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International Energy Agency
IEA Implementing Agreement on District Heating and Cooling,
including the integration of CHP

Distributed Solar Systems Interfaced to a District Heating System that has Seasonal Storage

International Energy Agency

IEA District Heating and Cooling

Program of Research, Development and Demonstration on
District Heating and Cooling, including integration of CHP

Distributed Solar Systems Interfaced to a District Heating System that has Seasonal Storage

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General Preface Annex IX 2008-2011

Introduction

The International Energy Agency (IEA) was established in 1974 in order to strengthen the co-operation between member countries and reduce the dependency on oil and other fossil fuels. Thirty years later, the IEA again drew attention to serious concerns about energy security, investment, the environment and energy poverty. The global situation is resulting in soaring oil and gas prices, the increasing vulnerability of energy supply routes and ever-increasing emissions of climate-destabilising carbon dioxide.

At the 2005 Gleneagles G8 an important role was given to the IEA in advising on alternative energy scenarios and strategies aimed at a clean, clever and competitive energy future. Two years later, at the Heiligendamm G8, it was agreed that “instruments and measures will be adopted to significantly increase the share of combined heat and power (CHP) in the generation of electricity”. District Heating and Cooling is an integral part of the successful growth of CHP: heat networks distribute what would otherwise be waste heat to serve local communities. The IEA is active in promoting and developing knowledge of District Heating and Cooling: while the DHC programme itself is the major global R&D programme, the IEA Secretariat has also initiated the International DHC/CHP Collaborative which assesses global markets and policies for these important technologies.

The IEA’s latest CHP report, "Cogeneration and District Energy: Sustainable energy technologies for today…and tomorrow", released at COGEN Europe meeting in Brussels on 21 April 2009, identifies proven solutions that governments have used to advance CHP and district energy, setting out a practical ‘’how to’’ guide with options to consider for design and implementation. The report concludes that these technologies do not need significant financial incentives; rather they require the creation of a government ‘champion’ to identify and address market barriers. This makes CHP and district energy ideal investments at a time of tight budgets.

The CHP report follows the IEA’s first report from March 2008, "Combined Heat and Power: Evaluating the Benefits of Greater Global Investment". There are also 11 "Country Scorecards" that evaluate different countries’ success in achieving increased use of CHP and DHC. In November 2009, the IEA joined with the Copenhagen District Energy Summit to issue the first Global District Energy Climate Awards in order to recognize communities that have embraced district heating and cooling as a vital sustainable energy solution.

The major international R&D programme for DHC/CHP

DHC is an integrative technology that can make significant contributions to reducing emissions of carbon dioxide and air pollution and to increasing energy security.

The fundamental idea of DHC is simple but powerful: connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating and cooling.

The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way, and also offers ongoing fuel flexibility. By integrating district cooling carbon-intensive electrically-based air-conditioning, rapidly growing in many countries, can be displaced.

As one of the IEA’s ’Implementing Agreements’, the District Heating & Cooling programme is the major international research programme for this technology. Active now for more than 25 years, the full name of this Implementing Agreement is ‘District Heating and Cooling including the integration of Combined Heat and Power’. Participant countries undertake co-operative actions in energy research, development and demonstration.

Annex IX

In May 2008 Annex IX started, with the participation from Canada, Denmark, Finland, the Netherlands, Norway, South Korea, Sweden, United Kingdom, United States of America.

Below you will find the Annex IX research projects undertaken by the Implementing Agreement “District Heating & Cooling including the Integration of Combined Heat and Power”.

Annex IX (2008 – 2011) research projects Implementing Agreement “District Heating & Cooling including the Integration of Combined Heat and Power”.

Project title	Company	Number
The Potential for Increased Primary Energy Efficiency and Reduced CO2 Emissions by DHC	SP Technical Research Institute of Sweden Project Leader: Monica Axell	8DHC-11-01
District Heating for Energy Efficient Building Areas	VTT Technical Research Centre of Finland Project Leader: Kari Sipilä	8DHC-11-02
Interaction between District Energy and Future Buildings that have Storage and Intermittent Surplus Energy	Gagest Inc. Project leader: Tom Onno	8DHC-11-03
Distributed Solar Systems Interfaced to a District Heating System that has Seasonal Storage	Gagest Inc. Project leader: Tom Onno	8DHC-11-04
Policies and Barriers for District Heating and Cooling outside EU countries	Energy-AN Consulting Project leader: Arto Nuorkivi	8DHC-11-05

Benefits of membership

Membership of this implementing agreement fosters sharing of knowledge and current best practice from many countries including those where:

- DHC is already a mature industry
- DHC is well established but refurbishment is a key issue
- DHC is not well established

Membership proves invaluable in enhancing the quality of support given under national programmes. Participant countries benefit through the active participation in the programme of their own consultants and research organisations. Each of the projects is supported by a team of experts, one from each participant country. As well as the final research reports, other benefits include sharing knowledge and ideas and opportunities for further collaboration.

New member countries are very welcome – please simply contact us (see below) to discuss.

Information

General information about the IEA Programme District Heating and Cooling, including the integration of CHP can be obtained from our website www.iea-dhc.org or from:

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The IA DHC/CHP also known as the Implementing Agreement on District Heating and Cooling, including the Integration of Combined Heat and Power, functions within a framework created by the International Energy Agency (IEA). Views, findings, and publications of the IA DHC/CHP do not necessarily represent the views or policies neither of all its individual member countries nor of the IEA Secretariat.

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Table of Contents

List of Tables

List of Figures

Executive Summary

The Drake Landing Solar Community seasonal storage district energy system at Okotoks, Alberta has been in operation for four years. The data for this period has been analyzed and the system has demonstrated a solar fraction of close to 80% after four years of operation. It will meet its 90% solar fraction target after five years.

This is a relatively small prototype system, supplying space heat for 52 low-energy house. Losses from the borehole storage are relatively high. Simulations indicate about a 50% yearly energy loss after the earth thermal masses have stabilized.

The objective was to establish whether the losses from a borehole storage of this size could be reduced either by different control strategies or by subsystem upgrades. It was established that the control systems that transfer energy between the short-term storage and the borehole storage are working at a high level of efficiency. In the present system configuration, with its high solar factor, there is very limited potential for improvements in this area.

It was seen that part of the reason for the high solar fraction is achieved by using the borehole system as a preheater for the backup boiler when the borehole delivery temperature is below that required in the district supply. This reduces the consumption of fossil fuel.

Some areas of possible improvement to the borehole storages losses have been formulated and simulated. Studies were done with a larger system, with most components doubled in size. Performance upgrades involved a high performance space heating system with lower return temperature, and studies with increased load, which resulted in a lower solar fraction. Both of these changes lowered the borehole system operating temperature and reduce losses. Also, since evacuated tube collectors are starting to become price-competitive with flat plate collectors, simulations were done with a high performance array based on these.

In-floor heating systems and liquid-to-aircoil heating systems were examined and it was concluded that for a low-energy house in the Canadian environment the air heating system was a better choice due to ventilation requirements, public acceptance and cost considerations. A water-to-aircoil space heating system was designed and a prototype constructed. By injecting cool ventilation air from a heat recovery ventilator into the air coil in counterflow mode it was possible to generate return temperatures within one degree of room air temperature, or slightly below room temperature depending on load and outdoor temperature.

With the combined upgrades in the modified system the seasonal storage energy recovery factor went from 42.4% in the measured Okotoks system to 62.2% in the simulated larger system.

The question of the most cost-effective solar fraction was examined. Even though a lower solar fraction will result in improved cost/performance in the borehole storage subsystem, if the cost of backup energy is high, the reduction in fuel cost can compensate for the larger losses of a system with high solar fraction.

With larger borehole systems the losses will be inherently lower. With a larger number of boreholes in series there are possibilities of further improvements in performance by more elaborate flow paths. Further study is recommended in this area

Introduction

This project has as a reference a new, innovative Canadian District Energy (DE) utility for which detailed performance data are available. In Okotoks, near Calgary, Alberta, the Drake Landing Solar Community is a DE system for space heating that is collected from solar panels and saved in a seasonal borehole thermal energy storage system for use later in the year.

There is some overlap in this document with a report done for the same IEA Annex IX entitled, "Interaction between District Energy and Future Buildings that have Storage and Intermittent Surplus Energy."[1]

Future trends in solar systems and storage

Because of relatively poor heat transfer capability to the ground, borehole storage systems perform best if there is a water-based buffer storage that can absorb the mid-day peak power levels and extend the transfer of energy from the water storage to the borehole over the full 24 hour period. In the case of the Okotoks system the borehole storage can absorb about one-third of peak power.

In large-scale seasonal solar systems there are many potential configurations that have been analyzed and, in some cases, constructed, with various locations of the solar collectors.

The main categories are:

- Large arrays of ground-mounted utility-owned solar collectors located near the seasonal storage
- Partially distributed utility-owned solar collectors, such as the Okotoks system, with collectors installed on garages within a maximum distance of 280 metres from the seasonal storage
- Fully distributed privately owned solar collectors installed on buildings connected directly to the DE distribution system[2,1] This category is more complex but will gradually evolve.

Since the primary emphasis in this study is on the thermal performance of large-scale centralized storage systems the details on the configuration of the solar energy source are not important and simulations are done on the characteristics of high performance collectors assumed to be close to the borehole system.

Objectives

- To develop a prototype low temperature liquid-to-air heating system to meet the Okotoks space heating requirement, with the water return temperature close to room temperature.
- To utilize the characteristics of the prototype space heating system for system-level simulations with a reduced return temperature. The present Okotoks average return temperature is in the 28-30°C range. Additional simulations are done with return temperatures reduced by 4°C and 8°C.
- To examine the interactions of energy transfers between the short-term storage and borehole storage to determine if these can be improved.

Solar Systems with Seasonal Storage

Okotoks solar seasonal storage system

The Okotoks DE system is an example of a solar system with seasonal storage. It has 52 low-energy houses supplied by a DE system that provides space heat with a supply temperature that varies from 55°C to 37°C as a function of outdoor temperature.

The 800 flat plate collectors are located on the garage roofs of detached houses. Glycol lines connect the collectors to a nearby energy centre where a heat exchanger transfers energy to a 250,000 litre water storage tank that can store one day's solar collection. This acts as a buffer for the borehole seasonal storage. It can also supply energy directly to the DE system.

Data is now available for four years of operation. It will be another year before the borehole system is fully stabilized in its final operating regime, but data to this stage indicates that the system is performing close to its specified values and will meet its target of 90% solar fraction. Considerable operational experience has been gained that has led to improvements in control strategies.

Figures 1 to 3 display the housing and collector layout.[3]

Source: Natural Resources Canada, CANMET

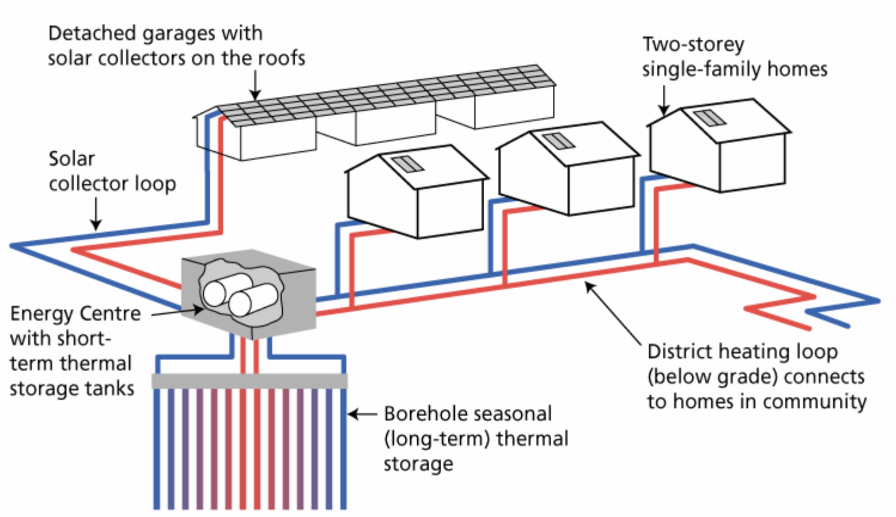
Figure 1: 52 Low-Energy Houses in the Drake Landing Solar Community, in Okotoks

Source: Natural Resources Canada, CANMET

Figure 2: Solar Collectors on Garage Roofs in Okotoks

The houses are constructed to an insulation standard considerably above current standards in the industry. Emphasis has also been placed on passive solar gain.

Simplified Okotoks Schematic



Okotoks Seasonal Solar System (Drake Landing Solar Community)
Source: Natural Resources Canada, CANMET

Figure 3: Simplified Schematic of Drake Landing Solar Community in Okotoks

Characteristics of Seasonal Storage

Losses in borehole seasonal storage systems

The typical borehole storage system can only be insulated at the top. Most of the thermal loss will occur on the sides of the earth mass. There is also considerable loss at the bottom, since the ends of the high temperature centre tubes are exposed to the earth at that location. Using data from Okotoks a simulation model of the borehole seasonal storage system was developed and validated in the IEA Annex IX project.[1] Simulations with that model will be used for this project analysis.

Since the borehole seasonal storage is relatively small, with a diameter of 30 metres, its losses will be high compared to a larger system. As the volume of the thermal mass is proportional to the square of the diameter while the surface area enclosing the boreholes is linearly proportional to diameter, the relative losses will be higher for smaller systems. The losses for a small system relative to stored energy will be larger in comparison to a system with increased volume. Simulations done to calculate the yearly losses indicate that the recovery fraction for space heating of energy stored during the summer will be somewhat below 50%.[4] However, the system will supply useful data on the accuracy with which simulations can be done, changes in soil conditions with heating and cooling cycles, etc. In addition, the system has already supplied considerable operational experience that has been useful in optimizing the energy transfer control systems during the last two years of operation.

Even in much larger borehole systems the losses will not be negligible and there is need for ongoing research to reduce these losses as much as possible.

Minimizing losses in seasonal storage systems is especially important at high northern latitudes where there is low solar radiation during the heating season. This is illustrated by simulations of solar energy collected at Stockholm which has a latitude of 59°, 17'N and comparing these to simulations using Okotoks weather data. Stockholm is typical of many regions of northern Europe while Okotoks, at latitude 50°, 43'N has exceptionally high radiation levels through most of the winter.

This example is the most challenging case where it is assumed that domestic hot water is supplied by the DE system and the minimum supply temperature in the distribution system is 65°C. Okotoks is a lower temperature system supplying only space heat.

An array of ten high performance evacuated tube collectors was used supplying a minimum of 65°C and up to 80°C while charging the seasonal storage during warm weather. The total energy collected is shown on Figure 4. The total absorber area was 27 m^2 and the collector angle was set to latitude minus five degrees. The energy values and total radiation available at the collector angle are shown in Table 1.

The energy collected in Stockholm from April until the end of August compares favorably with that of Okotoks. However, during the winter months there is very little energy collected above 65°C.

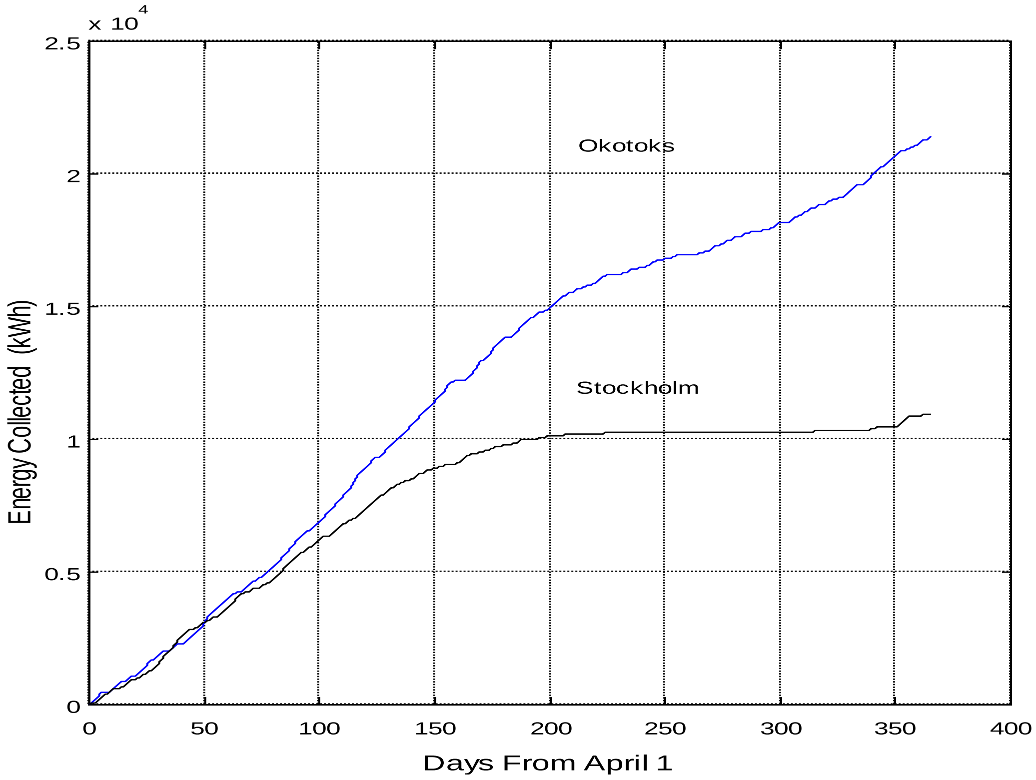


Figure 4: Simulated Energy Collected above 65°C by Evacuated Tube Array, Tin = 23°C

City	Okotoks	Stockholm
Energy collected (kWh) above 65°C	21400	10919
Yearly radiation on collector (kWh/m^2)	1772	1070

Table 1: Simulated Energy Collected above 65°C and Yearly Radiation on Collector Array

The Okotoks system is in a rather unique climatic condition as shown by the total solar energy available. The collectors in Stockholm do very little useful work during the heating season, especially if flat plate collectors are used. The significance is that at this location, if losses from the borehole system are a high value such as 40%, then almost the sole function of 40% of the collectors is to supply these losses. Since the collectors are a major part of the cost of the system considerable saving can be achieved by reducing the losses.

