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Interaction between District Energy and Future Buildings that have Storage and Intermittent Surplus Energy

International Energy Agency

IEA District Heating and Cooling

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

Interaction between District Energy and Future Buildings that have Storage and Intermittent Surplus Energy

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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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Executive Summary

Interaction between district energy and future buildings

A significant fraction of future buildings will have heat loss factors below half of that of present construction. They will maximize passive solar gain and often will have active solar system with associated thermal storage. Their low-energy load corresponds to low-energy density and the district energy (DE) industry is concerned that the capital cost of connecting them will not be economic.

By taking advantage of the unique characteristics of low-energy buildings it is possible to design configurations that will be economically viable in, at least, some limited scenarios. The success of these designs is conditional on all parts of the future subdivision being optimized at the overall system level.

Various methods of low cost load shedding will enable enhanced utilization of waste heat from cogeneration plants. These take advantage of the thermal mass of the building together with its very long cool-down time constant.

Measurements conducted on a low-energy passive solar house indicated:

- A temperature drops of 0.33°C per hour at -20°C, which is one-third the rate of modern standard construction.

- A high ratio of domestic hot water (DHW) energy usage compared with that of space heat. Using weather data for Calgary, 4,000 kWh/year are for DHW out of a total energy usage of 12,000 kWh/year. This indicates the load-shedding and off-peak charging potential by use of DHW storage tanks.

Various simulation packages were developed partially based on measured data from the Drake Landing Solar Community in the Town of Okotoks, near Calgary, Alberta in Canada. Detailed models were developed for a generic low-energy house, solar system and borehole seasonal storage. Cases were run using weather data for Okotoks, Stockholm and London. They utilize peak load shedding by small drops in room temperature, such as 0.7°C, to avoid startups of the backup boiler, charging DHW buffer tanks only when waste heat is available and the use of night setback (NSB). In some configurations up to 45% of the cogeneration energy being dumped could provide energy for additional loads when compared with the basic reference house that maintains a constant temperature, simulated at the same backup boiler ratio and with no DHW storage. This, together with lot sizes of 16 meters width in the new subdivision, brings the cost of energy using natural gas to the $0.051 to $0.067/kWh range, depending on the backup boiler ratio to waste heat usage.

Simulated studies of high temperature active solar systems with optional seasonal storage were done in a future subdivision of 240 low-energy houses with only a gas-fired boiler. Some houses would have privately owned active solar systems that could sell surplus energy to the distribution system. A high-temperature evacuated-tube solar system was designed with ten collectors. It was assumed that active solar could be competitive if the owner already had a five collector system to meet the building's DHW load and part of its space heating load. The extra five collectors and additional storage were added to sell energy to the DE system and economic analysis was done using only the incremental cost. The control logic was to always retain an amount of energy in storage equal to the previous day's requirement.

In order to optimize solar and seasonal storage applications a highly efficient air handler and storage system was prototyped. The forced-air heating system was designed to have a low return temperature by using ventilation air preheat and a counterflow layout. On testing, the return temperature was found to be within two degrees of room temperature. A multi-tank, highly stratified storage was also constructed and tested.

If there were less than 16 solar systems all energy surplus above local requirements could be utilized directly by the remaining houses. In this example, the system would recover its capital costs in a 20 year life at about $0.040 to $0.052/kWh using Okotoks weather, depending on whether the branch line needed to be added. Above 16 systems there is a gradual drop in the percentage of surplus energy that the network could absorb, especially in the summer.

Simulations also indicate that if borehole seasonal storage is included, the surplus solar energy from all 120 systems, servicing 240 houses, could be sold in the above subdivision. This results in 978 MWh delivered renewable energy after both borehole and line losses are accounted for. The cost is considerably increased by the relatively small borehole storage, two times larger than Okotoks. The break-even price is estimated to be about $0.179/kWh for a 20 year life and $0.151 kWh for 30 year life in Okotoks.

Introduction

Future buildings will have low-energy consumption due to reduced heat loss, heat recovery and renewable energy. By improving cost/performance they will be built in large numbers, mixed with conventional buildings or in complete subdivisions. The result is similar to low-density housing and can have a negative impact on district energy (DE). Some passive solar buildings, with large windows, may present high loads on cold nights following days of low solar gain, although average energy consumption is low.

The challenge is: ***"How can district energy contribute to the advancement of low-energy building designs and DE integration for a net reduction in energy use and greenhouse gas emissions?"***

The objective of this study is threefold. It is to develop DE system-level design guidelines and methodologies for cost-effective integration of low-energy buildings by merging benefits of centralized and decentralized energy generation and storage systems. In addition, to develop methodologies to estimate the optimum configurations of low-energy buildings to maintain utility cost effectiveness in areas remote from a central DE plant. And, finally, using experimental work to evaluate control system interactions and establish guidelines for efficient system-level operation.

Many innovative experimental low-energy buildings have been constructed in different countries in recent years. Future houses will incorporate the best of these methods and some have been included in this study. Innovation is always risky until the cost, performance and long-term reliability are proven.

Background

The common perception is that low-energy buildings and DE systems are incompatible. However, strategies can be developed that both enhance the viability of low-energy building designs and demonstrate the added value, in economic and environment terms, of incorporating such buildings into a DE network. There are a number of reasons why DE connections to loads that may currently appear non-economic will become an area of activity in the future. These relate to future cost and availability of fossil fuels, new technologies and increased concern over the environment and rising carbon dioxide levels. Because a DE system encompasses many different subsystems, there is need for system-level analysis and design using the most recent research results from a number of other Implementing Agreements.

The overall strategies to illustrate the benefits of connection to DE are:

Economic

- To offer the building owner a net benefit in capital and operating costs, realizing that efficient connection to the DE system will likely add cost and complexity to the building mechanical systems.

Energy/Environmental

- To lower the amounts of fossil fuel consumed and decrease the carbon dioxide emissions by providing a means of buying and selling low or no-greenhouse gas energy into the network.

While making the case for the potential customer or building owner, it is also necessary to make a good case for the economic and environmental ***benefits to the DE system*** **o**f having such customers.

Problems of DE expansion

Many DE networks will reach capacity limits and have difficulty supplying peak loads to outlying regions where there is new residential construction but it is not practical to add a large co-generation power plant. This situation may present economic benefits of building-level demand side management (DSM) and distributed generation.

Demand side management and in-building storage

Future buildings will often have active storage systems plus long cool-down time constants, up to 100 hours. These attributes will support DSM, with load shedding and off-peak energy inputs. Work in Annexes VI and VII has indicated the general benefits of these features[1 2], including two-way communication to the heat meter with control inputs. Previous IEA work has usually involved large loads but as long ago as in 1982 the Tennessee Valley Authority, USA, demonstrated load shedding on DHW tanks with a radio control link at a cost of $75 per building[3]. By using storage and avoiding large peak loads, connection to the DE system can be done with much smaller pipe than usual, for additional cost savings. It is assumed that off-peak charging of storage will usually be controlled by the owner. Ideally, the utility would post the current cost of energy on the internet and this would be used for charging strategy. These low-energy buildings usually have very efficient heating systems with low return temperature and this enhances DSM.

Distributed generation

Future buildings will often have integrated energy sources that will have surplus power part of the time. Co-operation between the building owner and the utility to utilize this will benefit both parties. In Annex VII comparison was done between central and distributed power plants[4] and the conclusion was that centralized power plants have an advantage due to economics of scale. This may not be true in future buildings. If the owner has already decided to install local generation to service part of the local requirement there will be interest in selling surplus thermal energy to the utility if technical and economic barriers can be overcome. This project will develop system-level design guidelines and methodologies for competitive payback.

The measurement of bi-directional thermal energy transfer is somewhat more complex than is the case for electrical energy due to fluctuating temperature sources. To cope with this, the utility can set some minimum standard, such as 65 ºC, and the heat meters would be certified to not record any reverse energy flow below this temperature.

Research in low-energy buildings

The characteristics of low-energy buildings have been studied for a number of years[5 6 7]. The emphasis in these programs has been on innovative features, leading to energy consumption well below the level possible with simple application of heavy insulation. A variety of active and passive techniques are used in low-energy buildings. Some of these will improve the cost-effectiveness of the connection to DE.

