4            ! Diverter:Flow rate at outlet 2 ->Flow rate at inlet 2
*** INITIAL INPUT VALUES
20.0 100.0 20.0 100.0
*------------------------------------------------------------------------------

* EQUATIONS "House DHW"
*
EQUATIONS 5
q_system = ([32,1] - [42,1] ) * 4.190 * [32,2]
waste_flow = (q_system) / (4.19 * (waste_temp - 7.3)) * waste_part / 100
waste_temp = 37
waste_part = 100
```

```
qDHW = -q_system
*$UNIT_NAME House DHW
*$LAYER Main
*$POSITION 898 882

*------------------------------------------------------------------------------


* Model "Type24" (Type 24)
*

UNIT 46 TYPE 24	 Type24
*$UNIT_NAME Type24
*$MODEL .\Utility\Integrators\Quantity Integrator\Type24.tmf
*$POSITION 1107 389
*$LAYER Main #
PARAMETERS 2
8760		! 1 Integration period
0		! 2 Relative or absolute start time
INPUTS 4
56,21		! Mattamy house:   21- (cooling demand)  QCOOL  1 ->Input to be integrated-1
56,22		! Mattamy house:   22- (cooling demand)  QCOOL  2 ->Input to be integrated-2
56,23		! Mattamy house:   23- (cooling demand)  QCOOL  3 ->Input to be integrated-3
Total_Q		! Total Load:Total_Q ->Input to be integrated-4
*** INITIAL INPUT VALUES
0.0 0.0 0.0 0.0
*------------------------------------------------------------------------------

* Model "Total Heating Load" (Type 65)
*

UNIT 47 TYPE 65	 Total Heating Load
*$UNIT_NAME Total Heating Load
*$MODEL .\Output\Online Plotter\Online Plotter With File\TRNSYS-Supplied Units\Type65a.tmf
*$POSITION 1111 307
*$LAYER Main #
PARAMETERS 12
4		! 1 Nb. of left-axis variables
0		! 2 Nb. of right-axis variables
0		! 3 Left axis minimum
100000000		! 4 Left axis maximum
0		! 5 Right axis minimum
10		! 6 Right axis maximum
1		! 7 Number of plots per simulation
12		! 8 X-axis gridpoints
0		! 9 Shut off Online w/o removing
47		! 10 Logical Unit for output file
2		! 11 Output file units
0		! 12 Output file delimiter
INPUTS 4
46,1		! Type24:Result of integration-1 ->Left axis variable-1
46,2		! Type24:Result of integration-2 ->Left axis variable-2
46,3		! Type24:Result of integration-3 ->Left axis variable-3
46,4		! Type24:Result of integration-4 ->Left axis variable-4
*** INITIAL INPUT VALUES
Basement_S 1st_S 2nd_S Heating_Demand
```

```
LABELS  3
"Sensible Load"
"Latent Load"
"TOTAL_LOAD"
*** External files
ASSIGN "House_Energy_Demend" 47
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "Diverter-2" (Type 11)
*

UNIT 48 TYPE 11          Diverter-2
*$UNIT_NAME Diverter-2
*$MODEL .\Hydronics\Flow Diverter\Other Fluids\Type11f.tmf
*$POSITION 560 786
*$LAYER Water Loop #
PARAMETERS 1
2               ! 1 Controlled flow diverter mode
INPUTS 3
27,3            ! Hot Water Tank:Temperature to load ->Inlet temperature
27,4            ! Hot Water Tank:Flowrate to load ->Inlet flow rate
Ground_Loop          ! Heat Pump Control:Ground_Loop ->Control signal
*** INITIAL INPUT VALUES
20.0 500 .7
*------------------------------------------------------------------------------

* Model "Mixer" (Type 11)
*

UNIT 49 TYPE 11          Mixer
*$UNIT_NAME Mixer
*$MODEL .\Hydronics\Flow Mixer\Other Fluids\Type11d.tmf
*$POSITION 465 861
*$LAYER Water Loop #
PARAMETERS 1
3               ! 1 Controlled flow mixer mode
INPUTS 5
44,3            ! GWHR:Cold-side outlet temperature ->Temperature at inlet 1
44,4            ! GWHR:Cold-side flow rate ->Flow rate at inlet 1
51,1            ! Diverter-3:Temperature at outlet 1 ->Temperature at inlet 2
51,2            ! Diverter-3:Flowrate at outlet 1 ->Flow rate at inlet 2
0,0             ! [unconnected] Control signal
*** INITIAL INPUT VALUES
20.0 100.0 20.0 500 0.5
*------------------------------------------------------------------------------