Difference between solar systems with seasonal storage and systems with only short term storage

An important aspect of a solar seasonal storage system is the relationship between the heat loss characteristics of the house and the economics of an active solar system. The usual recommendation is that heat loss from the building be reduced as much as possible before an active solar space heating system is added by the building owner. This approach will certainly reduce the number of collectors required to lower the purchased fossil fuel heating energy to some target value. It will, however, diminish the economic return on the investment. The heating season of a passive solar house becomes shorter as the heat loss factor is reduced and space heat becomes more concentrated in the December to January period when solar radiation is at its lowest level. The economics are best illustrated by the following example - in a highly insulated passive solar house the useful energy delivered per unit area of active solar collectors is much less than for a solar domestic hot water system that delivers energy throughout the year.

The significant exception to this situation occurs with seasonal storage that is part of a DE utility. The utility invests a certain amount for infrastructure of the solar collectors and the seasonal storage. The energy stored at the end of summer is proportional to this investment and this energy is sold and combined with the utility's conventional energy supply. The goal of the utility is to maximize profit on its investment and also to supply a service to as large a number of customers as possible. The stored energy is a rapidly depleting resource due to thermal losses to the surrounding ground. The longer it is stored the higher the percentage of losses. This characteristic is ideally matched to a well insulated passive solar house. Its peak heating demand is relatively early in the cold season, since passive gain is low in December and January. In this case energy stored is used in the most efficient manner. The building owner simply sees purchased energy from the utility and by having a well insulated building the purchased amount will be reduced. This will also result in a larger number of buildings being supplied from a given size of solar and storage system. A heating demand cycle that peaks early in the winter is to the utility's advantage.

Measurements in the Okotoks solar seasonal storage system

The Okotoks solar seasonal storage system is fully instrumented with 96 channels of data, five of which measure a photovoltaic system, being measured at ten minute intervals via a data/control system. These can be seen in Figure 5.

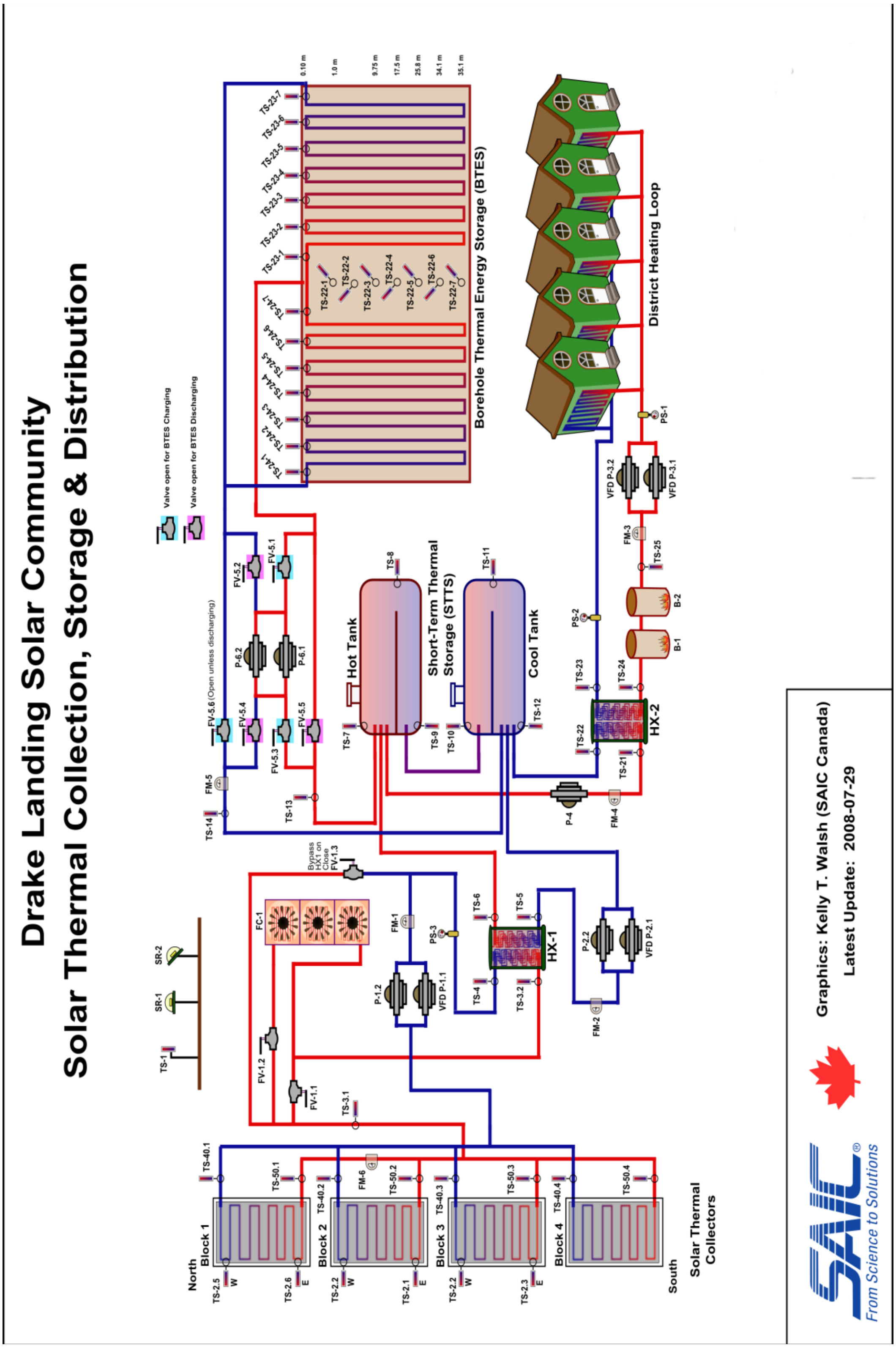


Figure 5: Okotoks Subsystems, Interconnections and Instrumentation[5]

Operational Characteristics of Borehole Thermal Energy Storage (BTES)

Since most of the borehole field earth volume has no insulation, the main mechanism by which thermal energy is retained in the field is by counterflow operation. During the summer charging period hot water is fed from the collectors to the centre of the field and circulated through multiple boreholes in series (six in the case of Okotoks), with the flow exiting from the last ring at the perimeter of the field after transferring most of its thermal energy to the earth. The exit water is then transferred via the short-term storage tanks back to the inlet of the collectors. When discharging the field during the heating season the flow is reversed, with the cooled DE system return water flow being directed to the outer boreholes and exiting in the centre of the field. As a result of this flow direction the region around the outer boreholes quickly reaches a temperature close to the district loop return temperature. This leads to a “guarding” or “shielding” effect where the reverse flow intercepts the thermal energy that is trying to escape from the borehole field, mainly through the large cylindrical side area encompassing the last ring of boreholes. There are also losses through the area below the ends of the pipes, especially at the ends of the hot pipes in the centre.

Through the summer period of intense solar radiation and high ambient temperatures, high levels of power are generated by the solar collectors, up to 1.5 megawatts. Towards the end of summer temperature levels of over 75°C are being directed to the centre of the borehole to charge the thermal mass. Since the ground temperature at 30 metres from the centre of the borehole field is about 6°C, large thermal gradients are set up in the borehole field.

Daily average temperatures at BTES for 2008 to 2011

In order to establish a reference case for simulations to do sensitivity studies for improvements to the energy recovery ratio on BTES the last three years of data from Okotoks was analyzed. By using the charge/discharge control bits the temperature data were separated into two sets.

Figure 6 shows the temperature of the water flow into and out of the borehole during the charging cycle and Figure 7 shows these temperatures during the discharge cycle. Because of short transients caused by the highly dynamic nature of solar radiation the data has been smoothed by calculating daily averages.

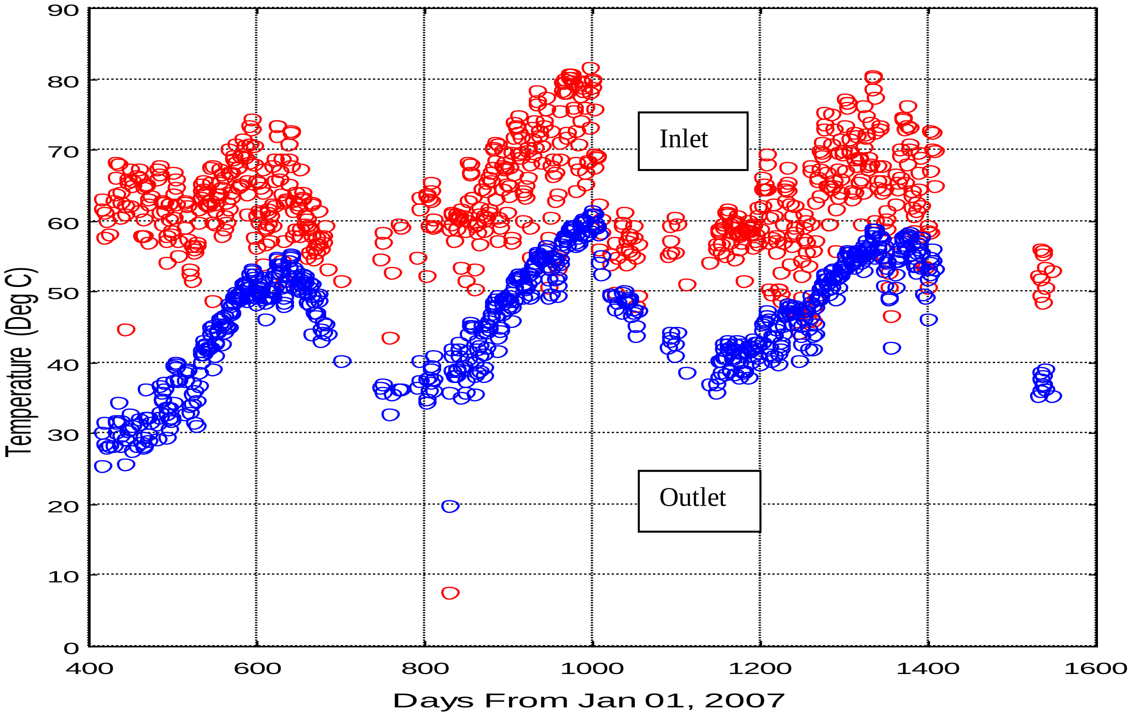


Figure 6: BTES Inlet and Outlet Temperatures during Charging (Daily Averages)

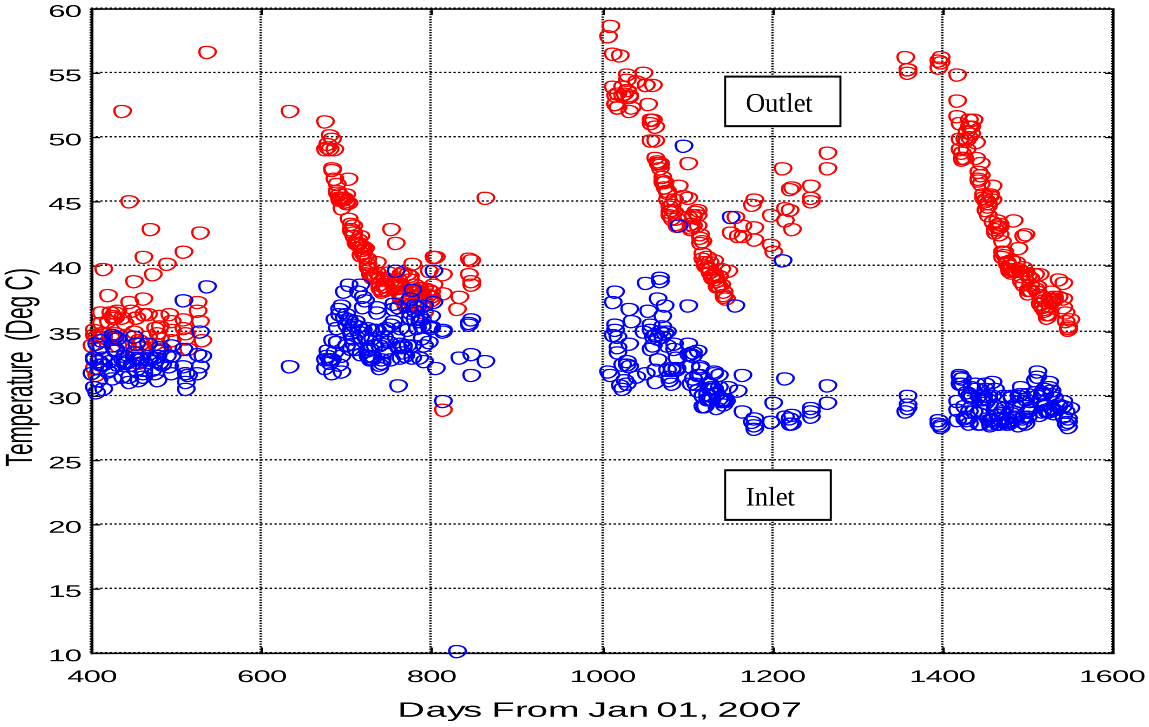


Figure 7: BTES Daily Discharge

As a result of improvements in the control strategy the return temperature during the 2010-11 heating season is considerably lower and much more consistent than previously, at around 28°C. By conventional DE standards this is certainly a low temperature but there is potential for improvement. The characteristics of air-tight low-energy buildings can make it relatively easy to achieve considerably lower temperatures, at or slightly below room temperature if cool air from the heat recovery ventilator is injected in counterflow mode into the cool end of the liquid-to-aircoil heat exchanger.

Two characteristics of this data are significant:

- Toward the end of the summer charging period the outer ring temperature is high, reaching 60°C.
- At the end of the heating season the BTES supply temperature has dropped to 35°C. This is seven degrees above the return temperature, indicating some potential for further extraction of low-grade energy. This could be used as a preheat source.

If the return temperature could be reduced further the ability to extract additional energy from the seasonal storage will increase due to lower losses.

The supply temperature function is shown in Figure 8.

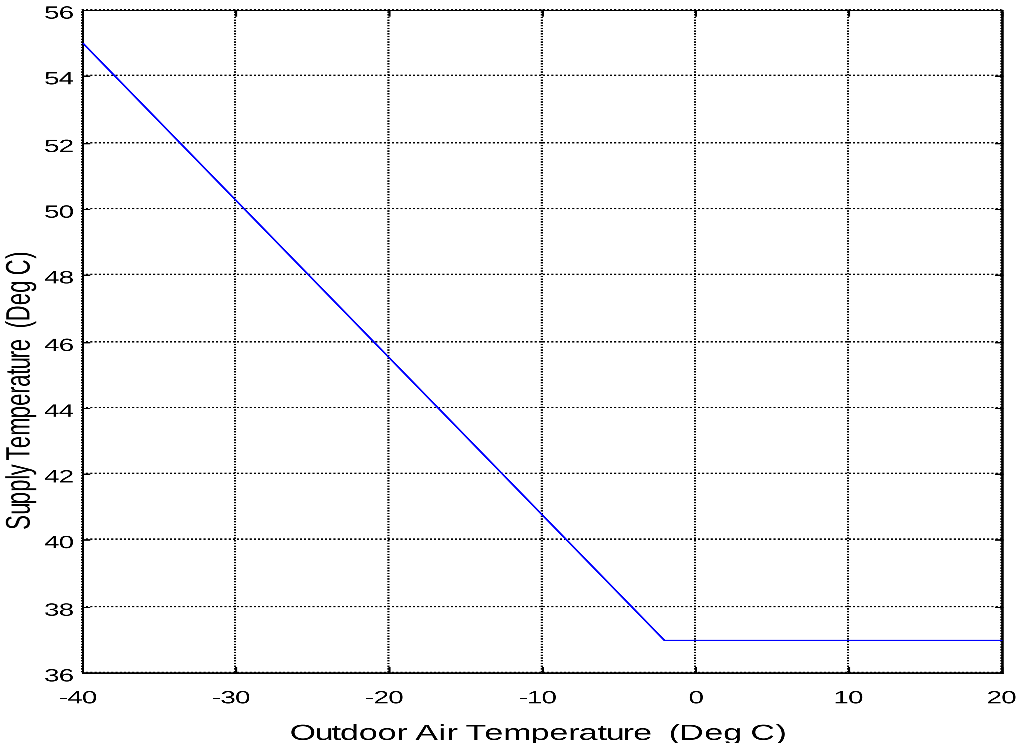


Figure 8: District Loop Supply Temperature for Okotoks

Optimization of solar storage system configurations

Because of the complexity of the components and control systems in a solar seasonal storage system there are many configurations that could be examined to establish the optimum for a given load. This could include some input by privately funded solar systems in a fully distributed format.[1]

The distributed privately funded solar system approach was evaluated as an option for this project but was found to be too complex to be used for case studies built on the Okotoks configuration. Some of the difficulties relate to the limitations of Simulink™ [6], as discussed below.

Simulink™ development software and its limitations of large dynamic system simulation

Simulations were done using Simulink™, which is a very versatile and flexible simulation software, with a highly informative graphical interface.

It does have limitations when linking a large and slow module, such as the borehole model, (with its seven hour run time) to interface with a highly dynamic module such as the short term storage and collector array. Some of the runs were done with an array of ten collectors in series, leading to highly transient conditions as the series collectors interacting with each other. For accurate results in a dynamic simulation a variable time step mode is used so that the system can track the transients. This version of Simulink™ executes all modules at the same time step as the fastest module, even if a module only varies slowly. The collector requires a fine time step during the day and radically slows the complete system.