DE and future building interactions

Assuming future buildings with a variety of operating and construction characteristics there is a broad spectrum of DE configurations possible.

The simplest one to implement is DSM with building owners encouraged, with financial incentives, to implement control systems for load shedding. They would be compensated for load shedding and supplied with a reduced rate for off-peak energy from the DE to charge their storage.

The other extreme of complexity is for the utility to install large-scale storage, ideally of a seasonal nature, near the site of new housing construction. This approach may not be economic at present, but is worth analysis as it has the best potential for minimizing emissions of greenhouse gasses. Surplus energy from all economic sources (private or utility) would be used to charge this storage. Incentive programs can be implemented to pay a premium for purchase of renewable energy, encouraging innovation in the private sector. Future houses that are planning to install active solar are to be encouraged to make use of high performance collectors that can deliver temperatures above 65ºC for maximum benefit to the utility. During periods of very little solar availability, the building owner is able to purchase energy from the utility, ideally supplied from seasonal storage and when excess solar energy is available, sell the surplus to the DE either to charge seasonal storage or to save fossil fuel.

Seasonal storage systems have been constructed in a number of countries. Canada has constructed a borehole seasonal storage system in the Drake Landing Solar Community located in the Town of Okotoks, Alberta[8] combined with short-term storage, supplied by a centralized solar system. It will supply 90% of space heating to 52 houses. The challenge is to establish whether privately funded small-scale generation, preferably of a renewable nature, can contribute to moving large scale or seasonal storage systems closer to economic viability.

Optimization of a Low-Energy Subdivision Layout

In order to compensate for the low-energy consumption in a future subdivision the layout must be as efficient as possible. If the number of buildings is small the use of low pressure and low temperature distribution systems based on plastic pipe will be practical. By isolating the new system from older ones with a heat exchanger maximum flexibility can be achieved.

Since the Drake Landing Solar Community project located in the Town of Okotoks, Alberta was an integrated design, it was possible to obtain an optimum layout as can be seen in Figure 1[9]. The streets are located in an east-west orientation and the lots are narrow to minimize pipe length. Future trends in city planning will evolve toward this layout as a standard approach.

Figure 1: Drake Landing Solar Community Housing Layout in Okotoks, Alberta

General approach and definition of case studies

Okotoks is a prototype system that is supplying data for feasibility studies on a much larger future system. Experience gained on performance analysis of this project acts as background for this report. Higher heat density can be achieved by high-rise residential buildings and trends in this direction will continue, especially as the average age of the population increases. However there is clear evidence that if possible younger families will prefer either a detached house or a row housing unit over living in an apartment building, even if a small building lot is used. In Canada about 55% of new residential construction is detached[10], with lot sizes as small as 12 by 30 metres becoming common due to the high cost of land.

Future subdivision layout for case studies

For the configuration used in the simulation case studies, the DE supply line is buried in the back yards of the houses, on an easement that guarantees access for a small excavator if repair is required. Included are a number of optional configurations to increase the ability to make use of waste heat from the cogeneration plant. This can be seen in Figure 2.

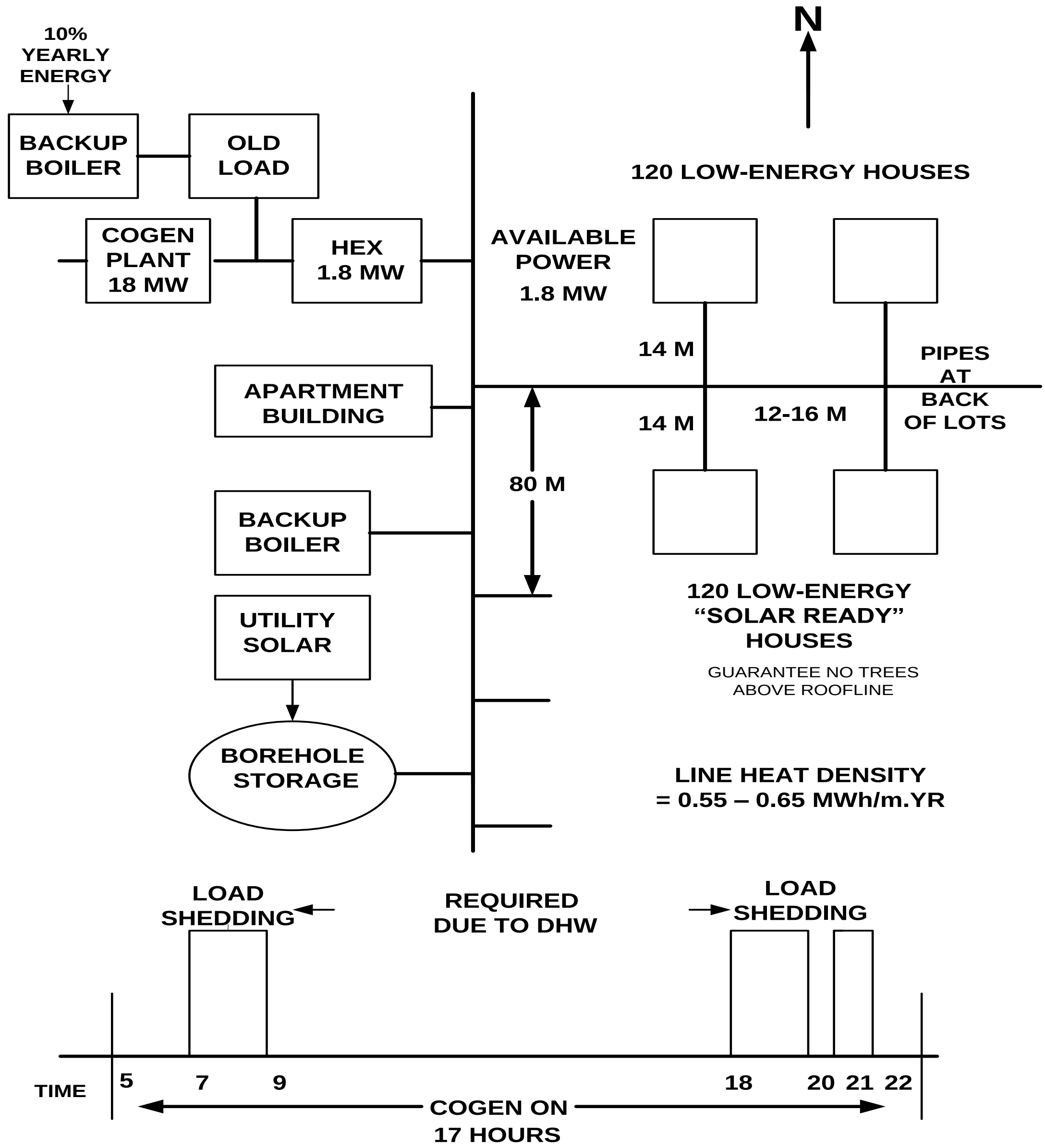

Figure 2: Future Subdivision Layout for Case Studies

Primary assumptions for the case studies:

- The cogeneration plant supplies 90% of yearly energy in the old system and operates on the time cycle as shown above[11].
- At low load the availability of thermal energy at the end of the distribution network is restricted to 10% of peak capacity by pipe size limitation
- An isolating heat exchanger is used to allow the low-energy houses to operate at low values of pressure and supply temperature.

The layout was optimized for the future possibility of adding solar collectors and seasonal storage. Houses south of the supply line would be defined as "solar-ready", by guaranteeing that no trees on the street right-of-way will be allowed to grow past the roofline of the houses. These houses would be constructed with insulated pipes going to rain-proof roof penetrations and having control wires already in place, considerably lowering the cost of later installing a solar system. If a decision is made at a future time to install a simple solar DHW system the opportunity is available to expand the system capacity to supply extra thermal energy, some of which could be sold to the DE utility. This expansion would require high temperature solar collectors, possibly evacuated units, since only energy above 65°C would be accepted by the DE utility.

The reference configuration has no storage and uses a once-through DHW (DHW) heat exchanger system plus a forced-air heating system. As discussed later, to meet the ventilation and space heating requirements of a low-energy house, the most economical approach appears to be use of a water-to-air coil. A prototype air-coil system has demonstrated water return temperatures close to room temperature at the required power level.