* Model "DHW Mixer-2" (Type 11)
*

UNIT 50 TYPE 11          DHW Mixer-2
*$UNIT_NAME DHW Mixer-2
*$MODEL .\Hydronics\Tee-Piece\Other Fluids\Type11h.tmf
*$POSITION 693 669
*$LAYER Main #
PARAMETERS 1
```

```
1                    ! 1 Tee piece mode
INPUTS 4
48,3                 ! Diverter-2:Temperature at outlet 2 ->Temperature at inlet 1
48,4                 ! Diverter-2:Flow rate at outlet 2 ->Flow rate at inlet 1
51,3                 ! Diverter-3:Temperature at outlet 2 ->Temperature at inlet 2
51,4                 ! Diverter-3:Flow rate at outlet 2 ->Flow rate at inlet 2
*** INITIAL INPUT VALUES
20.0 500 20.0 100.0
*------------------------------------------------------------------------------

* Model "Diverter-3" (Type 11)
*

UNIT 51 TYPE 11          Diverter-3
*$UNIT_NAME Diverter-3
*$MODEL .\Hydronics\Tempering Valve\Other Fluids\Type11b.tmf
*$POSITION 704 744
*$LAYER Main #
PARAMETERS 2
4                    ! 1 Tempering valve mode
7                    ! 2 Nb. of oscillations allowed
INPUTS 4
35,1                 ! Slab pump:Outlet fluid temperature ->Inlet temperature
35,2                 ! Slab pump:Outlet flow rate ->Inlet flow rate
27,3                 ! Hot Water Tank:Temperature to load ->Heat source temperature
0,0                  ! [unconnected] Set point temperature
*** INITIAL INPUT VALUES
22 500 55 40
*------------------------------------------------------------------------------

* Model "Solar Control" (Type 14)
*

UNIT 52 TYPE 14          Solar Control
*$UNIT_NAME Solar Control
*$MODEL .\Utility\Forcing Functions\General\Type14h.tmf
*$POSITION 45 594
*$LAYER Main #
PARAMETERS 12
0                    ! 1 Initial value of time
0                    ! 2 Initial value of function
6                    ! 3 Time at point-1
0                    ! 4 Value at point -1
6                    ! 5 Time at point-2
1                    ! 6 Value at point -2
17                   ! 7 Time at point-3
1                    ! 8 Value at point -3
17                   ! 9 Time at point-4
0                    ! 10 Value at point -4
24                   ! 11 Time at point-5
0                    ! 12 Value at point -5
*------------------------------------------------------------------------------

* Model "Cooling Sch" (Type 14)
*
```

```
UNIT 53 TYPE 14          Cooling Sch
*$UNIT_NAME Cooling Sch
*$MODEL .\Utility Library (TESS)\Forcing Functions\Cooling Season (Annual)\Type14l.tmf
*$POSITION 576 359
*$LAYER Main #
PARAMETERS 12
0.0             ! 1 Start of the year
0               ! 2 Control signal-1
2982            ! 3 Start of cooling season
0               ! 4 Control signal-2
2982            ! 5 Start of cooling season again
1               ! 6 Control signal-3
6575            ! 7 End of cooling season
1               ! 8 Control signal-4
6575            ! 9 End of cooling season again
0               ! 10 Control signal-5
8760.0          ! 11 End of year
0               ! 12 Control signal-6
*------------------------------------------------------------------------------

* EQUATIONS " Control"
*
EQUATIONS 2
Solar_Loop = [52,2]*0.1
pump_sinal = ([52,2] +Fan_signal)*0.5
*$UNIT_NAME  Control
*$LAYER Main
*$POSITION 43 702

*------------------------------------------------------------------------------


* Model "Heating Sch-2" (Type 14)
*

UNIT 57 TYPE 14          Heating Sch-2
*$UNIT_NAME Heating Sch-2
*$MODEL .\Utility Library (TESS)\Forcing Functions\Heating Season (Annual)\Type14k.tmf
*$POSITION 64 785
*$LAYER Main #
PARAMETERS 12
0.0             ! 1 Start of the year
1               ! 2 Control signal-1
2880            ! 3 End of heating season
1               ! 4 Control signal-2
2880            ! 5 End of heating season again
0               ! 6 Control signal-3
6552            ! 7 Begin of heating season
0               ! 8 Control signal-4
6552            ! 9 Begin of heating season again
1               ! 10 Control signal-5
8760.0          ! 11 End of year
1               ! 12 Control signal-6
*------------------------------------------------------------------------------

* EQUATIONS "Total Load"
```

```
*
EQUATIONS 1
Total_Q = [56,17]+[56,18]+[56,19]
*$UNIT_NAME Total Load
*$LAYER Main
*$POSITION 1110 202