When the borehole system was simulated in only three case studies for a previous contract[1] these were done by isolating the borehole model from the rest of the system and using an iterative approach. The dynamic system was operated to generate an input data set for the borehole model. The borehole model was run in stand-alone mode and the resulting data set used as feedback input back to the dynamic system. After three or four iteration cycles the accuracy of convergence was acceptable. This was made easier since the previous configuration studies made use of evacuated-tube collectors which are much less sensitive to inlet temperature in comparison to flat-plate units, which are used now at Okotoks.

For the purposes of this contract a four year simulation run would have required a few hundred hours. Efforts to expedite the software proved difficult. The final solution was to simplify the highly transient sections as much as possible. Test runs were done on the series collector array over a range of operating conditions and a linear equation generated that tracked the full array within six percent. This, together with fine-tuning other parts of the simulation resulted in runs that could be done overnight.

The present borehole model consists of 2600 elements. To decrease the run time, it would need to be rebuilt with variable element sizes, with the cells becoming larger as they are further from the boreholes. This would decrease the number of elements but would require an extensive level of effort that was not possible for this contract.

Low Temperature Space Heating System

Benefits of low temperature space heating systems

The benefits of operating DE systems at low return temperature have been previously examined.[7] These studies mainly concentrated on cost savings for the distribution network and more efficient use of low-cost waste heat.

When hot water storage is used there are additional benefits from low return temperatures:

- The effective storage volume is increased in proportion to the temperature difference. Storage occupies useful space in a building and with lower physical size there will be a reduction in the cost of the tanks.
- Increased temperature difference across the heat exchange units will reduce the required flow for a given power level. This increases the efficiency of the diffusers in the storage tanks. The improved stratification also increases the effective volume of storage.
- The branch line to the house can be a smaller diameter, allowing the use of supply and return lines in a common jacket.

The use of low temperature heating makes the system compatible with solar systems and heat pumps. In addition, if a borehole seasonal storage system is used, even a small reduction in water return temperature will have significant reduction in the thermal losses of the borehole system.

Forced-air system

The main options for space heating systems with ultra-low return temperatures are in-floor heating and forced-air, using liquid-to-air coils. In-floor heating has some attractive features but tends to be expensive and has not been widely accepted in Canada. There are also indications that forced-air may have the best price-performance characteristics for a low-energy air-tight house that has mandatory ventilation to each occupied room. For these reasons a decision was made to use forced-air heating system in the Okotoks project.

The usual criticism of forced-air heating systems is that they are noisy and cause drafts. These are certainly valid for poorly designed, oversized systems that cycle in an on-off mode between 100% and 0 capacity in an older building with high heat demand. Realizing that a well insulated house has maximum demand of 5.6 kW at -32°C and can be equipped with a system that modulates both water and air flow, these characteristics can be made to have a much smaller impact.This is true even if the air delivery temperature is somewhat lower than that from a combustion furnace. Properly designed air diffusers at the duct outlets can spread the flow and enhance mixing with room air at reduced velocity. Part of the air flow can be released in the centre of the building without causing condensation on the windows, since the heat loss factor has been reduced by more than half in recent years with modern windows. In addition, it is possible to add various forms of air filters and purification in a forced-air heating system. This can be of special benefit to people with allergies and asthma or other respiratory problems.

Problems in forced air heating system ductwork

Before examining the performance of a prototype low temperature forced-air system it is important to review some design aspects of the associated air ducts, since these can have considerable impact on the performance of the heating system.

In Canada, most forced air space heating systems are supplied by a natural gas or oil furnace. As a result of the combustion process the efficiency of these systems is relatively immune to an elevated air temperature entering the furnace heat exchanger. This has led to some ductwork construction methods that are not well suited to low temperature water to air-coil systems.

Short-circuiting of hot air to the cold air return ducts can be a problem. The test bungalow house had been equipped with cold air return points that are high off the floor, up about 2.2 metres, probably in case the house is later equipped with air conditioning. The hot air floor grates release the air vertically, with a clear path to the cold air return grates. With the gas furnace in operation the cold air return was close to 30 °C, much too high for the solar requirement. When the cold air ducts were opened at floor level, it led to considerable improvement but did not completely eliminate elevated return temperature.

Figure 9 shows the relationship between the cold air return temperature and the temperature on the main floor after the first modification.

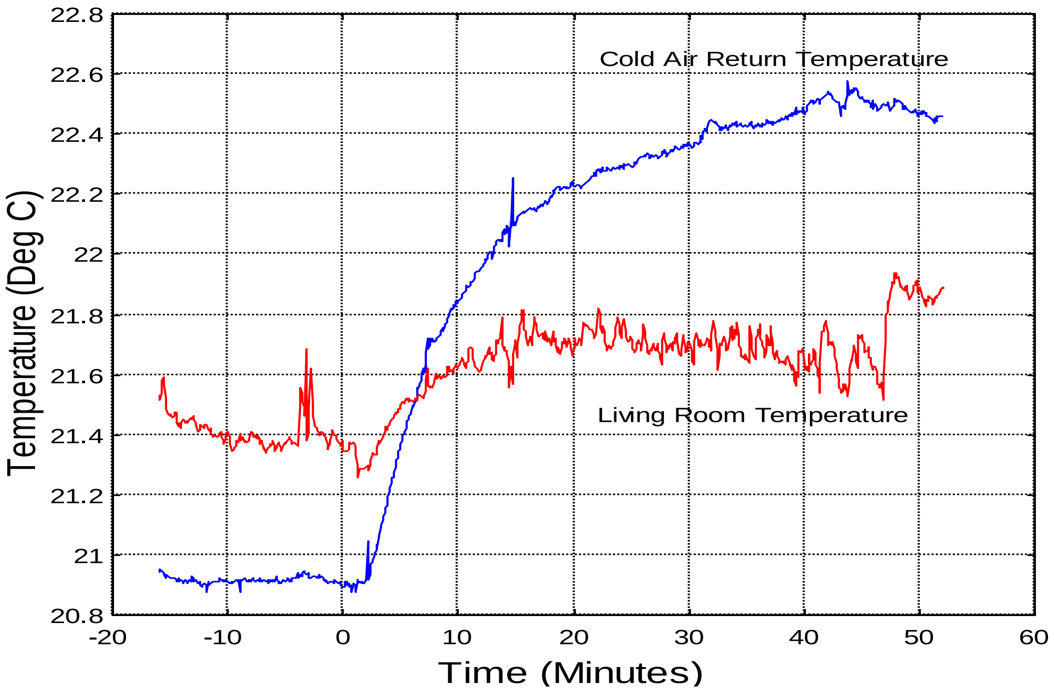


Figure 9: Elevated Cold Air Return Temperature due to Duct Leaks

The air circulation was kept steady at 540 litres per second. Before the water flow is initiated the cold air return temperature is 0.5°C below the main floor temperature. After flow starts the cold air return quickly rises about 1.0°C above the main floor temperature. The most likely cause relates to the way in which the cold air return duct runs along the basement ceiling. The main cold air return duct is a flat metal sheet nailed to the space between the bottom of two floor joists. The spacing of the nails is typically 16 cm. and there are many small gaps where the sheet metal sags between nails and there is no gasket or caulking to seal the metal-to-wood joint. There are also gaps where return ducts from the main floor have a poor fit into the master return duct. All the basement hot air grates are at the ceiling and the warm air will form a layer where the negative pressure of the return duct will pull in part of this air to mix with the main flow, elevating the temperature. Since the air temperature at the inlet side of the air coil has a direct effect on the water return temperature these air leaks will impose a limit on the capability of the heating system.

In order to achieve the full benefit of an efficient air coil the following is required:

- If high cold air return points are required for air conditioning there is a need for dual entry levels, with a tight damper to switch between heating and cooling operation.

- Hot air grates should have diffusers to slow the exit air and direct it horizontally to allow full mixing with cool air at floor level.
- If the space between two floor joists is used for a return duct all joints need to be carefully sealed.
- Warm air grates in the basement ceiling should be avoided by extending the ducts to the floor. The stratification due to ceiling grates causes the basement floor to be cold, even if the floor is insulated. In the test house 14°C was measured at the basement floor in the middle of winter.

Prototype Low Temperature Forced Air Space Heating System

A study was done to evaluate the performance that could be available for the next generation solar seasonal storage DE systems. A space heating system with a very low return temperature is shown in the drawing in Figure 10. This prototype was designed, constructed and tested and shown in Figures 11-13. It is assumed that microprocessor control will be used to optimize the system performance and continually adjust its characteristics to match the operating conditions. This is accomplished by making use of a DC pump to vary the flow through the air coils and by using an electronically commuted motor (ECM) to drive the blower.

By varying both the water and air flow in an optimum manner the power demand can be met while keeping the water return temperature consistently low and minimizing the air velocity and its associated electric power consumption.

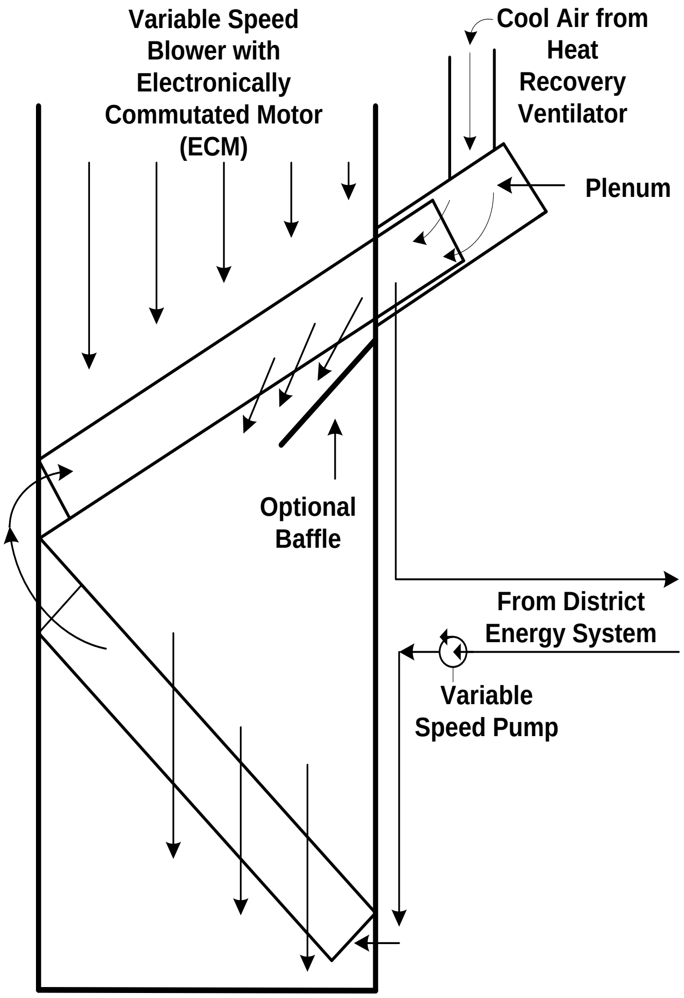


Figure 10: Schematic of a Space Heating System with Single Row Air Coils

Figure 11: Space Heating System Prototype with Single Row Air Coils

The features of this system are:

- Above some lower threshold of required power, the system operates continuously with fully modulated water and air flow.
- Utilizes two single-row coils in series with counter-flow orientation.
- Air coils with large surface areas minimize air pressure drop.
- The coils are angled to add a component of counter-flow of air against water flow direction.

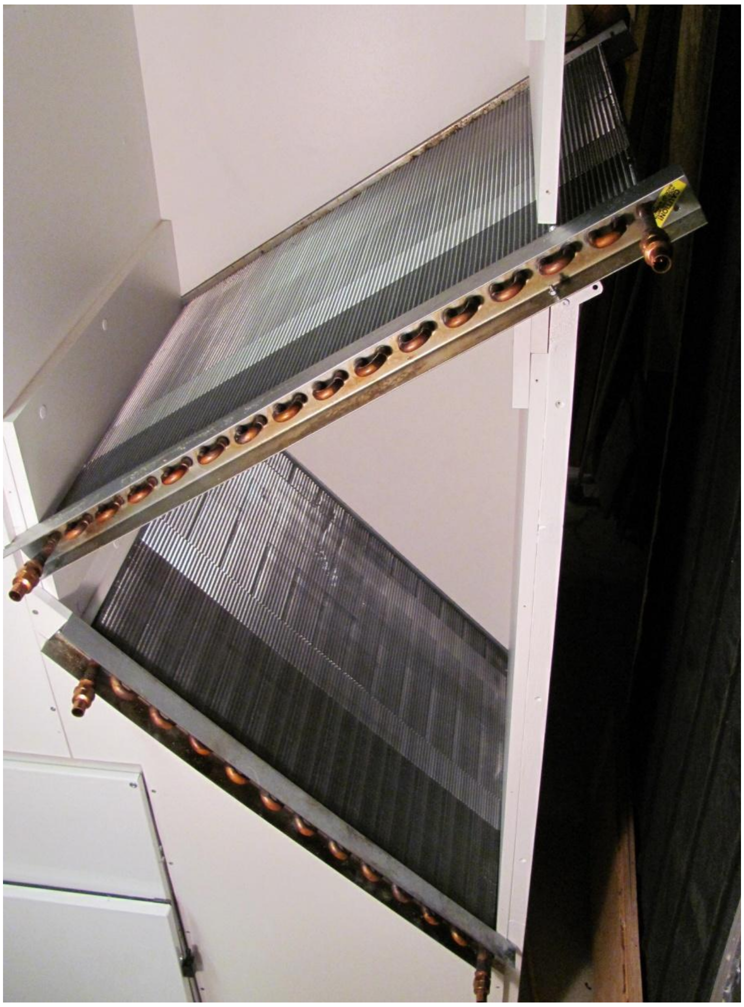


Figure 12: Front View of Air Coils

The coils are 61 cm by 76 cm.

The exit end of the cooler coil is extended out of the air handler into a small plenum that injects air from the heat recovery ventilator (HRV) as can be seen in Figure 13. Even a high efficiency HRV will have exit temperatures as low as 12°C at -32°C. As will be seen later this has the potential to reduce the water return temperature by more than 3°C at low power levels, such as on a cold day with high radiation. Interlocks are required for freeze protection in case the HRV fails, for example, due to frost buildup. If the air temperature entering the plenum approaches freezing temperatures redundant controls would stop the intake air blower.

Figure 13: View of Extended Plenum from the Top Coil

Testing of prototype space heating system

In order to meet the requirements of a low temperature district heating system the following characteristics need to be met:

- The heating system must cover the supply temperature range of 55°C down to 37°C in a reasonably linear manner so that a feedback control system can control the operating temperature effectively, with minimum water flow rate
- It must meet the peak power demand of 5.6 kW at a supply temperature of 55°C without significant rise in the water return temperature. This power level is the peak demand at -32°C of a low-energy house that was used for experimental work.[1]
- The cost and complexity of the system must not be excessively above conventional design practice.

Testing was done by varying both the supply temperature and the water flow while keeping the air flow constant at 0.54 m^3 per second. Cold air return into the air coil varied in the range of 20 to 21°C. Power measurements were taken by a heat meter that meets the EN 1434 standard and are accurate to 1.5% at these conditions. Figure 14 shows that power is above 7.0 kW at a flow of 180 litres/hour (0.05 litres/sec.). As seen in Figure 15, the water return temperature had a maximum offset above the inlet air temperature of 1.9°C at a power level of 7.3 kW, with no ventilation air injection. As seen later, this offset is reduced to slightly below zero over the normal operating range below the peak load due to injection of cool ventilation air from the HRV. At a typical load in the range of 3.0 to 4.0 kW this offset is in the range of -1.0 to -3.0°C.

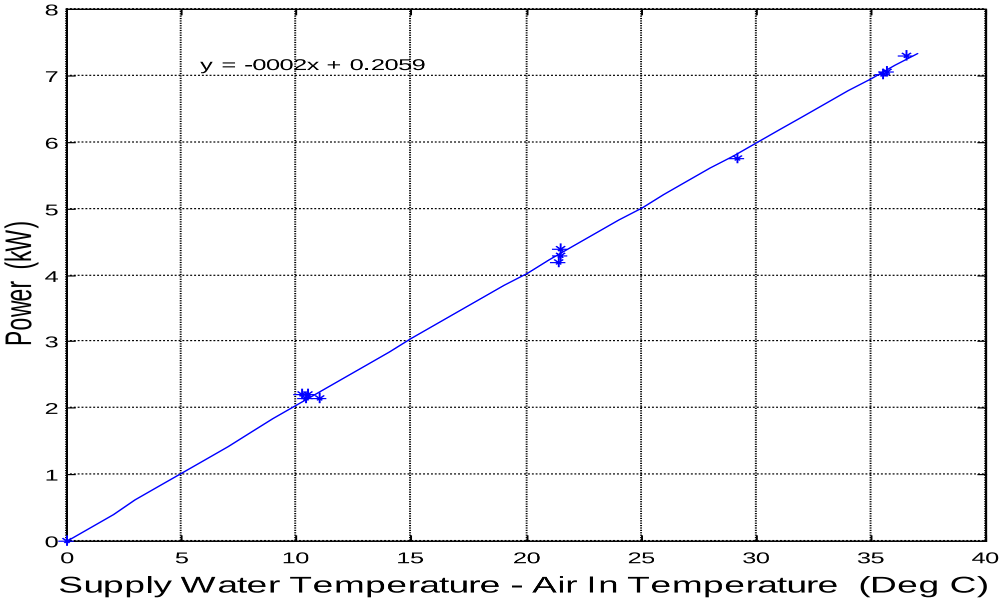


Figure 14: Flow Varies from 183-187 l/Hr; Cold Air Return Varies from 23.9°C to 26.2 °C (Air temperature is from the cold air return.)