Preliminary assessment of low-energy density economics

The initial feasibility study to establish if future, low-energy residential buildings can be connected to a DE system, is best done for a cold climate location. If this location has marginal economic viability the situation will be less so in warmer climates, since much of the cost is in the distribution network infrastructure. All economic studies were done for the Canadian conditions.

Three locations were examined, Okotoks, Stockholm, and London. Okotoks has the coldest climate, at 5,033 heating degree-days, base 18°C. The design temperature is -32°C. Considerable experience has been gained at Okotoks related to the solar seasonal storage project at this location, which is in its fourth year of operation. Since 91 channels of high resolution data are available at ten minute intervals during the 3.75 years of monitoring from the energy systems on the Okotoks project, this location was used for the primary case study.

The case studies are based on a subdivision of 240 detached houses with exceptionally low space heating demand. The reference for these buildings is a house built by Rob Dumont in Saskatoon, Saskatchewan, one of the coldest parts of Canada, with a design temperature of -36°C. When this house was built in 1992 it was considered the most energy efficient one in Canada in terms of heat loss per unit floor area. The Okotoks climate is slightly milder than Saskatoon with a design temperature of -32°C instead of -36°C. This building, if located in Okotoks, would have a peak heating demand of 5.6 kW and, including DHW, will have a yearly energy consumption of approximately 12,000 kWh.

Since this house has all input energy from electric sources it can be accurately monitored. It was fully instrumented and the performance is described later. A description of the construction methods used is given in Appendix A.

Depending on the building lot size the line heat density for houses similar to the Dumont residence is in the range of 0.55 to 0.65 MWh/m,yr. This is slightly better than the lowest values that are considered economically viable for connection to a DE system. Under certain circumstances, the practical lower limit of line heat density in Europe is estimated to be 0.3 MWh/m,yr if the design is done in the most efficient manner[12].

Different thermal energy sources from the DE system

In practice the thermal energy supplied from the DE system varies from "free heat" in the form of heat rejected by a cogeneration plant or from sources such as incineration to heat from a peaking boiler with 85% efficiency, fired by a fossil fuel such as natural gas. The ratio of these two sources is a function of load on the system and the design characteristics.

The boundaries of economic performance can be identified by case studies at the two extremes where all energy is supplied to the new subdivision from the first or second source.

The following spreadsheet does a cost breakdown for the Okotoks location. The spreadsheet gives the parameters used in the calculations. The major life-cycle cost in a DE system is in the distribution infrastructure, with a smaller component in the building substation and heat meter. In a reference system based on a typical natural gas heating system the distribution network is lower cost but the cost for the building heat exchange systems is higher than that of a DE connection, especially to supply DHW. There are various ways in which the assumptions regarding avoided costs can be applied.

The cost of energy at Okotoks delivered to the building:

- For all "free energy" cost = 5.1 cents /kWh
- For all energy from natural gas cost = 6.7 cents/kWh

For comparison, the equivalent cost of using heat for individual gas furnaces is $0.041. In all cases the cost of the heating system inside the homes, including the DE substation, are considered part of the house purchase.

Cost Breakdown for the energy costs in Canada for 240 future low-energy houses, spaced 16 metres apart, is found in the following Tables 1-5. Based on the Okotoks project the estimated electrical energy for pumps is less than 3%. Since it is approximately the same for all cases and is converted into heat it has not been included.

IEA Economic Project Summary Results 20 yr lifetime

Case description	Base case, 100% gas boiler	
Main results:		
Total capital cost 240 home community	$1,759,868	
Total capital cost per home	$7,333	
Cost of heat	**$0.067**	**/kWh**
Main dimensions:		
Solar collector area per home	0	m^2
Energy centre heat exchanger capacity	11.0	l/s
Distribution pump power capacity	5.0	kW
Number of distribution pumps	2	-
Total peak/back-up boiler capacity (excl. spares)	1,700	kW
Spare peak/back-up boiler capacity	625	kW
Primary buried distribution pipe type	Single PEX	
Primary buried distribution pipe diameter 80 homes	63	mm (DN)
Total primary buried distribution pipe length	2,120	m
Secondary buried distribution pipe type	Twin PEX	
Secondary buried distribution pipe diameter	16	mm (DN)
Total secondary buried distribution pipe length	3,360	m

Table 1: Description of Cost Items for a 240 Low-Energy House Project

Capital cost summary - 240 homes						
	Purchased equipment cost in $	Fraction total purchased equipment cost	Installation cost in $	Fraction total installation cost	Total installed cost in $	Fraction total installed cost
Solar collectors	0	0.0%	0	0.0%	0	0.0%
Buried piping remote collectors to energy centre	0	0.0%	0	0.0%	0	0.0%
Energy centre (heat exchanger, pumps, boilers)	89,539	23.4%	139,539	12.9%	229,078	15.6%
Heat exchangers	15,499	4.1%				
Pumps	6,755	1.8%				
Peak/back up boilers	67,285	17.6%				
Buried piping energy centre to homes	292,545	76.6%	944,933	87.1%	1,237,478	84.4%
Primary distribution piping	220,352	57.7%				
Secondary distribution piping	72,193	18.9%				
Heat users	0	0.0%	0	0.0%	0	0.0%
(Paid by Utility) Substations	0	0.0%				
Hot water tanks	0	0.0%				
DHW tanks	0	0.0%				
Pumps	0	0.0%				
Buried piping energy centre to seasonal storage	0	0.0%	0	0.0%	0	0.0%
Seasonal storage	0	0.0%	0	0.0%	0	0.0%
Totals:	382,084	100.0%	1,084,472	100.0%	1,466,556	100.0%
Engineering, supervision & commissioning	146,656					
Contingency	146,656					
Grand total investment cost	$1,759,868					

Table 2: Capital Costs for a 240 Low-Energy House Project

Economic assumptions cash-flow analysis (per home where applicable):		
Annual heat consumption space heating	8,209	kWh (heated air)
Annual heat consumption DHW	3,997	kWh (heated water)
Natural gas consumption	16,189	kWh (NG heating value)
Natural gas cost in year 0	$0.010	/kWh (NG heating value)
Annual real natural gas cost escalation	2.0%	
Annual O&M expenses as fraction of total capital cost	0.5%	
Lump sum payment by owner/government grant in year 0	$0	
Real discount rate (corrected for inflation)	5.0%	
Project lifetime	20	years
Carbon tax	$0	/tonne CO_{2eq}

Table 3: Economic Assumptions: Cash Flow Analysis (per home, where applicable)

Cash flows year 1 (for 240 homes):	
Carbon taxes paid	$0
Electricity and natural gas expenses	$39,632
O&M expenses	$8,799
Revenues	$196,654
Net cash flow to utility	$148,223

Table 4: Cash Flow in Year 1 for 240 Homes

Maximizing the sale of waste heat from the cogeneration plant

The thermal load on the DE system is highly dynamic during the heating season, due to rapid changes in solar radiation, DHW and other loads. By careful system design and cooperation between the low-energy building owners and the DE system a considerable part of the peak load supplied by fossil fuel can be eliminated and shifted to the waste heat from the cogeneration plant.

The method of analysis used to compare the effectiveness of different types of load shedding is to increase the total load of the new subdivision in steps for each simulation case study. This will result in an increase in the percentage of energy supplied by the backup boiler. The simulations are done up to some level of local boiler energy such as 30%.

As various levels of load shedding are applied the quantity of waste heat that can be made available to the new houses will increase. This generates income for the utility that was not previously available. In the simulations the extra energy could be consumed by adding houses but that requires additional distribution pipes at each stage of the analysis, complicating the simulations. In practice the layout of the new subdivision is likely to be fixed at a certain number of houses due to the land available. Since the main objective is to illustrate that load shedding has the potential to increase the sale of waste heat it is useful to keep the analysis to a single distribution network. The analysis can be simplified by assuming that the additional energy available is consumed in a single apartment building that is increased in size as the simulations indicate more energy is available. In effect a single parallel load is assumed to absorb any low cost energy made available by design changes and more sophisticated control strategy. The apartment building has the potential to have larger and more efficient energy storage but the question of the economics of low-energy houses can best be answered by assuming that the transient and steady-state heat transfer characteristics of the apartment building are the same on a per unit basis as the detached low-energy houses.