*------------------------------------------------------------------------------


* Model "Load" (Type 65)
*

UNIT 60 TYPE 65        Load
*$UNIT_NAME Load
*$MODEL .\Output\Online Plotter\Online Plotter With File\TRNSYS-Supplied Units\Type65a.tmf
*$POSITION 1137 510
*$LAYER Main #
PARAMETERS 12
4              ! 1 Nb. of left-axis variables
0              ! 2 Nb. of right-axis variables
-100000        ! 3 Left axis minimum
100000         ! 4 Left axis maximum
0              ! 5 Right axis minimum
10             ! 6 Right axis maximum
1              ! 7 Number of plots per simulation
12             ! 8 X-axis gridpoints
0              ! 9 Shut off Online w/o removing
50             ! 10 Logical Unit for output file
2              ! 11 Output file units
0              ! 12 Output file delimiter
INPUTS 4
56,17          ! Mattamy house:   17- (heating demand)  QHEAT  1 ->Left axis variable-1
56,18          ! Mattamy house:   18- (heating demand)  QHEAT  2 ->Left axis variable-2
56,19          ! Mattamy house:   19- (heating demand)  QHEAT  3 ->Left axis variable-3
0,0            ! [unconnected] Left axis variable-4
*** INITIAL INPUT VALUES
Basement 1st 2nd Attic
LABELS  3
"Sensible Load"
"Latent Load"
"Load"
*** External files
ASSIGN "INS_House_Energy_Demend" 50
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "Heating Sch-3" (Type 14)
*

UNIT 54 TYPE 14        Heating Sch-3
*$UNIT_NAME Heating Sch-3
*$MODEL .\Utility Library (TESS)\Forcing Functions\Heating Season (Annual)\Type14k.tmf
*$POSITION 1014 807
*$LAYER Main #
PARAMETERS 12
```

```
0.0             ! 1 Start of the year
1               ! 2 Control signal-1
2882            ! 3 End of heating season
1               ! 4 Control signal-2
2880            ! 5 End of heating season again
0               ! 6 Control signal-3
3550            ! 7 Begin of heating season
0               ! 8 Control signal-4
6550            ! 9 Begin of heating season again
1               ! 10 Control signal-5
8760.0          ! 11 End of year
1               ! 12 Control signal-6
*------------------------------------------------------------------------------

* Model "Cooling Sch-2" (Type 14)
*

UNIT 59 TYPE 14     Cooling Sch-2
*$UNIT_NAME Cooling Sch-2
*$MODEL .\Utility Library (TESS)\Forcing Functions\Cooling Season (Annual)\Type14l.tmf
*$POSITION 907 807
*$LAYER Main #
PARAMETERS 12
0.0             ! 1 Start of the year
0               ! 2 Control signal-1
2982            ! 3 Start of cooling season
0               ! 4 Control signal-2
2982            ! 5 Start of cooling season again
1               ! 6 Control signal-3
6575            ! 7 End of cooling season
1               ! 8 Control signal-4
6575            ! 9 End of cooling season again
0               ! 10 Control signal-5
8760.0          ! 11 End of year
0               ! 12 Control signal-6
*------------------------------------------------------------------------------

* Model "HOUSE_TEMP" (Type 65)
*

UNIT 62 TYPE 65     HOUSE_TEMP
*$UNIT_NAME HOUSE_TEMP
*$MODEL .\Output\Online Plotter\Online Plotter With File\TRNSYS-Supplied Units\Type65a.tmf
*$POSITION 1128 649
*$LAYER Main #
PARAMETERS 12
4               ! 1 Nb. of left-axis variables
0               ! 2 Nb. of right-axis variables
-20             ! 3 Left axis minimum
50              ! 4 Left axis maximum
0               ! 5 Right axis minimum
100             ! 6 Right axis maximum
1               ! 7 Number of plots per simulation
12              ! 8 X-axis gridpoints
0               ! 9 Shut off Online w/o removing
52              ! 10 Logical Unit for output file
```

```
2                    ! 11 Output file units
0                    ! 12 Output file delimiter
INPUTS 4
56,1                 ! Mattamy house:    1- (air temperature of zone)  TAIR   1 ->Left axis variable-1
56,2                 ! Mattamy house:    2- (air temperature of zone)  TAIR   2 ->Left axis variable-2
56,3                 ! Mattamy house:    3- (air temperature of zone)  TAIR   3 ->Left axis variable-3
56,4                 ! Mattamy house:    4- (air temperature of zone)  TAIR   4 ->Left axis variable-4
*** INITIAL INPUT VALUES
Basement 1st 2nd Attic
LABELS  3
"HOUSE_TEMP"
""
"HOUSE_TEMP"
*** External files
ASSIGN "test" 52
*|? What file should the online print to? |1000
*------------------------------------------------------------------------------