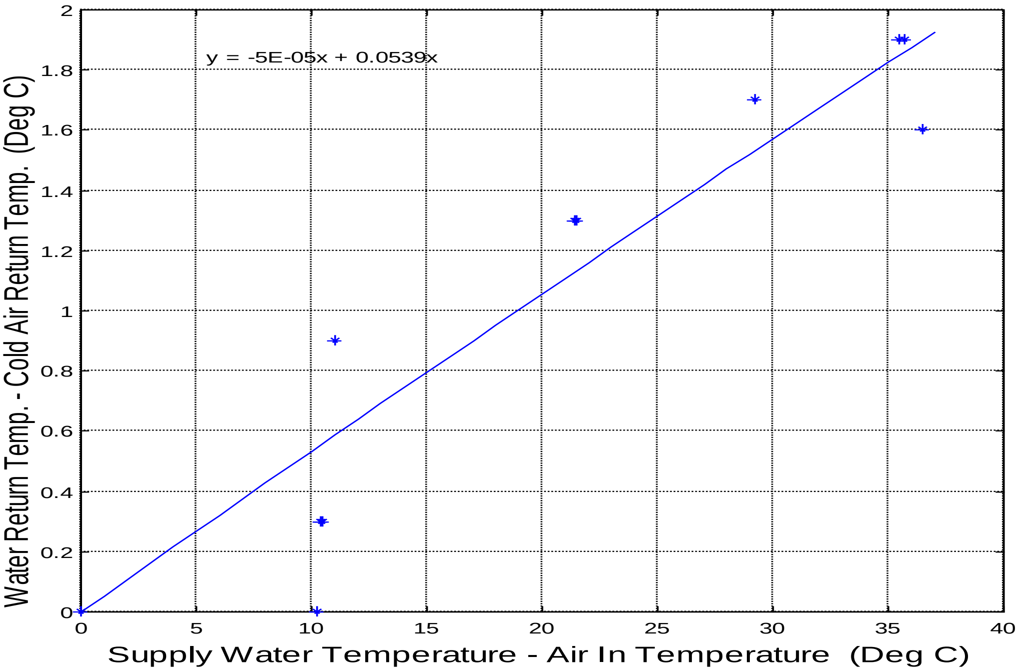


Figure 15: Water Return Temperature as a Function of Supply Temperature (Air temperature is from the cold air return.)

In the elementary application of this system it would be directly linked to the district utility via a flow control system.

There are a number of methods of controlling the flow in either a multi-stage mode or fully modulated:

- Dual Griswold constant flow valves. These can control flow within 5% over a pressure range of 10:1. If two valves adding to 100% are used there will be three steps, for example 30%, 70% and 100%. Below 30% the system can operate in on-off mode.
- Motorized modulating flow valve, possibly preceded by a pressure regulating valve to give more linear feedback control.

- Redundant control of freeze protection is required to turn off the ventilation blower if the HRV fails.

In a more elaborate system there can be use of a buffer storage in the building to enable peak load shedding and off-peak charging. In this case a variable speed pump would be required to modulate the flow from storage to the air coil. This was the method used in testing the system. An electric hot water tank was used to emulate a DE system. A DC motor drove the pump at the required flow rate by using a variable voltage DC power supply.

Additional testing was done for the high power, cold weather case where the temperature from the HRV ventilation air can be up to eight degrees below room temperature. The supply temperature was kept constant at 55°C.

Three cases of ventilation air temperatures were measured at a flow of 35 l/sec from the HRV into the air coil plenum.

- Ventilation air temperature = room temperature
- Ventilation air temperature = 4°C below cold air return temperature
- Ventilation air temperature = 8°C below cold air return temperature

The results are shown in Figure 16 and Figure 17.

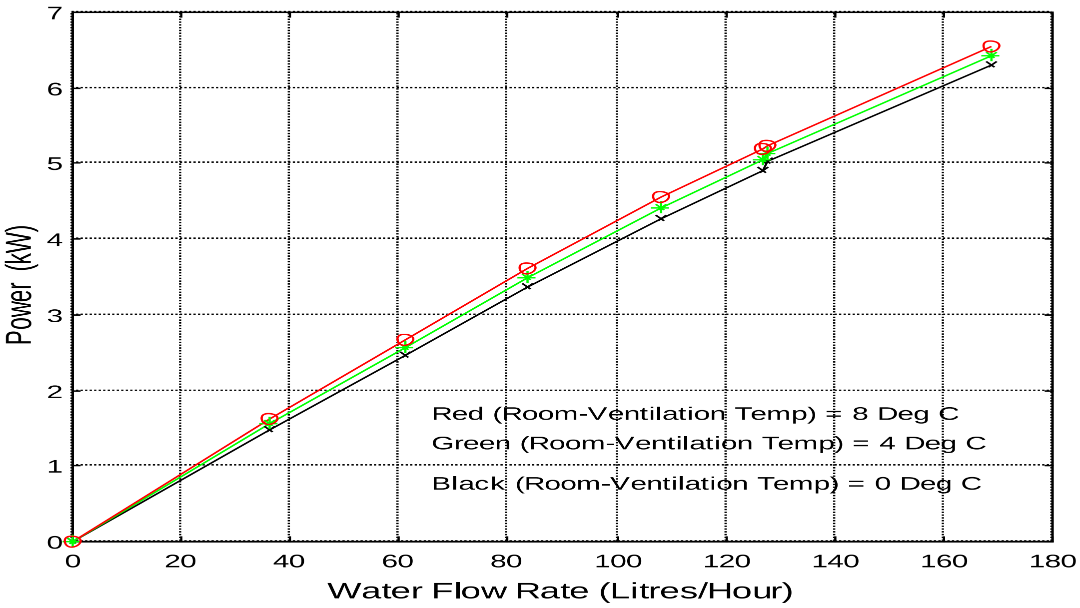


Figure 16: Air Coil Power at Different Ventilation Air Temperatures with Supply Temperature = 55°C, Room Air Temperature in the Range of 20-21°C

The peak demand of 5.6 kW can be met with a water flow rate of 140 litres per hour (0.039 l/sec) at the 55°C supply temperature. Varying the ventilation air temperature has relatively small effect on power level, since the system is operating with return water temperature very close to room temperature over the range of ventilation air temperature. The main benefit is in the lower water return temperature, which has the improvements discussed previously.

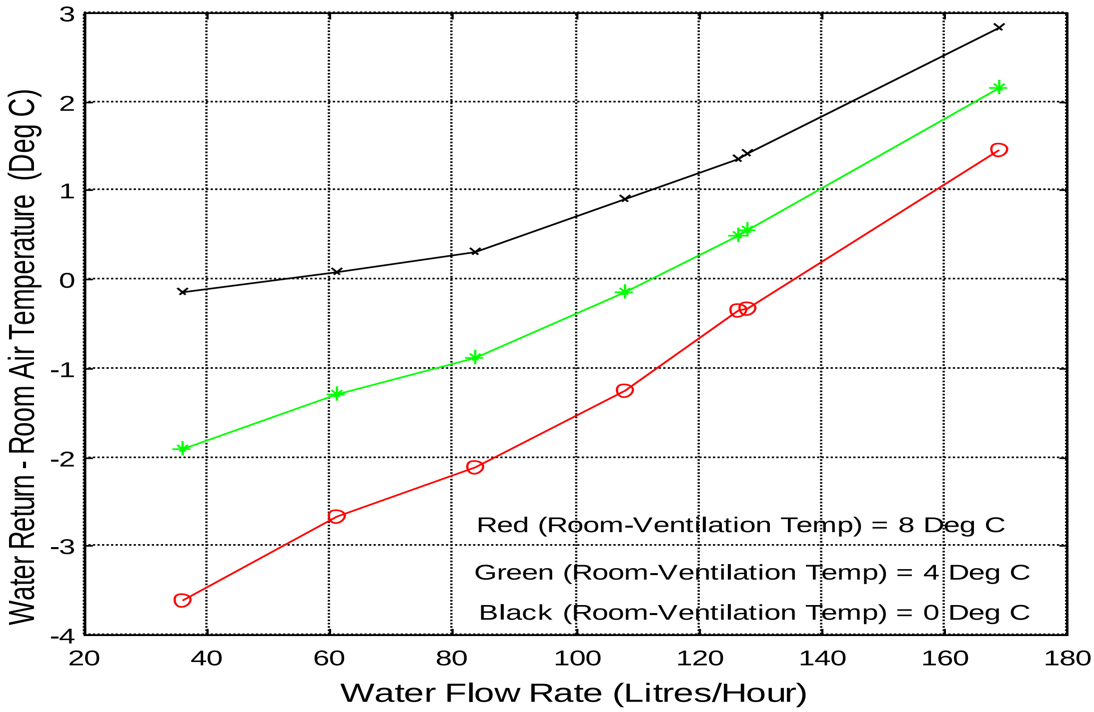


Figure 17: Effect of Ventilation Air Temperature on Water Return Temperature

Figure 17 shows the relationship between the room air temperature and the water return temperature. It can be seen that near peak power the water return temperature will be very close or slightly below room temperature.

The testing was done at an air flow rate that generated minimum water return temperature at peak power. With slightly lower air flow rate a small increase in water return temperature was seen. In practice a heating system will spend very short periods of time at peak power, depending on the shape of the load duration curve. The operating strategy will be to automatically lower the air flow rate until the required power can be met with minimum rise in water return temperature. This will ensure that optimum conditions of minimum electrical power, maximum exit air temperature and minimum air velocity are set.

Extra cost of low temperature heating system

The total cost of the two air coils was $1,050.

Item	Cost in $
Estimated air coil cost above standard practice	400
Extra cost of electronically commutated blower	300
Water flow control	400
Connection to HRV	100
Freeze protection	100
Micro processor thermostatic controller	400
Total cost premium	**$1,700**

Table 2: Extra Cost of Low Temperature Heating System

Heating System Control

The air-coil heating system has multiple variables: water flow, air flow and supply temperature.

In order to use these variables in the most effective manner computer control is required. Specialized microprocessor-base controllers are now available at reasonably low prices. The installed cost of this controller will be in the range \$300 - \$400, including the required sensors. Installation and wiring of an outdoor temperature sensor can be expensive. Since this installation will have a HRV the outdoor air measurement is conveniently available in the intake air duct and does not require protection from rain or other elements.

Use of a microprocessor-based controller makes available accurate feedback control and self-compensating methods that can cope with extremes of input. For example, the system gain is reduced as outdoor temperature drops and building loss absorbs more power. The DE utility supply temperature is raised to increase the power capability of the air coil and compensate for the loss of gain. If the building has significant passive solar gain there can be situations when the supply temperature is high but the building load is relatively low. This could cause a tendency for the system with a high gain controller to overshoot the setpoint temperature as it responds to transients. A microprocessor-based controller can compensate for these conditions by various methods. If highly accurate thermostatic control is required, an offset based on outdoor temperature is a method that will achieve this.

The controller algorithm is described in the following section. For these simulations the supply temperature was kept at its highest value of 55°C and outdoor temperature varied over the full range. The system appears to be stable under all conditions.

This controller was selected because of ease of implementation, simplicity and performance without requiring an accurate plant model in the controller. This makes the controller easier to realize in the in the real world. The controller was put into the velocity form to allow for bumpless transfer and to remove integral windup that will occur due to maximum supply power saturation. The controller uses a very small proportional gain term to reduce oscillation in the pump flow as much as possible and to keep the system stable when a time delay exists. The controller is primarily controlled through the integral term.

The house characteristics are the same as a low-energy house in Saskatoon.[1]
The primary parameters are:

- average heat loss factor is 109 watts/degree C
- thermal capacity is 39 megajoules/degree C
- maximum power = 10 kW
- solar heat gain factor = 0.57
- window area, south side = 14.1/m^2
- maximum flow = 0.0748 litres/sec.

The selected heating system controller used in the model is a standard proportional, integral derivative (PID) controller in the velocity form.

Small proportional gain in the system often results in the system becoming unable to reach the setpoint. To compensate for this, a linear offset against Tambient is added to the setpoint and is shown below.

The equation for this is:

$$Setpoint\ Offset\ =\ Tambient * -0.00625\ +\ 0.142$$

The system response is shown as a function of previous time stops.

$$u(t_k)\ =\ u(t_{k-1})\ + K_p((1 + \frac{T_s}{T_i} + \frac{T_d}{T_s})e(t_k)\ +\ (-1\ -\ \frac{2T_d}{T_s})e(t_{k-1})\ +\ \frac{T_d}{T_s}e(t_{k-2}))$$

Sample time in seconds= Ts = 30
Proportional gain (Kp) = 0.04
Integral gain (Ti) = 20
Derivative gain (Td) = 0.5

Voltage to Flow = 0 @ 0V, 0.0897129L/s@10V, linear
Measurement delay is 270s

The heating system block diagram of the system is in Figure 18.

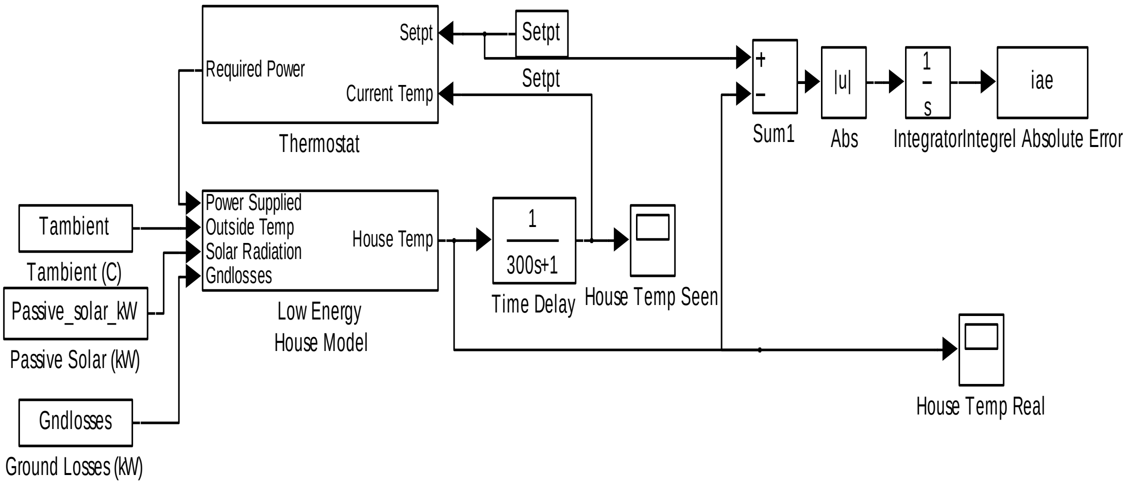


Figure 18: Heating System Block Diagram

The house model is a fully dynamic one that includes transient response to passive solar input.

The velocity form of the PID equation is the derivative and can be seen in Figure 19.

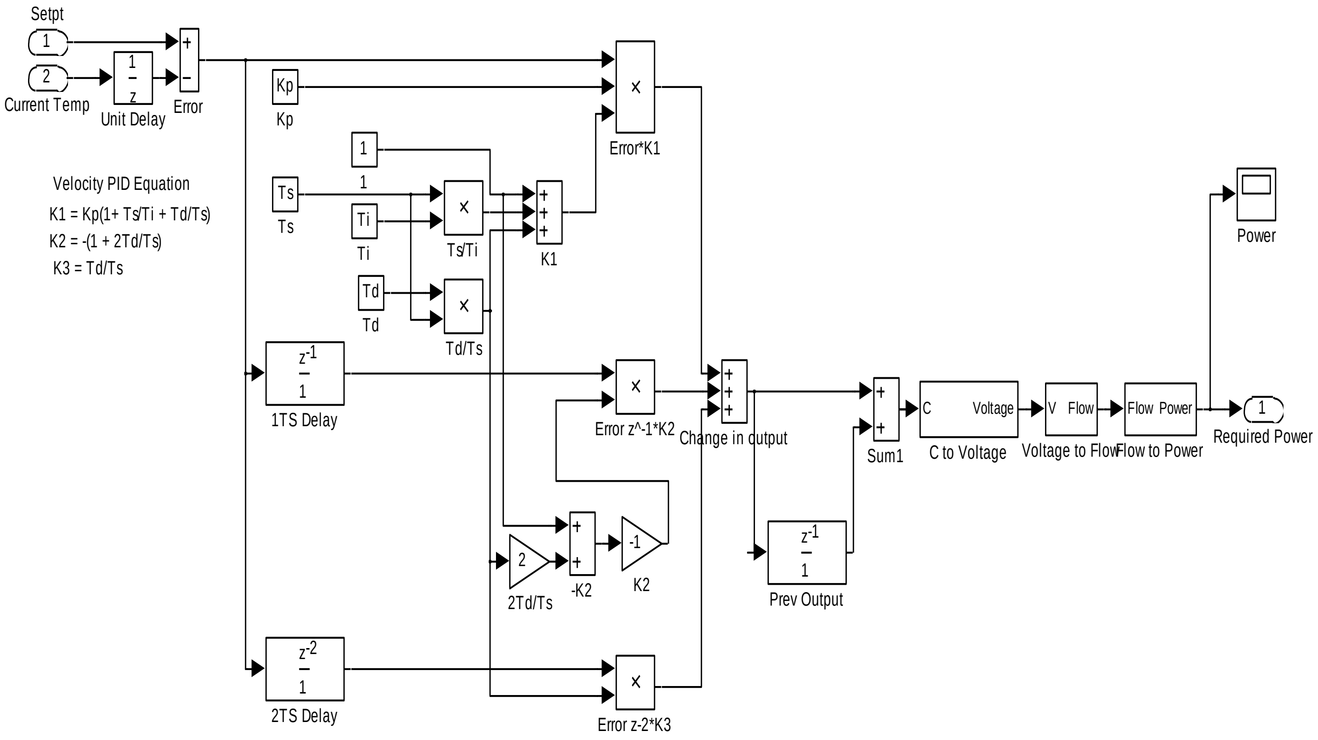


Figure 19: Digital Control System Transfer Functions

Simulation tests were done on the controller with different outdoor temperatures.