Description of simulation case studies developed in conjunction with the Experts Group

1. Reference case – low-energy buildings, similar to Dumont house, wood frame construction with small addition to thermal mass. Operated with a constant indoor temperature and standard substation with a one pass DHW heat exchanger.
2. Same as #1 with utility-controlled shedding of space heat, down to 0.7 ° below set point.
3. Same as #2 with doubling of building thermal mass.
4. Same as #3 with a DHW, heat exchanger and thermostatic flow valve to maintain low return temperature to DE system.
5. Buildings with active thermal storage, ranging from 1000 - 2000 litres, supplying both space heating, DHW, and storage for solar collectors.
6. Same as #5 with active solar system and bidirectional heat metering for sale of surplus energy to the DE system.
7. Same as #6 with borehole seasonal storage system to store solar energy

Case 2 is an almost zero cost implementation, since it only requires two-way communication to a heat meter with control capability. This was examined in the study by Drysdale[2].

The extra thermal mass for case 3 will often already be in place for passive solar houses that are designed to minimize overheating due to excessive solar gain.

Case 4 makes use of standard components and will have reasonable economic return to the building owner if the utility is heavily loaded and charges higher peak rates. As in case 2 the building owner needs to be informed of the variable rates.

The cases 5 to 7 became progressively more complex and expensive and need to be examined carefully to establish cost-performance characteristics.

Load shedding

Load shedding can be necessary to:

- off-load a distribution network that is temporarily at full capacity
- time-shift loads to enable use of lower cost thermal energy

It is assumed that most utilities will make use of peaking boilers during a significant part of the heating season, unless they have a very large incineration component. Regardless of the fuel used in peaking boilers there will be an extra cost. If a utility has a consistent policy on premium rates for peak thermal loads and this is expected to be in place for a number of years, the building owner will be able to make a rational decision on what constitutes a reasonable investment.

Purchase of privately generated thermal by the utility

Contact with four DE Canadian and five European utilities has indicated that at present they are hesitant to give out information on what might be acceptable in long-term contracts to encourage private investment in distributed generation of thermal energy. This is in contrast to the electrical industry in which feed-in-tariffs for renewable energy have been in place in a number of countries in recent years.

In the future some houses will be constructed in a “solar-ready” format. This means that pipes going to rain-proof roof, penetrations, control wiring, etc are already in place, considerably lowering the cost of later installing a solar system. If a decision is made to install a simple solar DHW system the question will come up regarding whether the system capacity should be expanded to supply extra thermal energy, some of which could be sold to the DE utility.

A simulation is done to predict the surplus energy generated by this extra capacity for each hour of the year. These parameters can be used to set a benchmark for a reasonable price on the energy at different times of the year, in order to cover the cost of the incremental investment.

If the utility operates a seasonal storage system the summer surplus solar energy can be use to charge this storage. Then a reasonable purchase price would be the winter rate, with allowance for the losses that occur in the seasonal storage.

Characteristics of Losses in Future Low-Energy Buildings

Because the transient and steady state characteristics of the future low-energy house are basic to the analysis of interfacing these buildings to the DE system, these need to be identified in detail.

Testing was done in a low-energy house constructed by Rob Dumont in 1992. At the time of construction it was considered to be the most energy efficient house in Canada in terms of heat loss per unit floor area. A description of the house is in Appendix A.

Other than the low heat loss of the Dumont house (5.6 kW at -32°C) the other unique characteristic of this house is the long time constant. Measurements were taken on this house and, for comparison, a new house constructed to Ontario standards. The space heat was turned off with air circulation maintained and the drop in temperature recorded. The outside temperature in both cases varied a few degrees around -20°C. The derivative of the drop in temperature was calculated and normalized to an indoor-outdoor temperature difference of 40°C. The integral of the results enabled accurate comparison between the two houses. The results are in Figure 3.

This shows that even though the Dumont house would not be considered a "high mass" passive solar building, it lost less than 0.5°C during one hour at -20°C outdoor temperature.

After the initial transient at the start the rate of cooling is 0.33°C per hour.

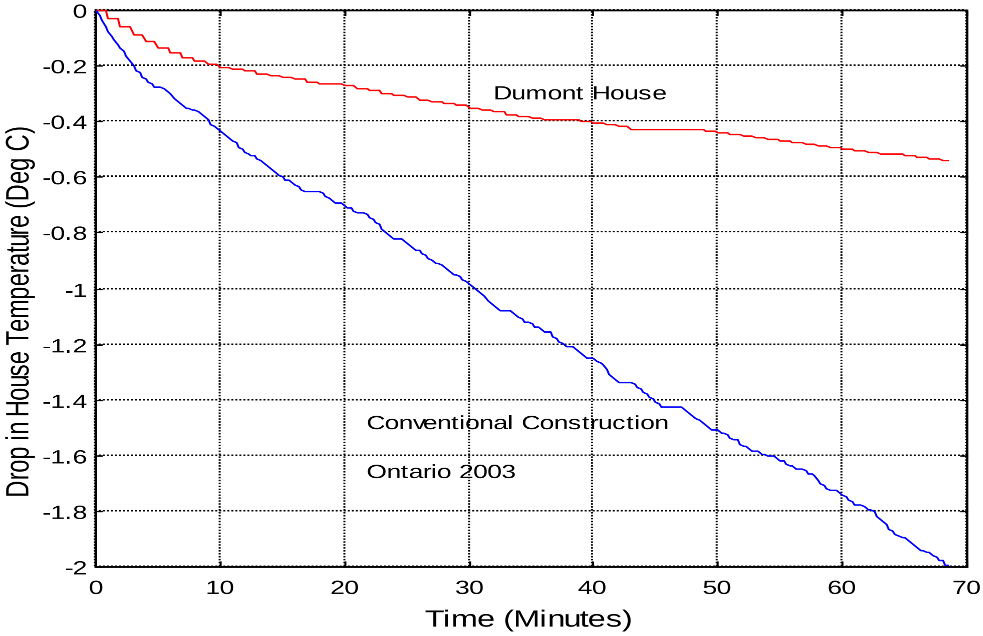

Figure 3: Loss in Temperature with No Space Heat (Tin-Tout normalized to 40°C)

This characteristic long time constant indicates the potential for one method of low cost load shedding. It is assumed that, in the future, with the ability to use variable-rate heat metering, the DE utilities will make use of peak load tariffs. If the occupants of low-energy buildings are willing to accept a small drop in temperature during a one or two hour period the peak load on the DE system will be reduced, with economic savings for the DE utility.

Low-energy house model

In order for simulations to predict DE system revenue in future low-energy building subdivisions it is important to accurately predict both the transient and steady-state heat loss characteristics of these buildings. This will also enable the accurate design of heating system components to meet the demand with acceptable comfort conditions, while at the same time achieving low values of flow and return temperature.

There is no single heat loss factor for a building, since a number of thermal loss components are a nonlinear function of outdoor temperature. Many of these are negligible but some require consideration even in the case of low-energy buildings.

Particular emphasis needs to be placed on the time constant of the low-energy building, since considerable load shedding is available from even a small drop in room temperature (such as 0.7°C).

The drop in temperature due to zero input of space heating power has a large rate change near the start. This is due to the low thermal mass of the air inside the dwelling and buildup of convection currents after the air temperature starts to fall. These currents transport power from the high mass regions of the building structure, including the walls and often from isolated areas such as the region behind furniture or inside of kitchen cabinets. Since the air has a certain amount of inertia, if a region of high mass is some distance from the source of cooler air there can be a noticeable delay before the small temperature difference begins to transfer a significant amount of energy from regions such as the wall panels. This effect can be modeled by placing a nonlinear element into the linkage between the cooler low mass and the high mass source of energy. The more slowly the air temperature drops the more time there is for these convection currents to build up. In the case of the Dumont house the optimum match between measurements and simulated results is achieved when the nonlinear element has a change in slope with an air temperature drop of 0.18 °C. If a building has a high heat loss factor the air temperature will drop rapidly relative to the time for buildup of convection currents. In older (1970's) houses a temperature drop of over one degree has been observed before the rate of change became lower.