* Model "HRV" (Type 667)
*

UNIT 64 TYPE 667          HRV
*$UNIT_NAME HRV
*$MODEL .\HVAC Library (TESS)\Heat Exchangers\Air-to-Air\Air-to-Air Heat Exchanger\Sensible and
Latent\Relative Humidity Inputs\Type667b.tmf
*$POSITION 976 93
*$LAYER Main #
*$# AIR-TO-AIR HEAT RECOVERY
PARAMETERS 2
2                    ! 1 Humidity mode
395.99999                    ! 2 Rated power
INPUTS 15
56,3                 ! Mattamy house:    3- (air temperature of zone)  TAIR   3 ->Exhaust air temperature
0,0                  ! [unconnected] Not used
56,11                ! Mattamy house:   11- (relative humidity of zone...)  RELHUM 3 ->Exhaust air %RH
0,0                  ! [unconnected] Exhaust air flow rate
0,0                  ! [unconnected] Exhaust air pressure
0,0                  ! [unconnected] Exhaust air pressure drop
109,1                ! Weather data:Ambient temperature ->Fresh air temperature
0,0                  ! [unconnected] Not used
109,2                ! Weather data:relative humidity ->Fresh air %RH
0,0                  ! [unconnected] Fresh air flow rate
0,0                  ! [unconnected] Fresh air pressure
0,0                  ! [unconnected] Fresh air pressure drop
0,0                  ! [unconnected] Sensible effectiveness
0,0                  ! [unconnected] Latent effectiveness
0,0                  ! [unconnected] On/Off Control Signal
*** INITIAL INPUT VALUES
23 0.005 60.0 311.040008 1.0 0.000246 20.0 0.005 50.0 311.040008 1.0 0.000246
0.67 0.3 1.0
*------------------------------------------------------------------------------
* Model "Type24-2" (Type 24)
UNIT 61 TYPE 24           Type24-2
*$UNIT_NAME Type24-2
*$MODEL .\Utility\Integrators\Quantity Integrator\Type24.tmf
*$POSITION 371 389
```

```
*$LAYER Main #
PARAMETERS 2
8760            ! 1 Integration period
1               ! 2 Relative or absolute start time
INPUTS 6
14,16           ! Type505b:Heat pump power ->Input to be integrated-1
14,19           ! Type505b:Auxiliary heater power ->Input to be integrated-2
14,11           ! Type505b:Sensible heat transfer to air ->Input to be integrated-3
14,12           ! Type505b:Latent heat transfer to air ->Input to be integrated-4
14,13           ! Type505b:Heat transfer to water ->Input to be integrated-5
14,14           ! Type505b:Heat transfer to DHW stream ->Input to be integrated-6
*** INITIAL INPUT VALUES
0.0 0.0 0.0 0.0 0.0 0.0
*------------------------------------------------------------------------------