As shown in Figure 20 the response to a step input becomes slower as outdoor temperature is reduced. This is due to building losses, leaving less power to charge the building thermal mass.

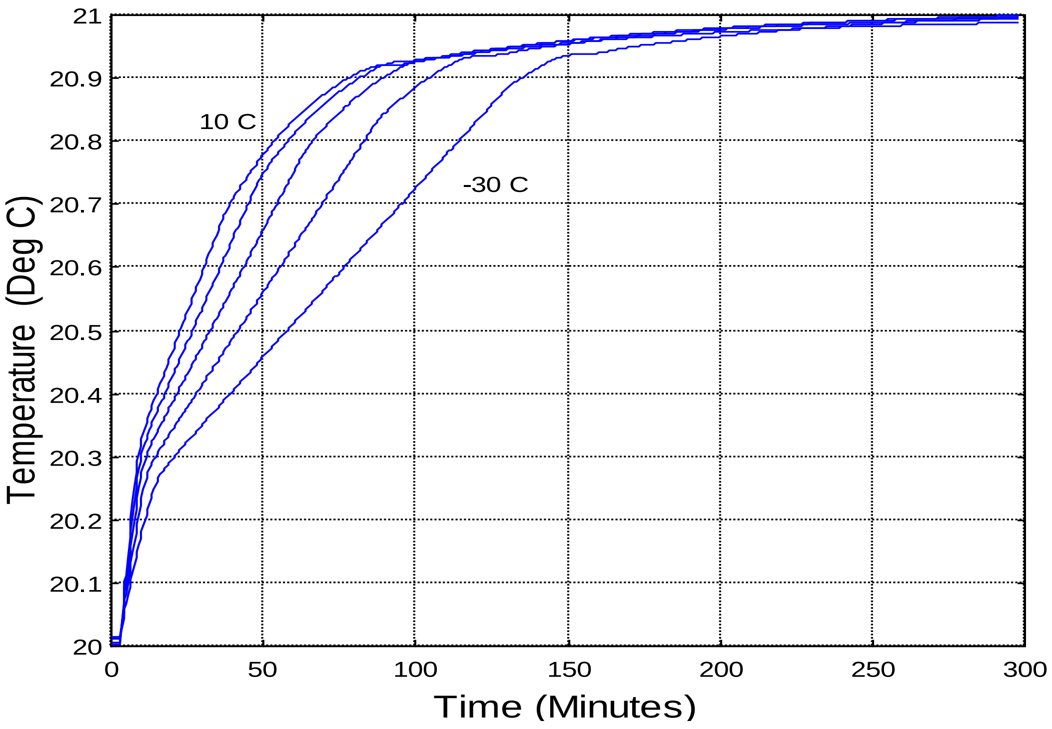


Figure 20: Indoor Temperature Response of Test House to Outdoor Temperatures of + 10°C, 0°C, -10°C, -20°C and -30°C

There is no evidence of temperature overshoot.

The power output of the heating system is shown in Figure 21.

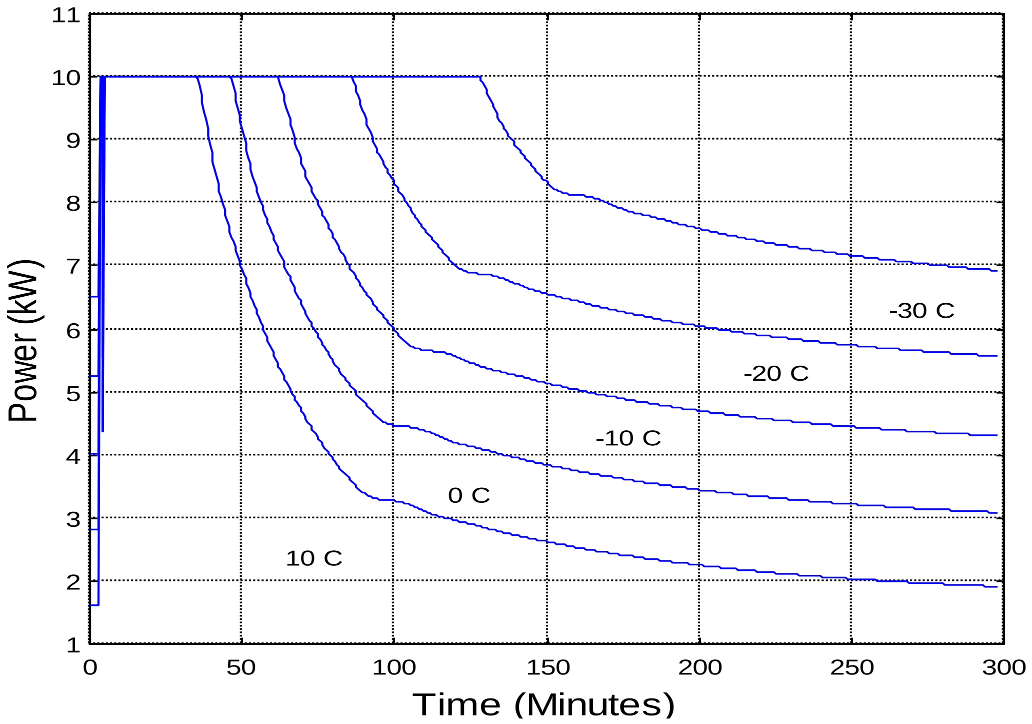


Figure 21: Power (kW) Response of Test House to Different Outdoor Temperatures

These tests give some indication of the recovery of building temperature from night setback. This can cause peak loads for a couple of hours during cold weather, depending on the maximum power capability of the heating system.

Optimization of Borehole Seasonal Storage

Energy transfers between seasonal storage and short-term storage

The solar fraction that has been achieved in the Okotoks system after four years of operation is close to 80% and will reach the design value of 90% after five years of operation.

Based on experience gained during the past years of operation at Okotoks the control strategies have been adjusted to optimize the energy transfers between the seasonal and short-term storage.

However, there is the question of how to extract the maximum quantity of energy from the borehole storage during the overall heating season, even when its available temperature is below the district loop supply setpoint.

A critical parameter is the quantity of energy that is retained in the short-term storage at the end of a day of solar energy collection. The goal is to meet as much the demand as much as possible during the next time period when there is no solar radiation. By supplying the load directly from the short-term storage, this avoids the losses inherent in the charge/discharge cycle of the borehole system. The control of this parameter is especially important towards the end of the heating season when the temperature available from the borehole seasonal storage is too low to meet the demand during cold weather.

Detailed control functions have been developed that define the quantity of energy to be kept in short-term storage as a function of:

- the time of day, and the estimation of the number of hours until solar energy again becomes available
- the present level of outdoor temperature, and the estimated load during the next night

Mixing of flow from the borehole storage and the solar collectors

There is provision in the Okotoks control system to extract energy from the borehole system at the same time as there is energy input from the backup boiler or the solar collectors. The energy from the solar collectors and the borehole are both transferred through the short-term storage system. The backup boiler follows the output of the short-term storage, allowing the other two sources to act as preheaters for the boiler.

The flow from the borehole system into the short-term storage is at a different point from the collector input but there is partial mixing of the flows. The data from the 2010/11 heating season was examined to analyze the interaction between the borehole and short-term storage. Simulations were done to establish whether there is potential to increase the energy that can be extracted from the borehole storage by improvements in the mixing of energy from the solar collectors and the borehole system when the temperature from the latter is low.

Figure 22 shows the temperature of the flow in and out of the centre of the borehole field during the heating season. There are periods of around a week when the backup boiler is on most of the time. The borehole discharge-on flag (Green) indicates that energy is being extracted from the borehole whenever the boiler is in steady operation, in a preheat mode for the boiler.

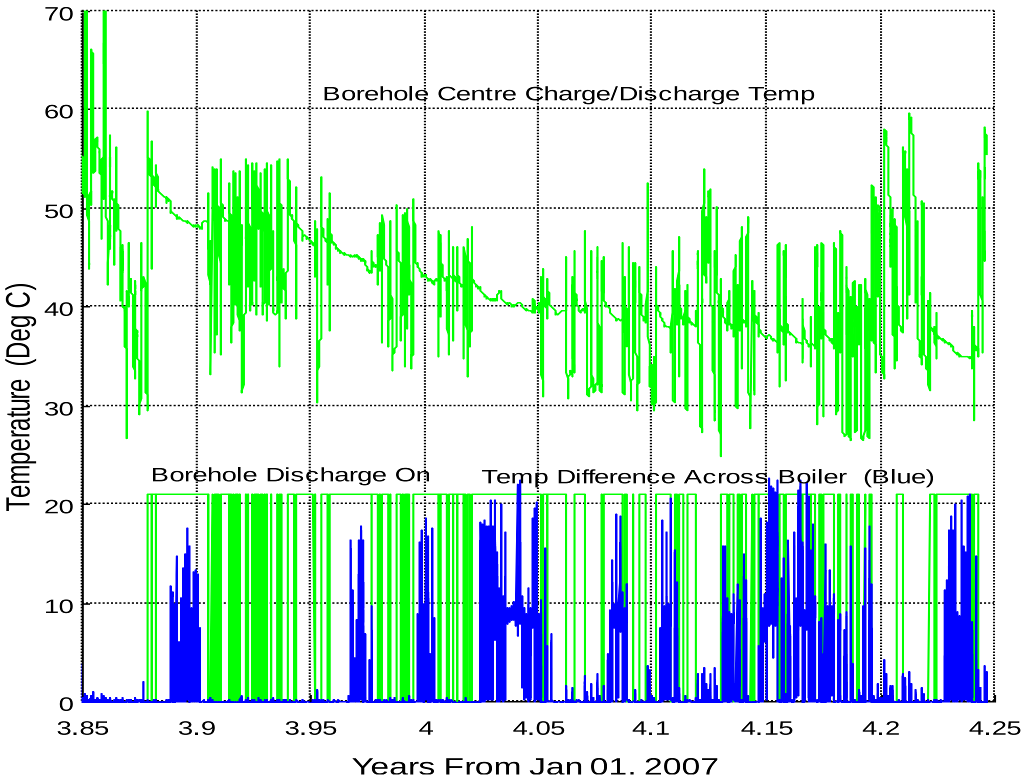


Figure 22: Borehole Centre Charge/Discharge Temperature and Discharge Pump Indicator

Figure 23 is an expansion of the previous graph. It shows that the borehole discharge temperature reaches its lowest value of 35°C at the end of March. This temperature is very close to the minimum supply temperature of 37°C in the district loop, corresponding to an ambient temperature of -2°C. After the first of April the heating loads will be low while solar collection increases and the borehole system will begin to recharge.

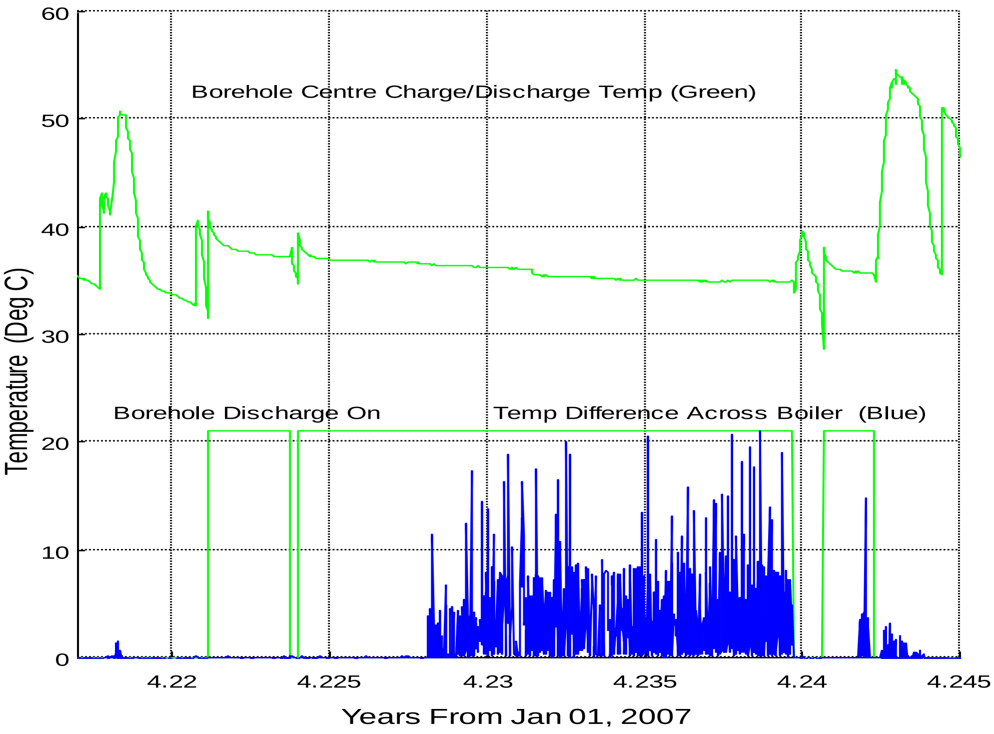


Figure 23: Expanded section of Figure 22

Figure 24 is the same data as in Figure 22, with the addition of the temperature of the solar collector flow into short-term storage. This shows that the boiler is on for extended periods when there is virtually no solar energy available. This could be due to periods of snowfall. The conclusion is that, at least for the weather conditions of 2010/11, the Okotoks system controls were operating close to optimum and there is limited potential to improve the efficiency of the borehole storage by different methods of controlling the interaction of flows from the borehole and collector system.

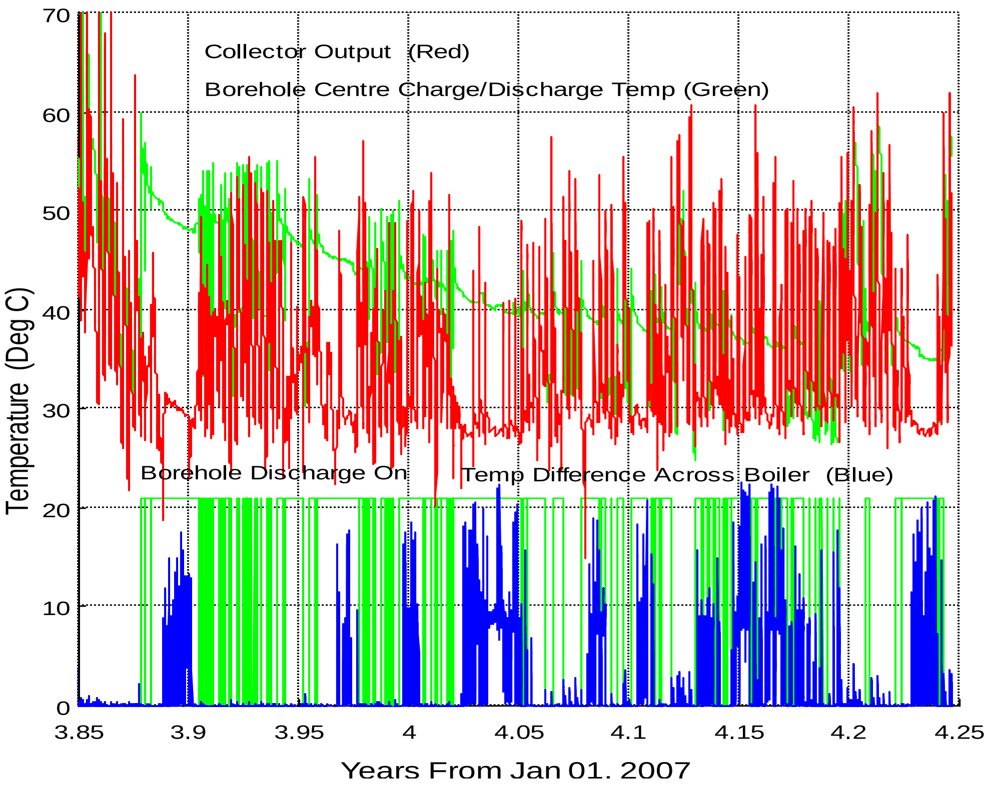


Figure 24: Borehole Centre Charge and Discharge Temperatures

Since the temperature available from the borehole storage never goes below 35°C by the end of March and the return temperature from the district loop is in the range of 28 to 29°C there is some potential to extract more energy from the storage. However, with the large solar array and high solar fraction there is limited need for energy from the borehole after April 1. The main potential for increasing the energy recovery ratio for the borehole storage is by reducing the operating temperatures and lowering borehole losses.

Optimization of energy recovery from borehole storage by lowering heating system return temperature

Testing on the prototype air-coil heating system has indicated it is possible to operate with return temperatures that are as much as 8.0°C below the present operating values at Okotoks. This would have benefits, but there are complications. To achieve the necessary temperature, which is close to room temperature, considerable investment and complexity are required for changes to the heating system. An additional $1,000 to $2,000 is needed in a system that is usually the responsibility of the building owner. Some arrangement would need to be established to compensate the owner. One option is to have a tariff rate reduction for a low return temperature. At least one heat meter company has options that enable calculation of "flow-weighted average return temperature" based on a cumulative value of the product of instantaneous temperature and flow. When this quantity is divided by flow volume for a given time period the effective temperature is produced. The other approach is to subsidize part of the hardware premium cost. A combination of these two approaches would be an incentive for the owner to maintain the heating system at high efficiency.