Components of energy loss in buildings

The most significant building heat losses are:

- losses due to air leakage
- losses due to heating of ventilation air
- quasi-steady-state basement losses to ground
- conductive losses through the building envelope

Some of these components are nonlinear and there is no single heat loss factor that accurately predicts the building load over the range of outdoor temperature. Since losses due to air leakage increase in magnitude at lower outdoor temperature a measurement of heat loss factor at an intermediate outdoor temperature will tend to under-estimate losses at peak load. For accurate simulations each component needs to be computed separately.

Computation of building loss components

The following method can be used to establish the loss components:

- Measure the total heat loss at a low outdoor temperature, or preferably a number of temperatures for crosschecking. Indoor heat gain needs to be measured or estimated.
- Calculate the first three loss components at the temperature used for the measurement of overall heat loss factor.
- Subtract the first three losses from the overall loss. This gives the linear term for conductive losses through the building envelope. This has minor errors as a function of temperature, since it also includes some nonlinear terms. For example, insulation has a small nonlinearity in thermal resistance as a function of

temperature and radiant heat losses and convective air flow over windows causes nonlinear losses. These are ignored in the present analysis.

Air leakage as a function of indoor/outdoor temperature difference

In low-energy buildings the emphasis is on air-tight construction and mechanical ventilation to meet standards of occupancy requirements. A building such as the Dumont house has exceptionally low air leakage, using construction trades workers that have been trained in these methods. The measured air leakage rate of the house is 0.47 air changes per hour at a pressure difference of 50 Pascals. Houses that are to be certified to the Canadian R2000 standards[13] must pass a pressurization test.

Since the air leakage at the design temperature is not negligible even for nominally airtight buildings, a detailed analysis can be done based on The Alberta Air Infiltration Model[14]. This method evaluates air leakage as a function of the distribution of leakage areas around the building envelope. Wind effects are addressed in this report but are not included in these simulations. The assumption is that in a future subdivision with relatively small lots the buildings shelter each other and wind effects will be negligible in an air tight building.

The air leakage flow, L_s, due to stack effect is of the form:

$$L_s = C\, f_s\, P_s^n$$

Where

- n can be in the range 0.5 to 0.67. For small buildings setting n to 0.67 has been found to give good agreement with measurements.
- P_s (stack pressure) = indoor/outdoor differential pressure generated by air density difference due to indoor/outdoor temperature difference
- C = total building leakage coefficient
- f_s = stack flow factor. This has been derived by a combination of analytical and empirical methods. In The Alberta Air Infiltration Model it is expressed as:

$$f_s = \left(\frac{1+nR}{n+1}\right)\left(0.5 - 0.5\left(\frac{X^2}{2-R}\right)^{1.25}\right)^{n+1}$$

Stack flow factor (f_s) for Dumont house

X relates to the leakage area at the ceiling to that at the floor. In a house with a carefully installed vapour barrier the leakage area in these locations can be assumed to be equal.

For symmetric leakage, X= 0

This reduces the equation to:

$$f_s = \left(\frac{1+nR}{n+1}\right)(0.5)^{n+1}$$

R takes into account the leakage distribution on the building envelope including the ratio of leakage between the ceiling, walls and the floor. R can vary from 0 to 1. If all the leakage is in the top level ceiling and the first level floor R = 1.

In the Dumont house it has been assumed that there is negligible leakage into the basement. On the main floors it is assumed that most of the leakage is in the windows.

Estimated distribution of leakage:

- Ceiling = 0.05
- Walls = 0.9
- Floor = 0.05
- This results in R = 0.1

  Then, $f_s = \left(\frac{1+0.67 \times 0.1}{1.67}\right)(0.5)^{1.67}$

  $f_s = 0.2$

Stack pressure (P_s) as a function of indoor/outdoor temperature difference

$$\boldsymbol{P_s = \rho g H \left(\frac{T_{iK} - T_{0K}}{T_{0K}}\right)}$$

- ρ = outdoor air density, kg/m^3
- g = gravitational constant = 9.8m/s^2
- H = building eave height = 5.2m

Absolute temperatures:

- T_{iK} = indoor temperature, °K
- T_{oK} = outdoor temperature, °K
- To = outdoor temperature , °C

Over the range of interest air density can be approximated as a linear function of temperature

ρ = 1.29-0.0047 T_o kg/m^3

Then stack pressure (P_s) in pascals

$$P_s = (65.7 - 0.24\ T_0)\left(\frac{T_{iK} - T_{0K}}{T_{iK}}\right) \text{ Pa}$$

This function is shown in Figure 4.

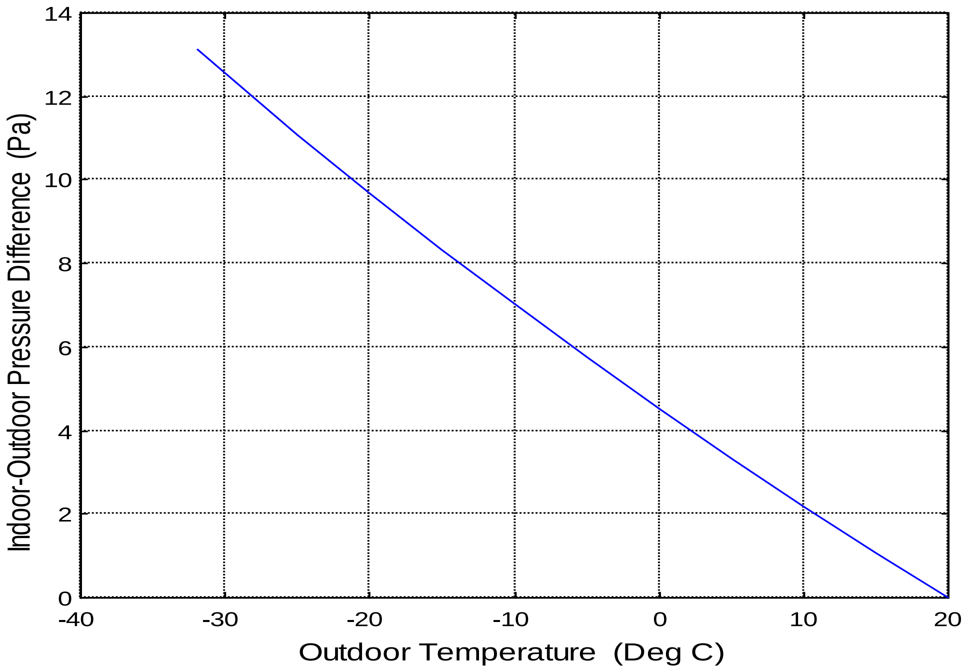

Figure 4: Stack Pressure as a Function of Outdoor Temperature

Pressurization test results for the Dumont house

In order to quantize the air leakage parameters a pressurization test is done.

Pressure difference ΔP (Pa)	Ventilation (litres/sec)
5	23
10	36
50	106

Table 5: Air Leakage Parameters

This data is shown in Figure 5, together with the curve fit.