END
```

Appendix - D

Heat Pump Performance Data

Specification Data - AT060

PERFORMANCE DATA-FORCED AIR											
WATER LOOP				GROUND WATER				GROUND LOOP			
FORCED AIR COOLING		FORCED AIR HEATING		FORCED AIR COOLING		FORCED AIR HEATING		FORCED AIR COOLING		FORCED AIR HEATING	
CAPACITY	EER	CAPACITY	COP	CAPACITY	EER	CAPACITY	COP	CAPACITY	EER	CAPACITY	COP
54,200	14.1	69,700	4.5	62,400	19.1	65,500	4.8	57,800	14.8	49,500	3.3

PERFORMANCE DATA-HYDRONIC					
WATER LOOP		GROUND WATER		GROUND LOOP	
HEATING		HEATING		HEATING	
CAPACITY	COP	CAPACITY	COP	CAPACITY	COP
72,000	4.6	68,200	4.9	52,200	3.4

BLOWER PERFORMANCE							
AVAILABLE STATIC PRESSURE (WITH WET EVAPORATOR)							
BLOWER SPEED	0.05	0.1	0.15	0.2	0.25	0.3	0.35
HIGH	2,400	2,350	2,320	2,300	2,280	2,200	2,165
MEDIUM	-	-	2,100	2,050	2,000	1,950	1,900
LOW	-	-	-	-	-	-	-

Specification Data - AT060

ELECTRICAL SPECIFICATIONS												
MODEL		COMPRESSOR			BLOWER		LOOP PUMP		DHW PUMP	LOOP PUMP	MIN AMPS	MAX FUSE
		MCC	RLA	LRA	FLA	HP	FLA	HP				
AT060	208-230/60/1	38	23	145	5.4	3/4	1.75	1/6	0.4	2	34	60
	208-230/60/3	38	19.6	123	5.4	3/4	1.75	1/6	0.4	2	34	50

HYDRONIC PRESSURE DROP					
SIZE	FLOW (GPM)	-1°C/30°F	10°C/50°F	21°C/70°F	32°C/90°F
AT060	8	3.0	2.8	2.6	2.4
	11	4.6	4.3	4.0	3.7
	15	6.9	6.4	6.0	5.5
	18	8.8	8.2	7.6	7.1

MECHANICAL SPECIFICATIONS			
EVAPORATOR			
SQ. IN.	ROWS DEEP	TUBE SIZE	FINS PER/IN
660	3	5/16	14

BLOWER SIZE	WEIGHT		REFRIGERANT
	NET	SHIP	
9x7	135 Kg	147 Kg	R-410A
	300 lbs	324 lbs	

Specification Data - AT060

FORCED AIR COOLING							
SOURCE TEMP	ENTER AIR	TOTAL CAPACITY BTUH	SENSIBLE CAPACITY HUMIDITY			INPUT WATTS	EER
			50%	60%	70%		
10C/50F	25C/77F	63,000	53,550	47,250	40,950	3,280	14.8
	30C/86F	75,400	64,090	56,550	49,010	3,240	17.9
	35C/95F	83,000	70,550	62,250	53,950	3,230	19.8
15C/59F	25C/77F	62,000	52,700	46,500	40,300	3,550	13.7
	30C/86F	74,000	62,900	55,500	48,100	3,510	16.5
	35C/95F	81,500	69,275	61,125	52,975	3,500	18.2
20C/68F	25C/77F	61,500	52,275	46,152	39,975	3,830	12.8
	30C/86F	73,000	62,050	54,750	47,450	3,790	15.3
	35C/95F	79,000	67,150	59,250	51,350	3,780	16.6
25C/77F	25C/77F	60,500	51,425	45,375	39,325	4,130	11.9
	30C/86F	71,500	60,775	53,625	46,475	4,090	14.1
	35C/95F	76,000	64,600	57,000	49,400	4,080	15.0

FORCED AIR HEATING					
BASED ON 230 VOLT			**INCLUDING FAN & FLOW CENTER**		
SOURCE TEMP	ENTER AIR	HEAT OF ABSORBTION	TOTAL CAPACITY BTUH	INPUT WATTS	COP
15C/59F	15C/59F	65,500	72,946	3,630	4.6
	18C/64F	63,500	71,479	3,890	4.3
	21C/70F	61,000	69,574	4,180	3.9
10C/50F	15C/59F	57,500	64,721	3,520	4.2
	18C/64F	56,000	63,733	3,770	3.9
	21C/70F	54,000	62,287	4,040	3.6
5C/41F	15C/59F	50,500	57,474	3,400	3.8
	18C/64F	49,000	56,487	3,650	3.6
	21C/70F	47,300	55,341	3,920	3.3
0C/32F	15C/59F	43,900	50,669	3,300	3.5
	18C/64F	42,500	49,762	3,540	3.2
	21C/70F	41,100	4,895	3,800	3.0

Specification Data - AT060

HYDRONIC HEATING					
SOURCE TEMP	ENTER HYDRONIC	HEAT OF ABSORBTION	TOTAL CAPACITY BTUH	INPUT WATTS	COP
15C/59F	25C/77F	70,000	77,712.8	3,760	4.8
	30C/86F	65,500	74,217.9	4,250	4.2
	35C/95F	61,500	71,284.6	4,770	3.6
	40C/104F	57,000	67,974.4	5,350	3.1
10C/50F	25C/77F	60,000	67,466.7	3,640	4.3
	30C/86F	56,500	64,889.7	4,090	3.8
	35C/95F	53,000	62,415.4	4,590	3.3
	40C/104F	49,400	59,964.1	5,150	2.9
5C/41F	25C/77F	51,500	58,700	3,510	3.8
	30C/86F	48,500	56,582.1	3,940	3.4
	35C/95F	45,500	54,566.7	4,420	3.0
	40C/104F	42,400	52,574.4	4,960	2.6
0C/32F	25C/77F	43,500	50,433.3	3,380	3.4
	30C/86F	41,400	49,194.9	3,800	3.0
	35C/95F	38,500	47,217.9	4,250	2.6
	40C/104F	35,900	45,684.6	4,770	2.3