Simulations with reduced return temperature

The thermal losses for the Okotoks borehole storage system are estimated to be somewhat below 50% after the system has reached stable conditions.[4] Data recorded up to April 2011, after four years of operation, indicate the same conclusion. The main possibility to reduce losses is to lower the average operating temperatures.

The present simulation analysis is limited to storage of a similar size as Okotoks, with up to double the thermal capacity.

The simulation program described in "Interaction between District Energy and Future Buildings that have Storage and Intermittent Surplus Energy[1]" was used for optimization studies of operation at Okotoks in Year 3 and Year 4.

Simulation accuracy verification during Year 3 and Year 4 is shown in Figure 25.

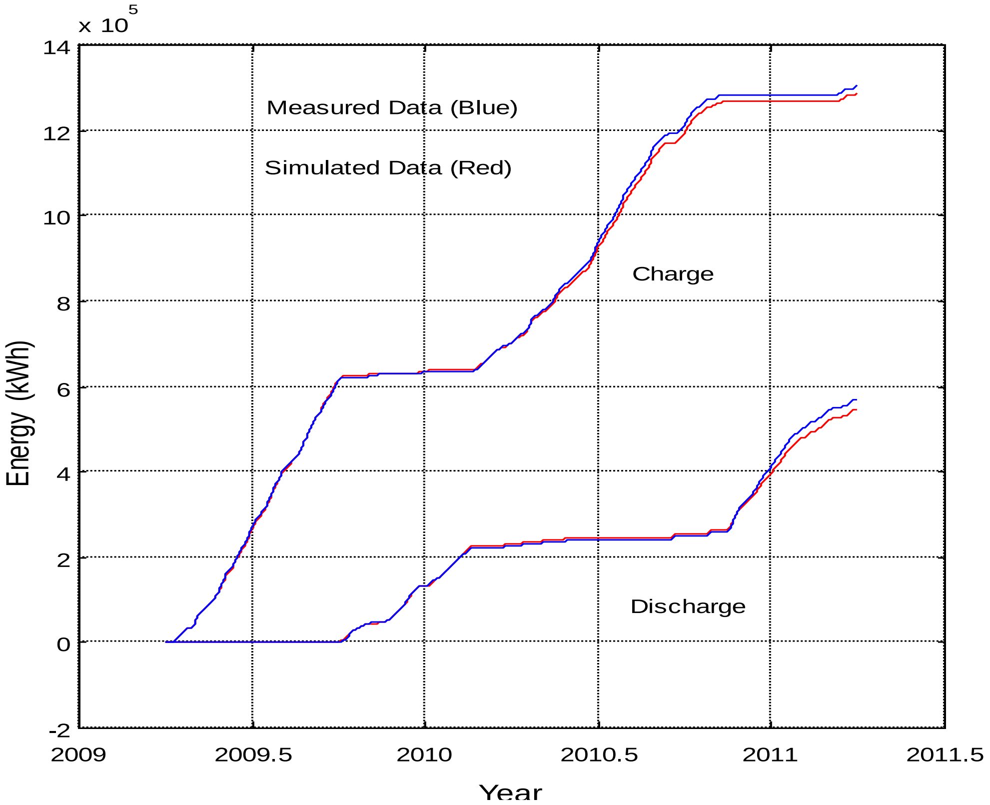


Figure 25: Comparison between Okotoks Measured and Simulated Data for Year 3 and Year 4

The cumulative errors for Year 3 and Year 4 are:

	Measured kWh	**Simulated kWh**	**Error %**
Total Charge	1.306^6	1.289^6	1.3
Total Discharge	0.569^6	0.547^6	-3.9

Table 3: Cumulative Errors for Year 3 and Year 4

By Year 3 the borehole storage was almost at average operating conditions, though small increases will occur until Year 5. In order to calculate the Discharge Energy/Charge Energy ratio it would be ideal to have a distinct charge period followed by a discharge cycle during a 12 month period. In practice, Year 3 and Year 4 have considerable overlap and the combination discharge/charge extends more than 12 months. It is especially true in Year 4 due to climatic variations. This characteristic makes it difficult to evaluate the energy recovery from the charge cycle. Over a number years, after stable operating conditions have been reached, the variations will equalize and give an accurate value of performance. The approach for the simulations was to average the performance achieved over the two years to obtain a realistic indication of the improvement in energy recovery with operational changes.

The first two years of operation at Okotoks involved a number of upgrades which are difficult to simulate. Therefore the initial conditions in the simulations have been set so that, after the first two years, the simulation results compare closely with measured data. Detailed simulations were done for Year 3 and Year 4 using temperatures measured at the storage during both charge and discharge cycles. This is defined as the reference case. During the heating season in Year 4 the heating system return temperature were typically in the range of 28 -29°C.

In order to establish the effect of having reduced return temperatures on a relatively small borehole system, such as the Okotoks one, three simulations were done on the borehole system by using the measured input temperatures and reducing these by assuming a more efficient space heating system in the houses. These are shown in Figure 26 and include:

- Reference case, borehole simulation with measured temperatures and flows
- 4.0°C subtracted from both the charging and discharging measured temperatures to the borehole storage
- 8.0°C subtracted from the same parameters

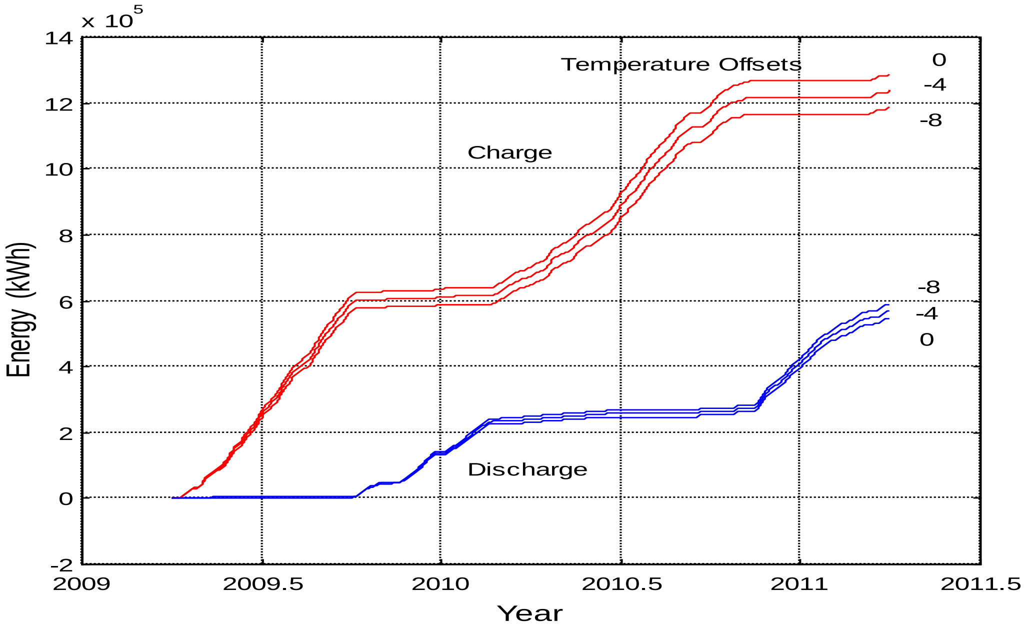


Figure 26: Borehole Charge and Discharge Energy with Reduced Temperatures

With the lower charging temperatures the total charge is reduced due to lower losses elevating the exit temperature slightly. The charging temperature could be elevated an equal amount with minimum effect on the recovery ratio.

The recovery ratios are in Table 4.

Temperature offsets	Energy recovery %
0	42.4
-4	45.8
-8	49.6

Table 4: Recovery Ratios

The reference case recovery factor of 42.4% is 16% higher than the 36.5% from simulations.[4] Part of this can be due to variations in load, weather and the increase in borehole discharge flow rate that was implemented in Year 4. The two simulations were done with different software and there are accuracy limitations in the simulations.

Use of borehole storage as preheater for backup boiler

It was seen previously that when the borehole cannot supply the load by itself and the boiler is in operation the energy extracted from the borehole can be an effective preheater.

If the borehole is at a typical value of 3.0 litres/sec and if the temperature rise through the storage is 2.0°C the power extracted is equal to 25.1 kW, enough to supply two houses at peak load.

Coefficient of performance of BTES pumping power

One mode of operation of the BTES is to use it as a preheater for the other energy sources to supply the DE loop. If a heat exchanger with high effectiveness is used between the DE loop and the BTES, the flow to the outer ring of the storage could be as low as 23°C with a high efficiency space heating system. Assuming that the solar fraction is in the 60%, range most of the energy stored in BTES would be extracted early in the heating season, mainly in the November to December period when solar radiation levels are lowest. If flow can be economically passed through BTES even when its exit temperature is low, during the rest of the heating season a slow extraction of residual energy will lower the BTES temperature and minimize losses during the next charge cycle.

In a climate such as Calgary where the radiation levels increase rapidly in the January to March period, the space heating supply could be a combination of passive and active solar plus ground source heat pumps and fossil fuel, as required.

Figure 27 shows the pumping power through BTES, assuming the efficiency of the motor and pump is 60%. With the 24 parallel paths through BTES and 25 mm diameter pipes, the pumping power through the storage at 3.0 litres per second is 120 watts. Most of this energy is recovered into the water. There are losses in the electrical motor which are not recovered. If the efficiency is 60% the total electrical power is 200 watts.

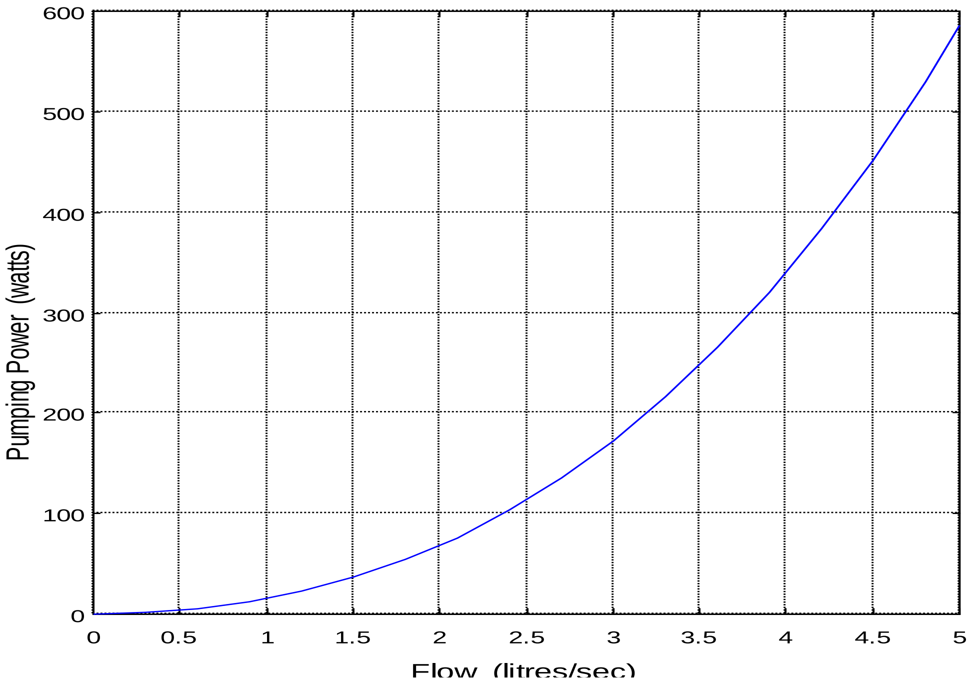


Figure 27: Borehole Pumping Power at Okotoks, Efficiency = 0.6

At first glance this would imply a coefficient of performance (COP) of over 100 and indicate the merits of extracting as much energy as possible from BTES. However, the losses from BTES are a very complex function of the time series temperature distribution and a simple calculation of COP can be misleading. The "effective COP" can only be done by system-level simulations under different scenarios and then comparing incremental results. For example, simulations could be done with a BTES discharge exit temperature lowered to 26°C. Then the simulations would be repeated with the same conditions except for lowering the discharge to 25°C.

The effective COP would then be:

(incremental energy recovered from BTES)/(incremental electrical energy)

These simulations were followed by more detailed ones based on a theoretical configuration twice the size of Okotoks. Results were generated up to the end of Year 4, using standardized hourly data sets for the Calgary area.

Considerable progress has been made in the cost-performance of evacuated tube collectors since the Okotoks project was initiated over five years ago and these were used for part of the simulations.

Reduction of losses in borehole storage systems

There are a number of options to reduce losses in a borehole seasonal storage system.
As discussed above, reducing the operating temperatures of the district loop will have benefits but does have the problem of increasing cost to the building owner, though some compensation should be possible.

The use of the borehole output as a preheater for the backup boiler was seen as a method of extracting considerable energy. The same method could be used to mix with high temperatures generated by the collectors if some radiation is available. Evacuated tube collectors have the potential to produce high temperature output even at low radiation levels. These collectors have been more expensive than flat plate units in the past but the technology is advancing quickly toward being price competitive.

A few of the options to potentially improve the energy recovery ratio of a relatively small borehole storage system are:

- Use arrays of evacuated tube collectors in series. This will generate high output temperature without excessive reduction of flow
- Increase the load on the district loop relative to the size of the borehole storage. This has the disadvantage of reducing the solar fraction but will result in the energy being extracted earlier in the heating season, with reduced time spent at high temperature.
- By using the borehole as a preheater to other energy sources it makes available more time for the borehole temperatures to be pulled down very close to the heating system return temperature.
- Improve stratification of the short-term storage. This enables the high temperature output of the evacuated tube collectors to be kept separate from the lower temperature output of the borehole storage.
- Implement automatic weather prediction to enable accurate calculation of the percent charge that should be retained in short-term storage. Contact was made with the federal weather service and discussions were held regarding work they have underway for internet-based weather forecasting but this is considered too complex to simulate at present.

System-Level Simulation Software

The following simulation modules were developed and are described in sequence:

- Complete Simulation System
- Boiler Model
- Solar Collectors
- District Loop
- Short Term Solar Storage
- Condition BTES Input

The Complete Simulation System can be seen in Figure 28 and shows how the components connect with each other. The source Selector includes the rules for when the BTES is Charging or Discharging and determines how the flows are combined in the mixing case. For the Reference Case, if the Short Term Thermal Storage (STTS) Charge Percentage is greater than the STTS Required Percentage, the BTES is being charged at the maximum flow rate. Otherwise the BTES is discharging unless the BTES Inner Temperature is less than the District Loop Return Temperature + 2°C or is less than the bottom of the Short Term Storage.

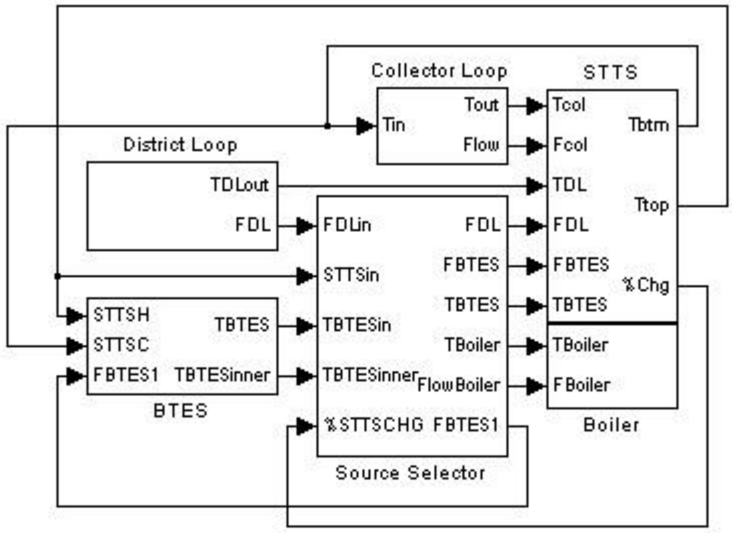


Figure 28: Complete Simulation System

The Boiler component works by calculating the amount of energy that is required to boost the flow from its input temperature to the District Loop Set Point temperature. The boiler does nothing if the temperature is already warm enough. It is shown in Figure 29.

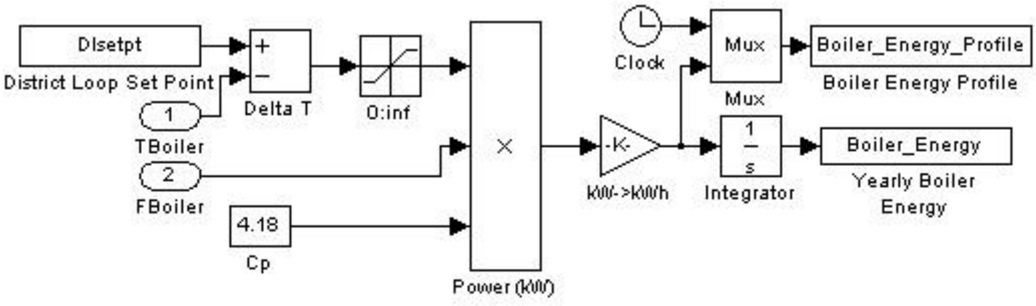


Figure 29: Boiler Model

The Solar Collector component, as seen in Figure 30, works by calculating the efficiency of the collector using the Solar Radiation, Incident Angle Modifier, Outdoor Temperature and the Input Temperature. The efficiency coefficient is then multiplied against the surface area of the collectors and the solar radiation. The water flow rate is varied to optimize the system. The pumps are off if the flow is less than 0.03l/s across a set of 10 collectors.