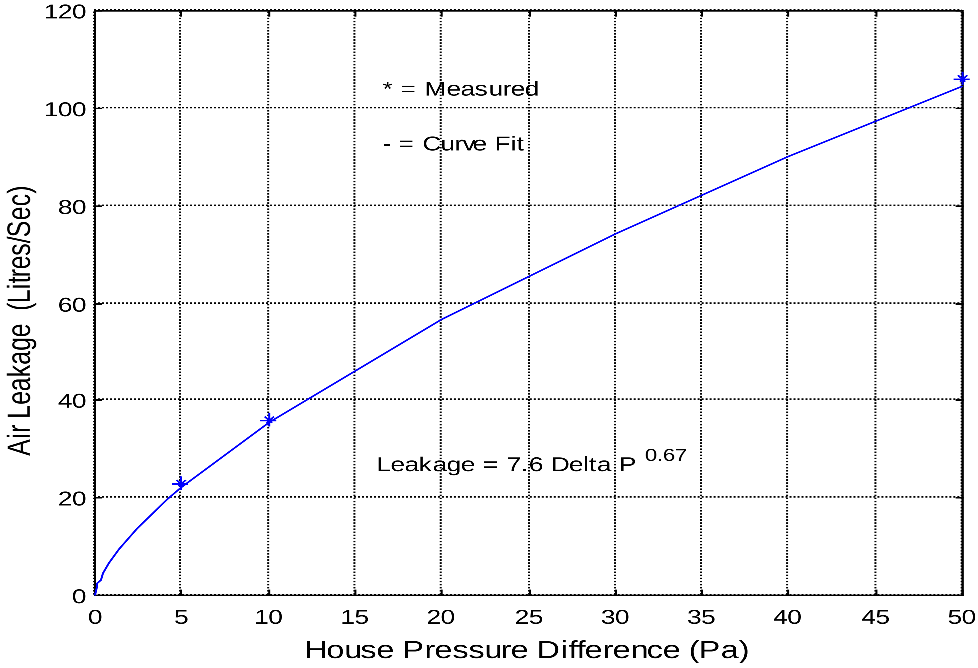

Figure 5: Air Leakage due to Pressurization Test

Air leakage due to pressurization test $= 7.6\ \Delta P^{0.67}$

Air leakage due to stack effect

Using the previously established stack flow factor (f_s) = 0.2 and expressing the above equations in terms of outdoor temperature (T_o) with indoor temperature = 20 °C, air leakage can be defined by:

$$\text{Air leakage} = 0.2 \times 7.6\ P_s^{\ 0.67} \text{ litres/sec}$$

$$= 1.52 \left((65.7 - 0.24\ T_0) \left(\frac{T_{iK} - T_{oK}}{T_{iK}} \right) \right)^{0.67}$$

This is shown in Figure 6:

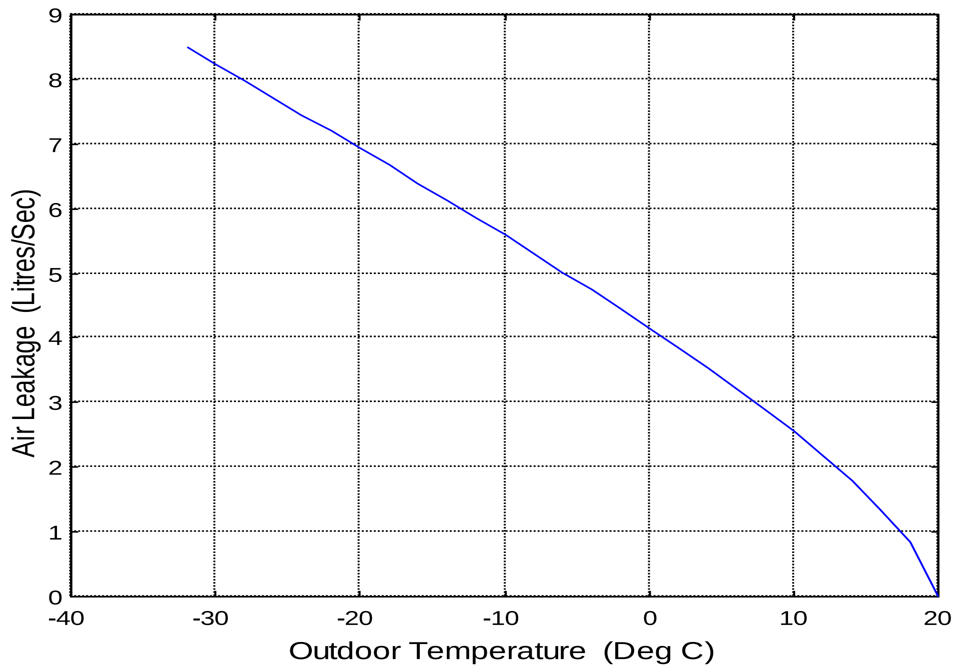

Figure 6: Air Leakage as a Function of Indoor-Outdoor Temperature Difference

At -32 °C, maximum air leakage = **8.5 litres/sec,** which is a relatively small fraction of the mechanical ventilation rate of 25 litres/sec. through the heat recovery ventilator in the Dumont house.

Power required to compensate for air leakage due to stack pressure

Air leakage power when T_i and T_0 are indoor and outdoor temperatures, °C

$$(P_L) = \rho\, C_p\, (Air\ Leakage\,)(T_i - T_0)$$

At room temperature

air density	ρ = 1.204 kg/m^3
specific heat	*Cp* = 1.006 kJ/kgK

$$\rho Cp = 1.204\ \times 1.006\ = 1.21\quad kJ/m^3$$

$$P_L = 1.21\ \times\ 1.52\ \left((65.7 - 0.24\,T_0)\left(\frac{T_{iK} - T_{oK}}{T_{iK}}\right)\right)^{0.67} \times\ \frac{(T_i - T_o)}{1000}\ kW$$

$$P_L = 1.84\ \times\ 10^{-3}\ \left((65.7 - 0.24\,T_0)\left(\frac{T_{iK} - T_{oK}}{T_{iK}}\right)\right)^{0.67} \times\ (T_i - T_o)\ kW$$

This function is shown in Figure 7.

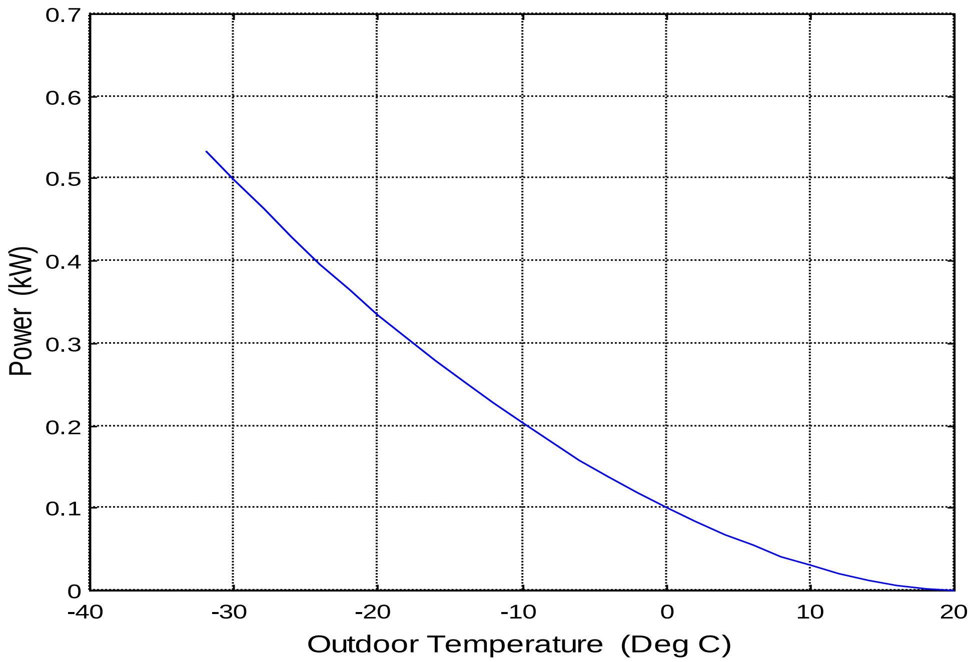

Figure 7: Power Required to Heat Air due to Leakage

This indicates that the maximum power at -32° is 0.534 kW and during most of the heating season the power loss due to air leakage is less than 0.3 kW.

Mechanical ventilation requirements

The criteria for ventilation air are based on the size of house and number of occupants. In the case of the Dumont house the ventilation rate was set to 25 litres/second.

For a typical family the ventilation value is assumed to be 35 litres /second and this is used in the later case study simulations.

Heat recovery ventilators (HRVs) are available with a broad range of performance characteristics. The HRV used in the Dumont house is a high performance one. The characteristic as a function of outdoor temperature is:

$$\textit{Effectiveness (EFF)} = 0.81 - 0.0012T_o$$

Since the exhaust air temperature equals indoor temperature, T_i, the standard definition of effectiveness gives this:

$$EFF = \frac{(Tvent - T_0)}{(T_i - T_0)}$$

Then $Tvent = EFF\,(T_i - T_0) + T_0$

It is assumes that this performance is also available at the slightly higher flow rate of 35 litres/sec.

For the above HRV performance the ventilation fresh air temperature (*Tvent*) is:

$$Tvent = (0.81 - 0.0012T_0)\ (T_i - T_0) + T_o$$

This is shown in Figure 8.

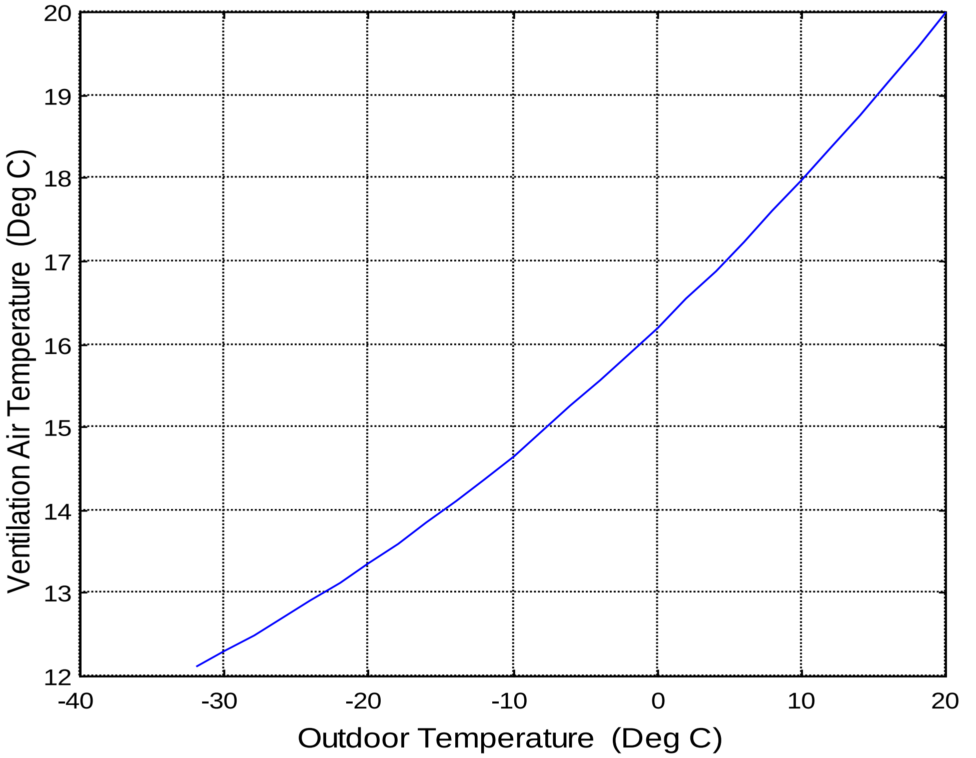

Figure 8: Ventilation Air Temperature from HRV

Power (*Pvent*) to raise the ventilation air to room temperature

At room temperature air density $\rho = 1.204$ kg/m^3
and specific heat $C\rho = 1.006$ kJ/kgK

$$P_{vent} = 1.21 \times volumetric\ flow \times (T_i - T_{vent}) \times 10^{-3} \quad kW$$

The power required to heat the ventilation air to room temperature is in Figure 9.

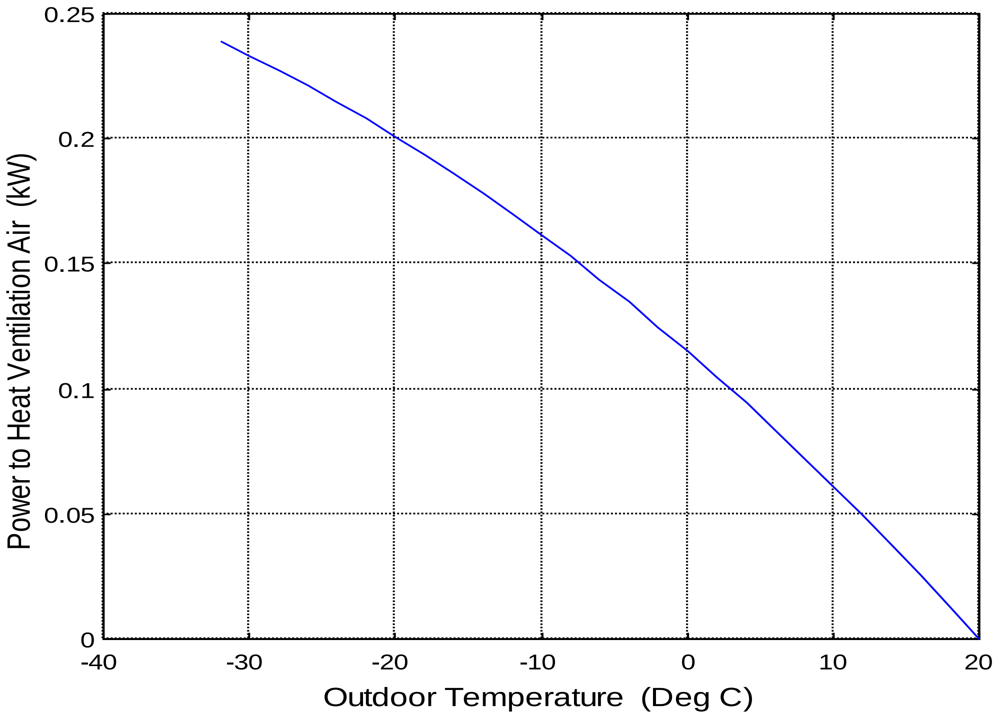

Figure 9: Power to Raise Ventilation Air to 20°C at 25 l/sec

At the design temperature the power required to heat the ventilation air to room temperature is 0.239 kW. If the same flow of fresh air were supplied by leakage the required power at design temperature would be 1.57 kW.

Calculation of basement losses

Basement losses are different from all other loss components in two regards:

- losses are almost constant during the heating season, regardless of outdoor temperature
- losses vary slowly during the year, with a time delay of about two months from the outdoor temperature cycle

Since it is difficult to take direct measurements of basement losses they need to be established by simulations based on basement construction parameters and in-ground temperatures. The HOT2000 program[15] has a basement loss module that outputs monthly values of energy loss. For the Dumont house these are converted to power and plotted in Figure 10. The data can be converted into a time series and used as input to the overall building simulations.

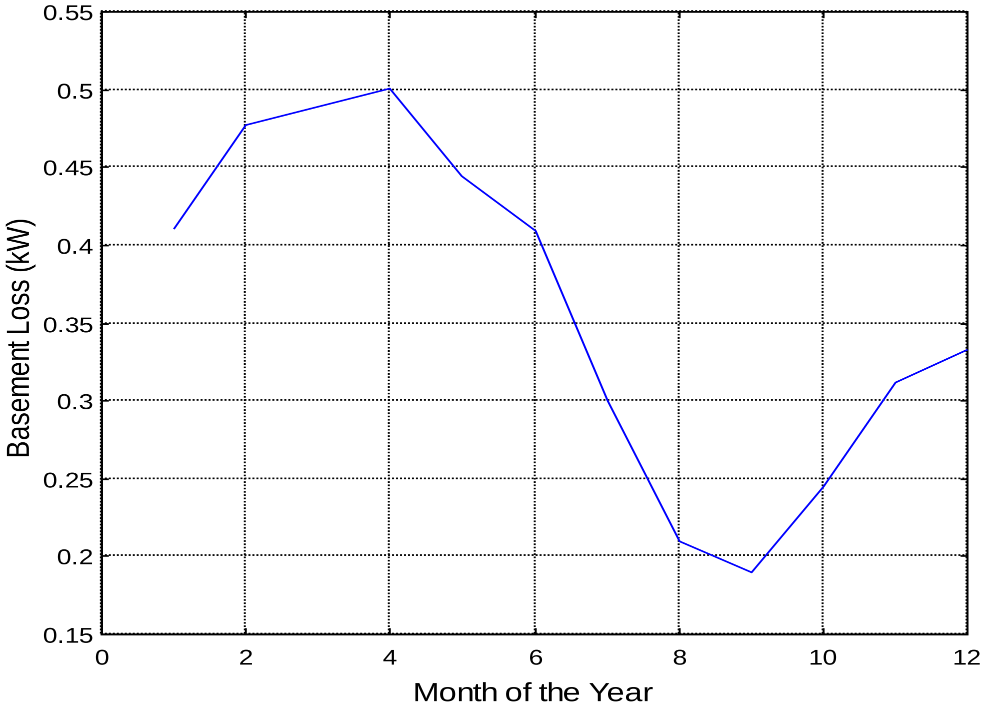

Figure 10: Basement Loss below Grade

Calculation of building envelope heat loss factor

Heat loss measurements were taken on the house at an indoor-outdoor temperature difference varying around 40°C. Measurements were taken at night to eliminate the effects of solar gain. Since all space heating energy input to the house is electric it was possible to obtain accurate values of heat loss.