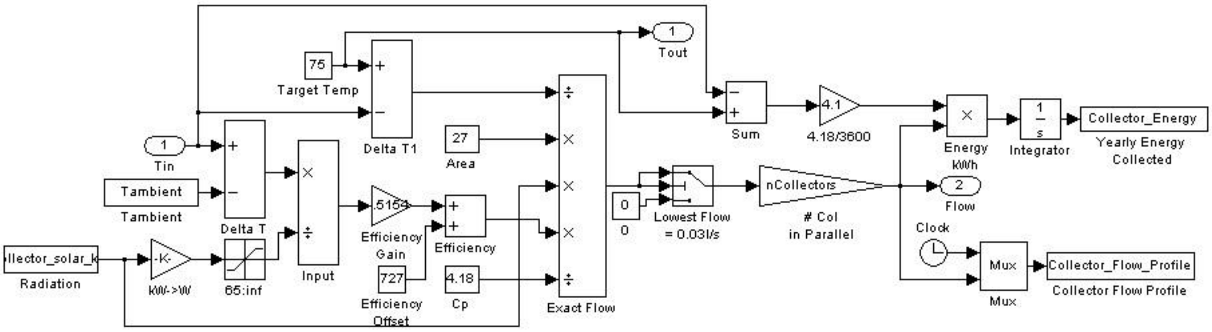


Figure 30: Solar Collectors

The District Loop Component in Figure 31 is built around the heating load for a single energy efficient house. The load is multiplied by the number of houses in the subdivision. A specific temperature is required by the housing network. This temperature is known as the District Loop Set Point and is a function of the outdoor temperature.

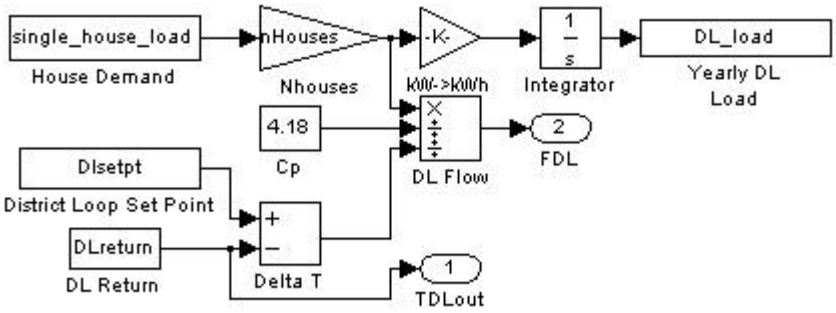


Figure 31: District Loop

The STTS is a one dimensional set of elements that have the same volume. The Temperatures of each element go through a mixing function that prevents any upper element being cooler than a lower one. The amount the storage is charged is determined by the STTS Charged subsystem. It works by varying the temperature required in the tank to be charged against the District Loop Set Point. This is shown in Figure 32.

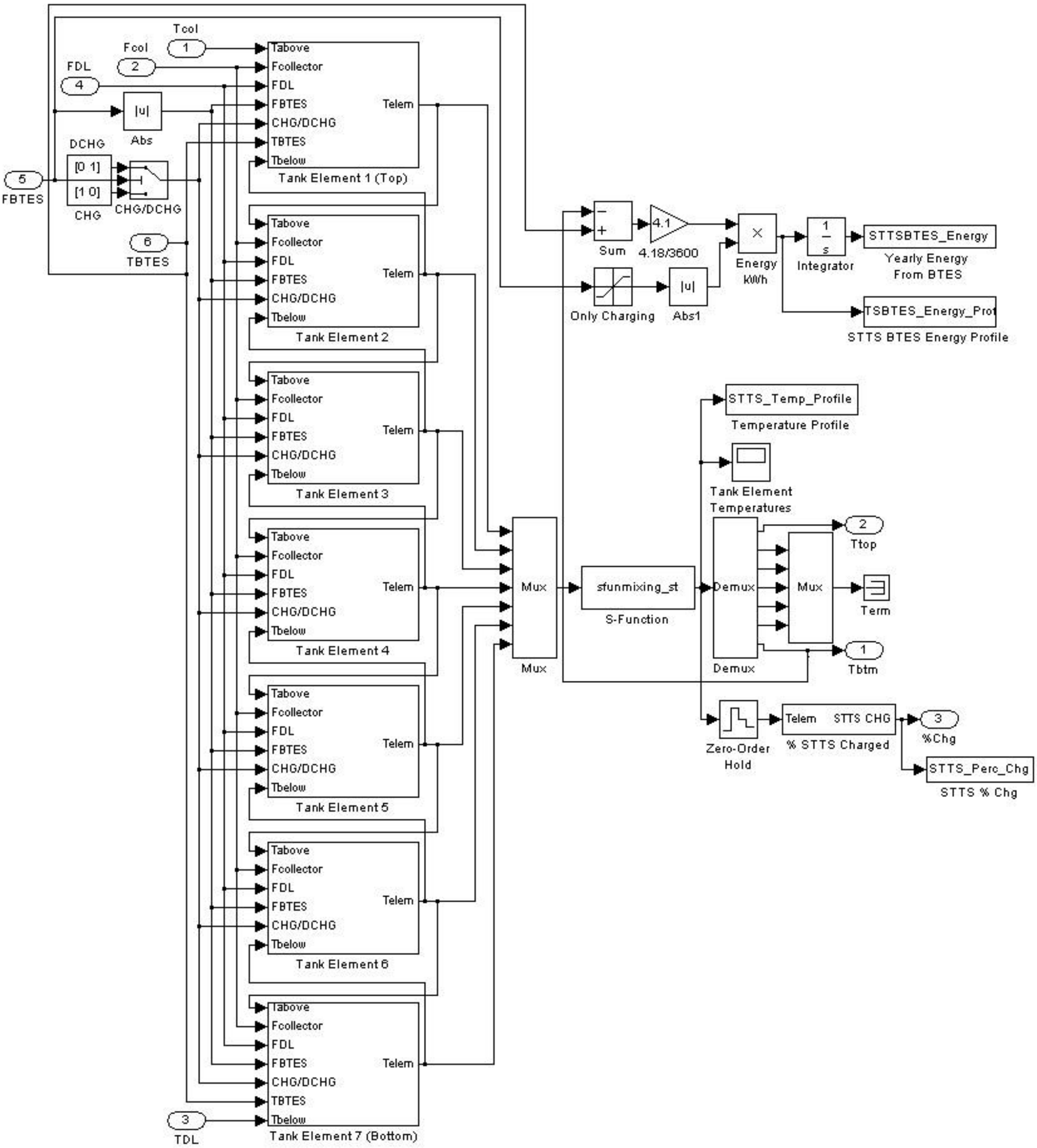


Figure 32: Short Term Thermal Storage

The subsystem described next in Figure 33 produces a set of inputs and outputs that allow a previously built BTES model to be used. The flow is separated into a magnitude and pump, charge and discharge flags. The output is determined by the direction of the flow. Energy Quantities entering and exiting the BTES are calculated here.

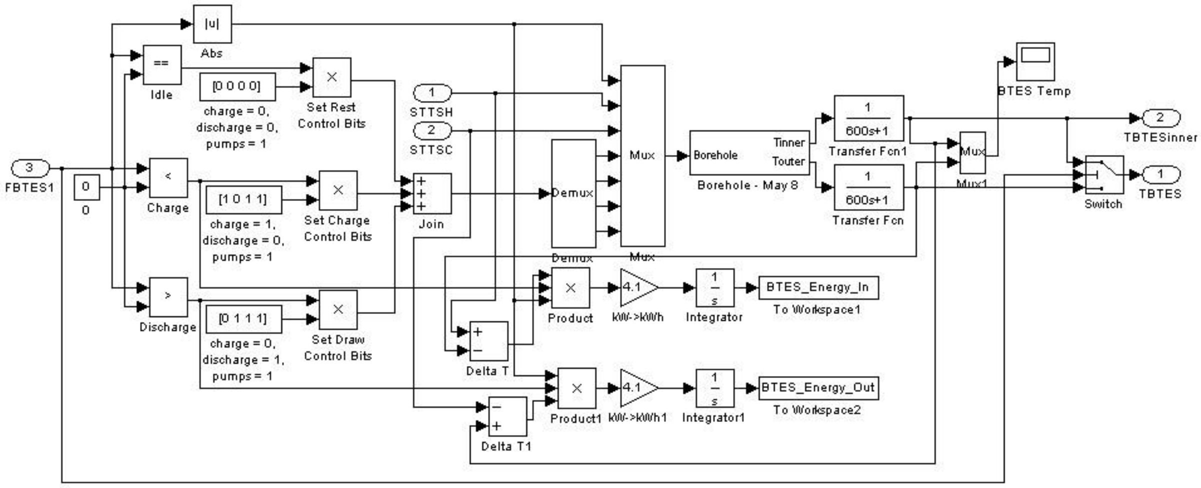


Figure 33: BTES Input Control

Case studies

Case studies were done for a theoretical system roughly twice the size of Okotoks, having the following parameters:

- Borehole storage – same horizontal cross section but tube length doubled to 70 metres
- Borehole flow increased to a maximum of 5.0 litres/sec, compared to 3 litres/sec at Okotoks
- Short-term storage volume doubled to 500 m^3
- Evacuated tube collectors (2.7 m^2 absorber area), with 80 arrays of 10 in series
- 260 low energy houses, heat loss factor of 109 watts/degree
- Three case studies with return temperature from heating system = constant 28, 24 and 20°C
- Control strategy similar to Okotoks

Simulation results for four years

Figure 34 shows the inlet and outlet temperatures at the borehole storage.

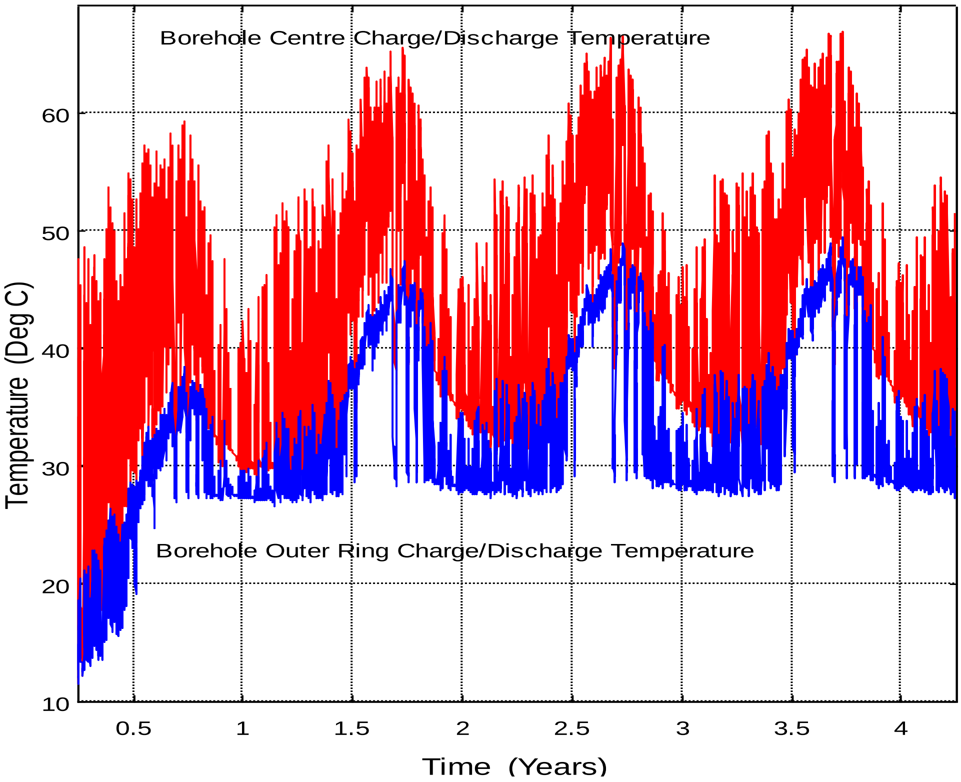


Figure 34: Simulation of BTES Inlet and Outlet Temperatures

The exit temperature from the borehole at the end of the summer charging period is somewhat lower than the measured data, approximately 50°C instead of 60°C. This is due to a larger load and a lower solar fraction during the heating seasons. The seasonal storage system appears to be near steady-state conditions after the first two years. This is somewhat deceptive, since the temperatures are at the boreholes. The earth thermal mass midway between boreholes and in the external earth outside of the outer borehole ring takes somewhat longer to reach final values.

Figure 35 shows the temperatures at three elements in the short-term storage, at the top and bottom plus one point in the middle. These are similar to the BTES temperatures.

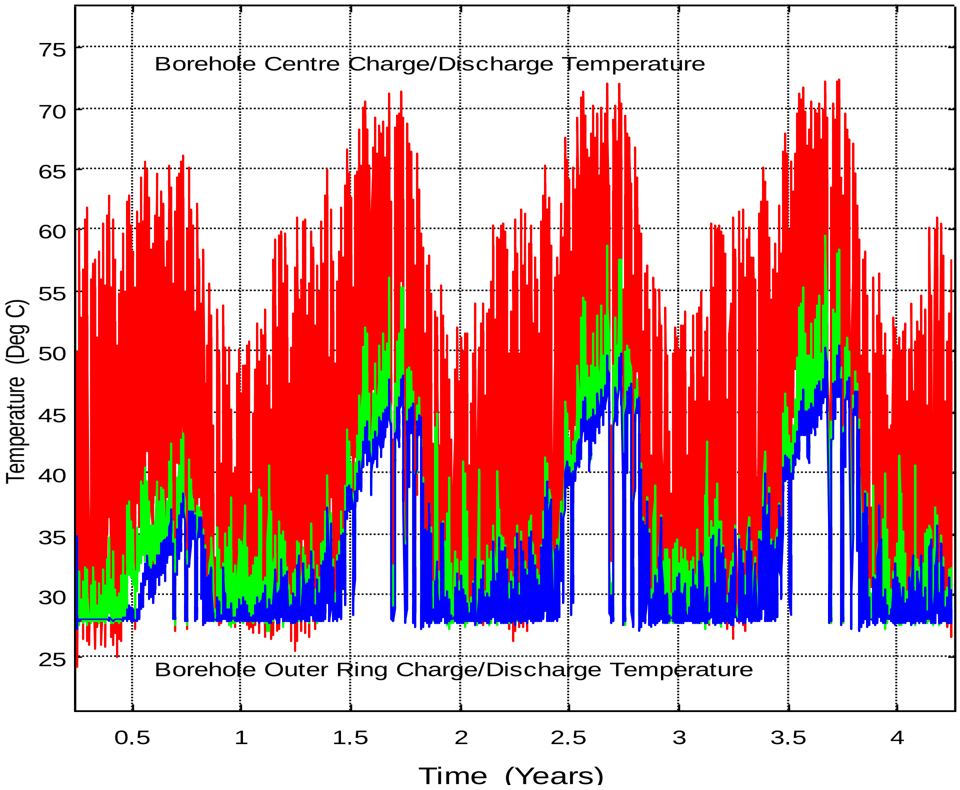


Figure 35: Simulation of STTS Element Temperatures

Figure 36 shows the power input to the system by the backup boiler. There is considerable boiler operation during the November to December period when solar collection is low.

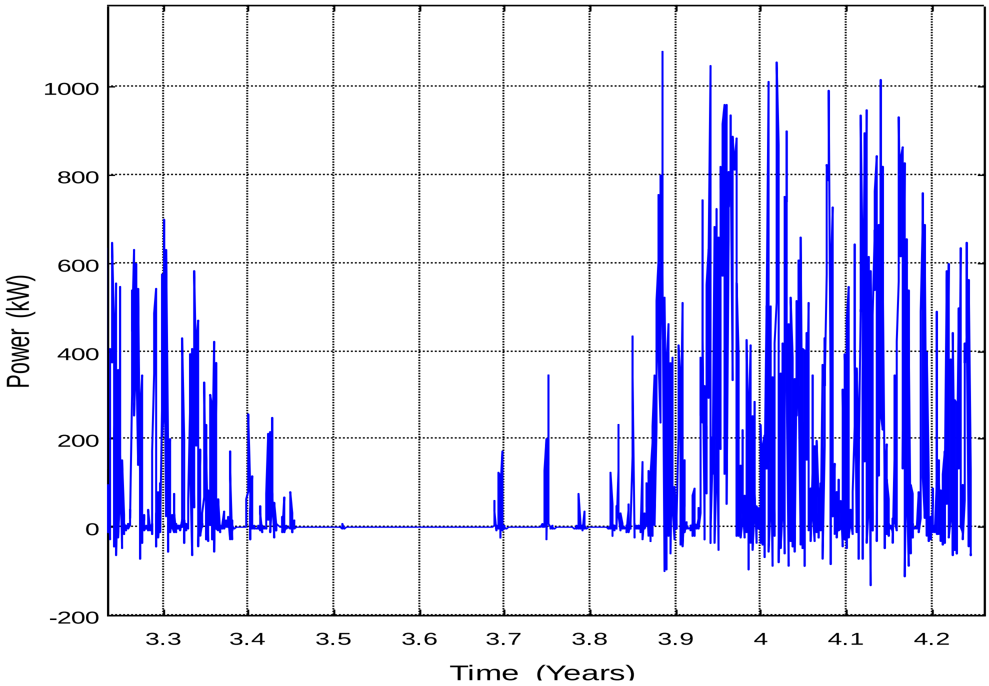


Figure 36: Simulation of Boiler Energy Profile

Figure 37 shows the percent charge held in the short-term storage. The reason for the 100% charge showing during the summer months is that it requires many hours to transfer the energy from a clear day of solar collection to the borehole storage. There are many periods when the short-term storage is not fully discharged before the next day's solar collection starts. The November to December period is seen to be a time of low solar collection.

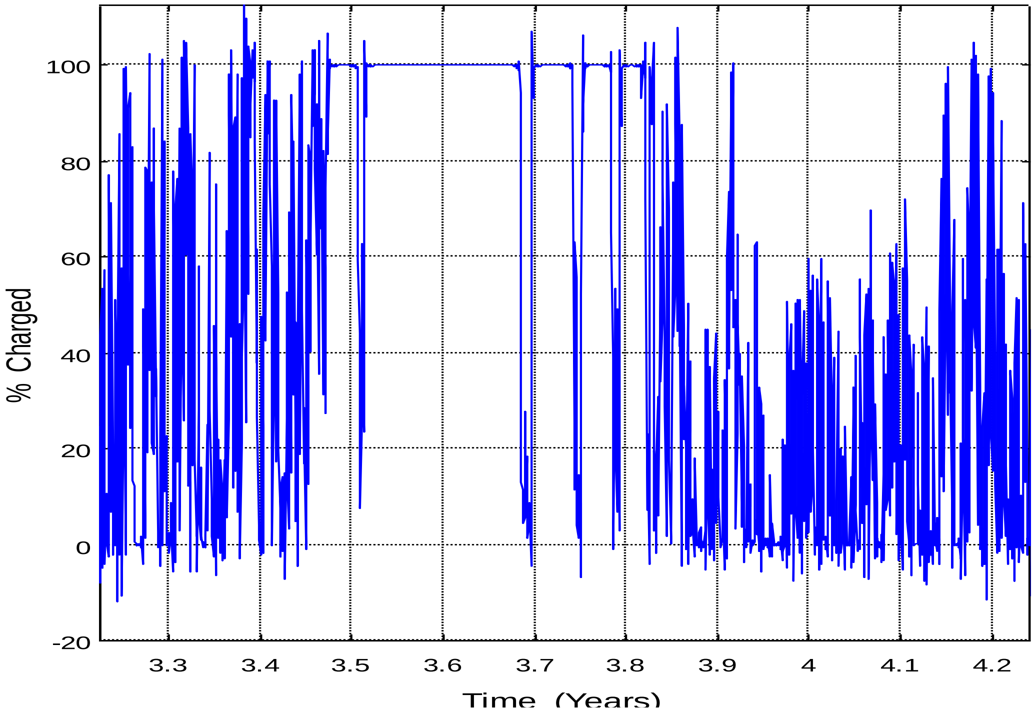


Figure 37: Simulation of STTS Percent Charged

Figure 38 shows the collector flow. The flow varies through the year so as to maintain a high exit temperature as the collector efficiency varies with ambient temperature and solar radiation level.

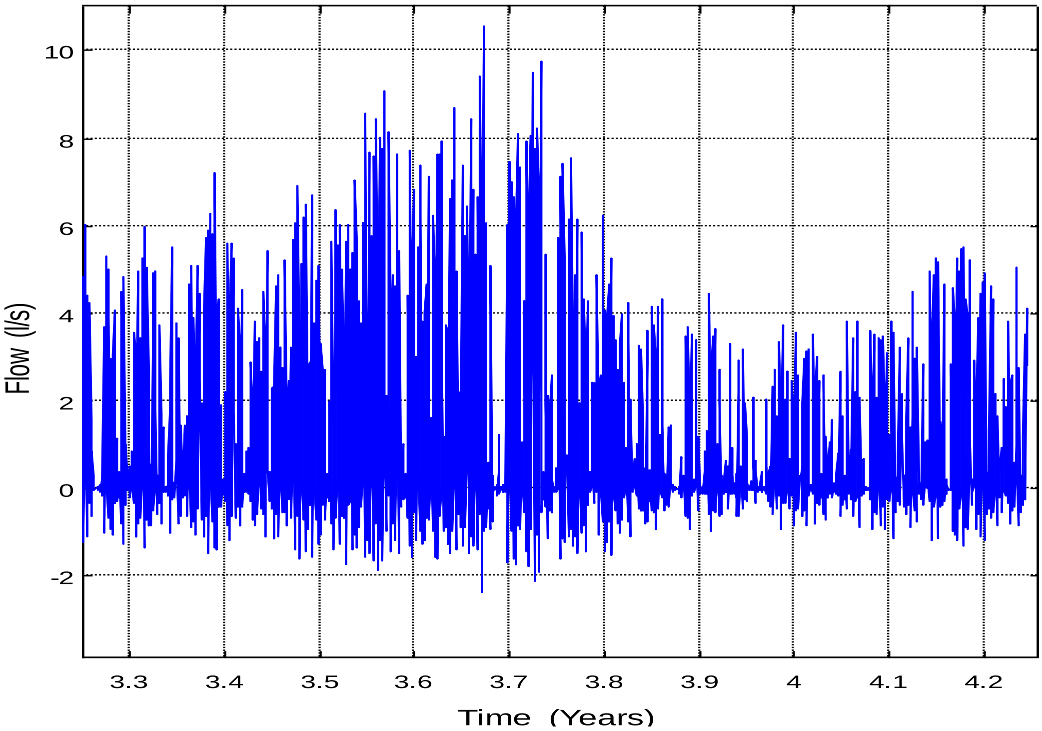


Figure 38: Simulation of Collector Flow Profile

The following Table 5 shows a summary of the four years of simulations.

Measurement	**Year**	**DL Return = 28C (kWh)**	**DL Return = 24C (kWh)**	**DL Return = 20C (kWh)**
Collector Energy	Year 1	1.918E+06	1.932E+06	1.939E+06
	Year 2	1.885E+06	1.902E+06	1.912E+06
	Year 3	1.877E+06	1.895E+06	1.906E+06
	Year 4	1.874E+06	1.893E+06	1.905E+06
District Loop Load	Year 1	2.138E+06	2.138E+06	2.138E+06
	Year 2	2.138E+06	2.138E+06	2.138E+06
	Year 3	2.138E+06	2.138E+06	2.138E+06
	Year 4	2.138E+06	2.138E+06	2.138E+06
Boiler Energy	Year 1	1.428E+06	1.254E+06	1.110E+06
	Year 2	1.092E+06	9.537E+05	8.483E+05
	Year 3	1.023E+06	8.954E+05	7.981E+05
	Year 4	1.004E+06	8.787E+05	7.830E+05
BTES Energy In	Year 1	1.533E+06	1.443E+06	1.396E+06
	Year 2	1.350E+06	1.356E+06	1.366E+06
	Year 3	1.329E+06	1.348E+06	1.363E+06
	Year 4	1.318E+06	1.342E+06	1.361E+06
BTES Energy Out	Year 1	2.919E+05	3.697E+05	4.506E+05
	Year 2	6.284E+05	7.012E+05	7.667E+05
	Year 3	7.095E+05	7.833E+05	8.409E+05
	Year 4	7.236E+05	7.949E+05	8.555E+05
BTES Return	Year 1	19.04%	25.62%	32.28%
	Year 2	46.55%	51.72%	56.11%
	Year 3	53.38%	58.11%	61.71%
	Year 4	54.90%	59.24%	62.85%
System Solar Fraction	Year 1	33.21%	41.35%	48.10%
	Year 2	48.91%	55.39%	60.32%
	Year 3	52.14%	58.12%	62.67%
	Year 4	53.06%	58.90%	63.37%

Table 5: Simulation Results for 260 Homes

There is considerable improvement in both the BTES energy return ratio and the solar fraction, with both at 63% after Year 4.

Figure 39 demonstrates the BTES energy recovery with reduced return temperatures.

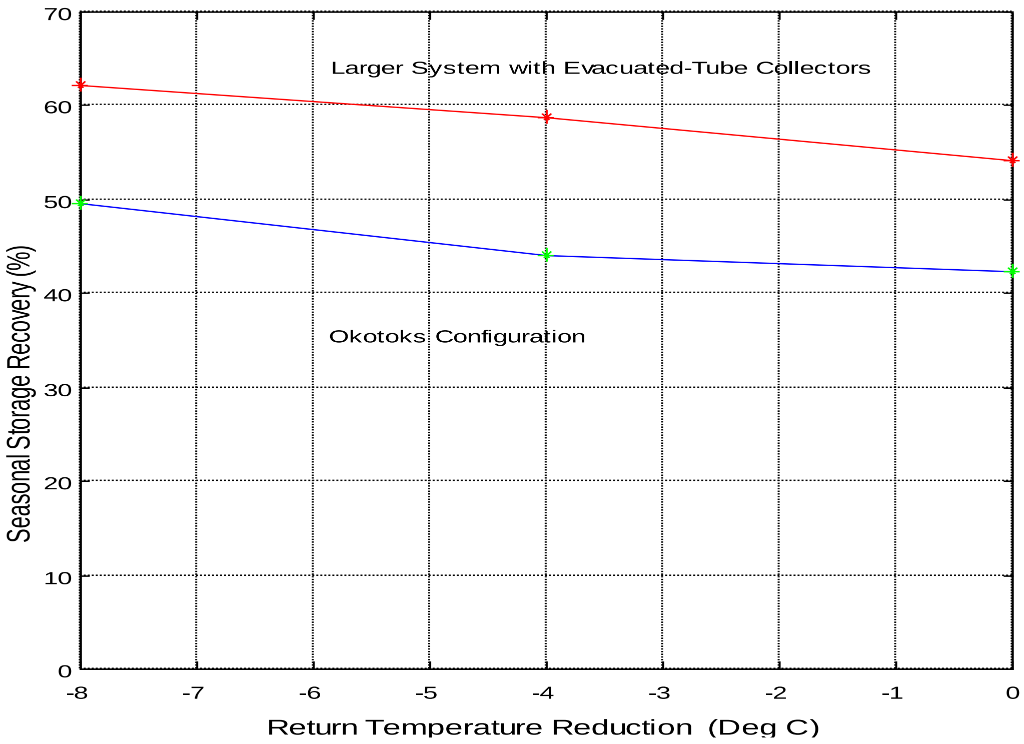


Figure 39: BTES Energy Recovery with Reduced Return Temperatures

Discussion of BTES energy return improvements

The comparison in Figure 39 is for two quite different systems. The system with higher performance is doubled in size. Other differences are below.

- Larger system load has been simulated (260 houses instead of 52)
- Uses different weather data - standard hourly data for modified system simulations compared with actual weather data
- Lower solar fraction; 53.1% vs. 79.6% for the reference case with 28°C return temperature
- The return temperatures differ slightly. In the modified system the return temperatures are fixed at 28, 24 and 20°C. In the Okotoks simulations the reference measurements are mainly around 28°C but vary upwards by one or two degrees.
- Collectors are evacuated tube rather that flat-plate

Figures 40 and 41 are an expansion of the borehole water flow temperature at the inner ring.

The first one shows that the temperature reaches 35°C at Year 4.075, which is about January 27. This is much earlier than the mid March when the Okotoks measured values reach the same temperature. This is due to the heavier load and lower solar fraction.

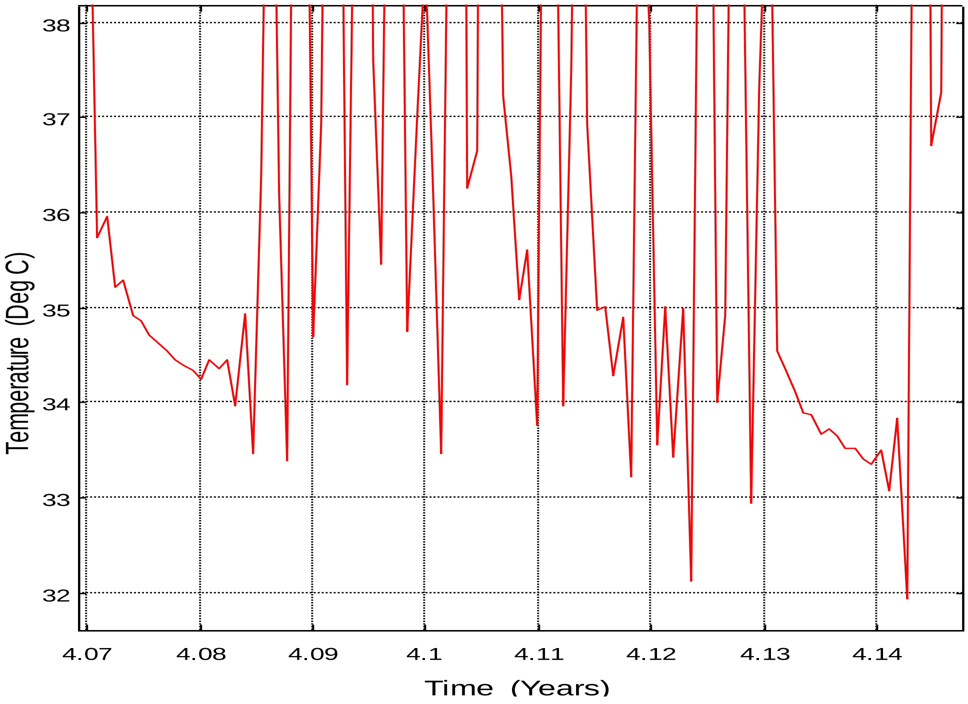


Figure 40: Expansion of BTES Charge and Discharge Temperatures

The second figure shows that a minimum value of 33.5°C is reached on February 20. The minimum temperature is within 5.5°C of the return temperature. After this the borehole begins to cycle between charge and discharge and maintains average values somewhat above 34°C. The high efficiencies of the evacuated tube collectors maintain this charge level in the BTES.

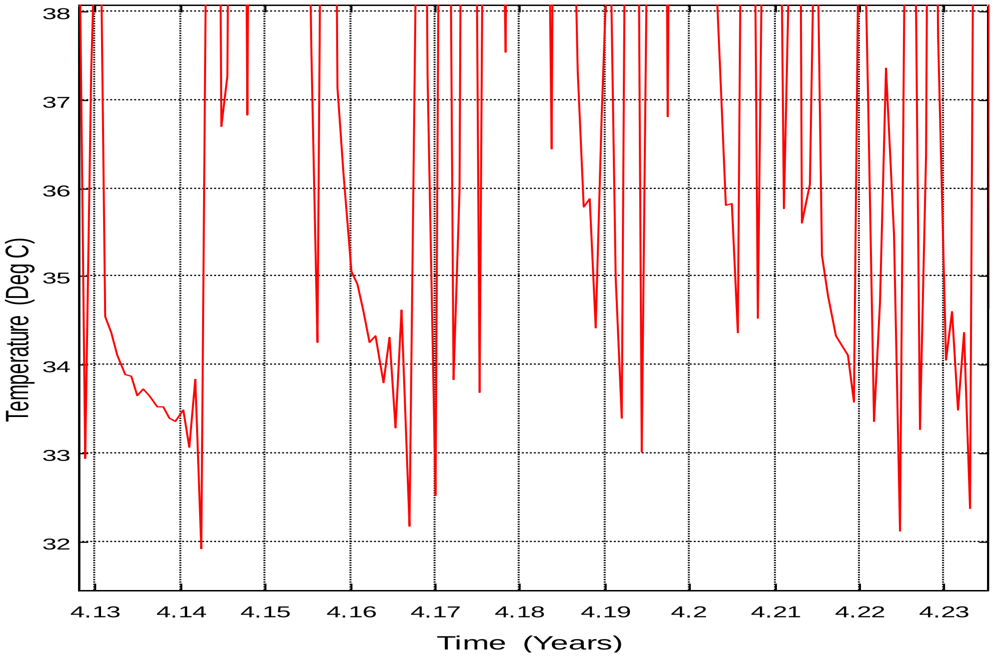


Figure 41: Expansion of BTES Charge and Discharge Temperatures

Conclusions

The Okotoks solar seasonal storage system has demonstrated a solar fraction of close to 80% after four years of operation. It will meet its 90% solar fraction target after five years.

Since borehole seasonal storage systems can only be insulated on the top surface the thermal losses are quite high. For a relatively small prototype borehole system such as the one at Okotoks, simulations project about 50% losses after the earth thermal masses have stabilized.

Extensive operational experience has been gained on the Okotoks system and a number of improvements have been made to both the control systems and the hardware subsystems. By analyzing the measured data for four years of operation it was established that the control systems that transfer energy between the short-term storage and the borehole storage are working at a high level of efficiency. In the present system configuration, with its high solar factor, there is very limited potential for improvements in this area.

Some potential improvements to decrease the borehole storages losses have been formulated and simulated. These involve:

- high performance space heating systems with lower return temperatures
- increased load, resulting in lower solar fraction of 53.1% at a return temperature of 28°C
- utilization of high performance evacuated tube array collectors, now almost price-competitive with flat plate collectors
- borehole pipe length doubled to 70 metres

A water-to-aircoil space heating system was designed and a prototype constructed. By injecting cool ventilation air from a heat recovery ventilator into the air coil in counterflow mode it was possible to generate return temperatures within one degree of room air temperature, or slightly below room temperature, depending on load and outdoor temperature.

The reduction of solar fraction will result in the borehole storage being depleted earlier in the heating season. Even when the borehole delivery temperature is below that required in the district supply it can be used as a preheater for the backup boiler, reducing the consumption of fossil fuel. The net result is for the borehole storage average temperature to be lowered, reducing the losses.

With these changes the seasonal storage energy recovery factor went from 42.4% (Okotoks measured) to 54.1% (simulations on modified system). By lowering the return temperature to 20°C the losses in the borehole were reduced further and a recovery factor of 62.2% was obtained by simulation.

It should be noted that even though a lower solar fraction will result in improved cost/performance in the borehole storage subsystem, if the cost of backup energy is high, this can compensate for the larger losses of a system with high solar fraction. Similarly, when the cost of backup energy is low, reducing the solar fraction may be somewhat worthwhile.

With larger borehole systems the losses will be inherently lower. With a larger number of boreholes in series there are possibilities of further improvements in performance by more elaborate flow paths. Further study is recommended in this area.

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