At 40°C temperature difference the total electrical load (including appliances) averaged 4.36 kW. The measurements were taken in February when the basement loss was 0.47kW.

Total load – basement loss = 3.89 kW

This includes losses for air leakage and heating of ventilation air at – 20°C outdoor temperature.

Using the previously established equations for these parameters:

- Air leakage loss = 0.335 kW
- Heating of ventilation air = 0.201 kW
- Building envelope loss = 3.89 – 0.335 – 0.201 = 3.35 kW
- Building envelope quasi-linear heat loss factor = **0.0838 kW/°C**

Total power required in Dumont house (*Phouse*) as a function of ΔT_{io}, $(T_i - T_o)$:

Phouse = 0.0838 ΔT_{io} *+ air leakage loss + ventilation air heating+ basement loss*

These components are shown in Figure 11, together with the total load, including average basement loss of 0.4 kW. The peak load at – 32 ° is 5.6 kW.

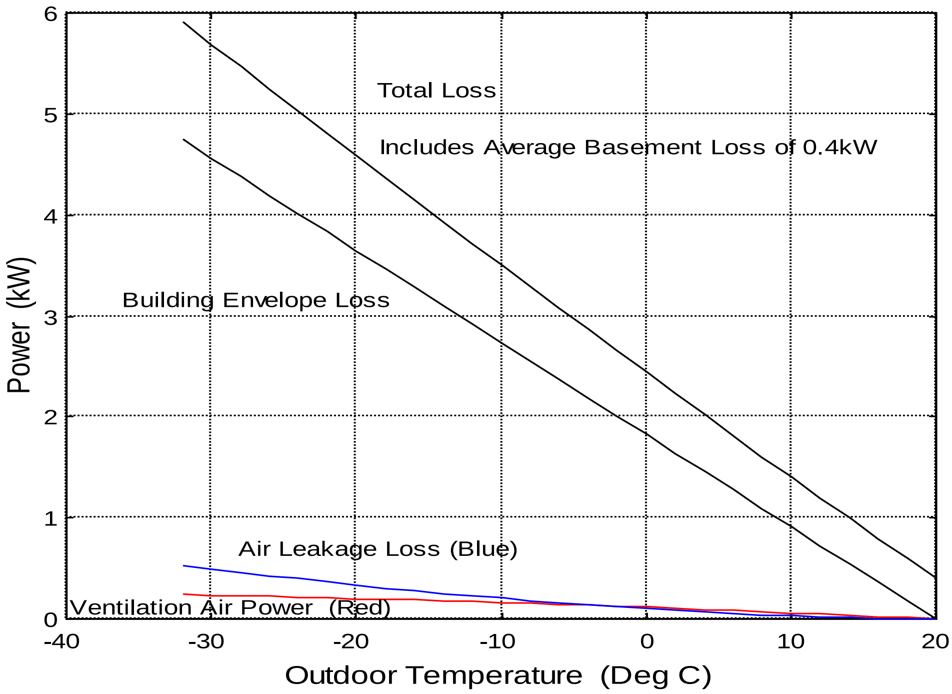

Figure 11: Components of Heat Loss in Dumont House

Some heat loss components have an upward curvature with colder temperatures. As shown in Figure 12 there is a partial compensating effect due to the more efficient operation of the heat recovery ventilator in colder conditions.

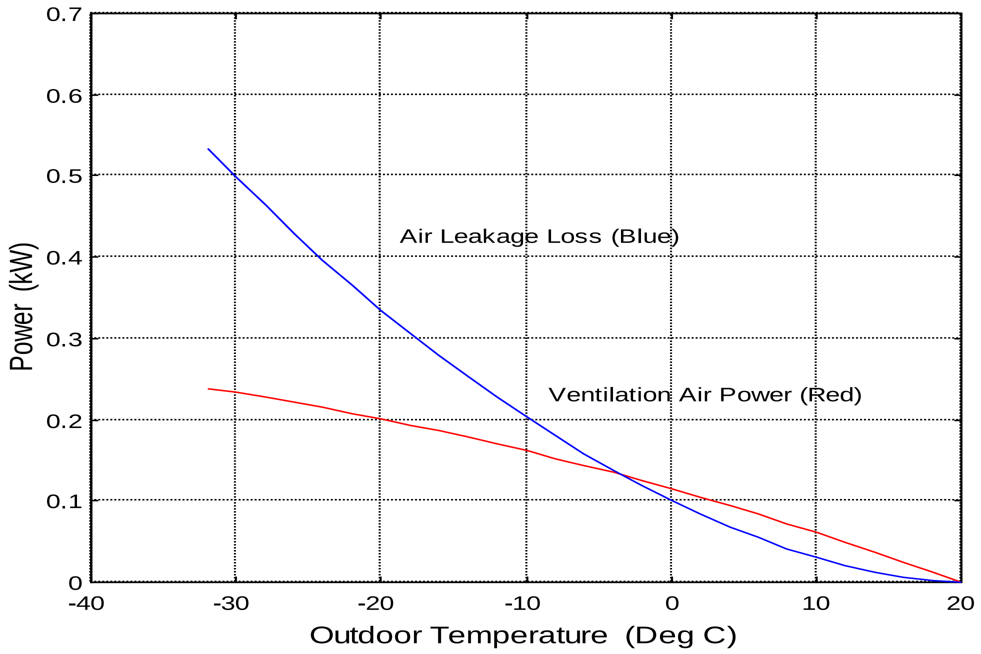

Figure 12: Comparison of Air Leakage Loss and Ventilation Power

Dumont House Model

The heat transfers that occur in a building are a complex combination of conduction, convection and radiation. A very large number of transfer functions and time constants are required to characterize the building. Programs exist that model these in great detail but these are too elaborate to be used as routine design tools.

It is possible to simplify the model. The building can be described in terms of two dominant time constants:

- Slow time constant embodied in the high thermal mass parts of the building, such as the wall panels and any masonary parts of the interior. As will be seen, in a low-energy building this can be used for a low cost method of peak load shedding for periods of over an hour with minimal effect on comfort.

- Fast time constant, consisting of the air mass and items such as furniture with a high ratio of surface area to thermal mass.

In the Dumont low-energy house the dominant means of heat transfer is by a combination of air movement by mechanical means and convection. The source is a liquid-to-air coil with a blower and a ducted air supply and return at each room. This system also supplies the ventilation requirements for each occupied room. This ventilation is mandated by the building code for any house that meets a criteria for air tight construction that requires a heat recovery ventilator.

In the simplified model both the heat supply and loss are through the air medium. Some radiant heat is lost through the windows but with triple glazing and low-e coatings this component is sufficiently low that it can be combined with the heat loss factor of the building envelope, which can be approximated as a linear function of temperature difference between the average room temperature and the outside temperature.

The fast and slow time constants are in series but they are loosely coupled by natural convective air flow, which has nonlinear components. This assumes that the warm air from the supply ducts is mostly mixed with room air within the first one or two metres from the duct exit point. For a low-energy building the overall time constant is in the order of 100 hours and the convective nonlinearities can be approximated with a nonlinear component linking the air mass and the larger thermal mass.

Passive solar gain is output from the model to allow the cumulative solar energy to be calculated. When the building air temperature reaches 25°C further gain is not considered useful and windows would be opened or air conditioning turned on. When the 25°C temperature is reached, solar gain is set to zero.

The block diagram of the building model is shown in Figure 13 and the detailed Simulink™[16] model is in Figure 14, with subsections shown in Figures 15 and 16.

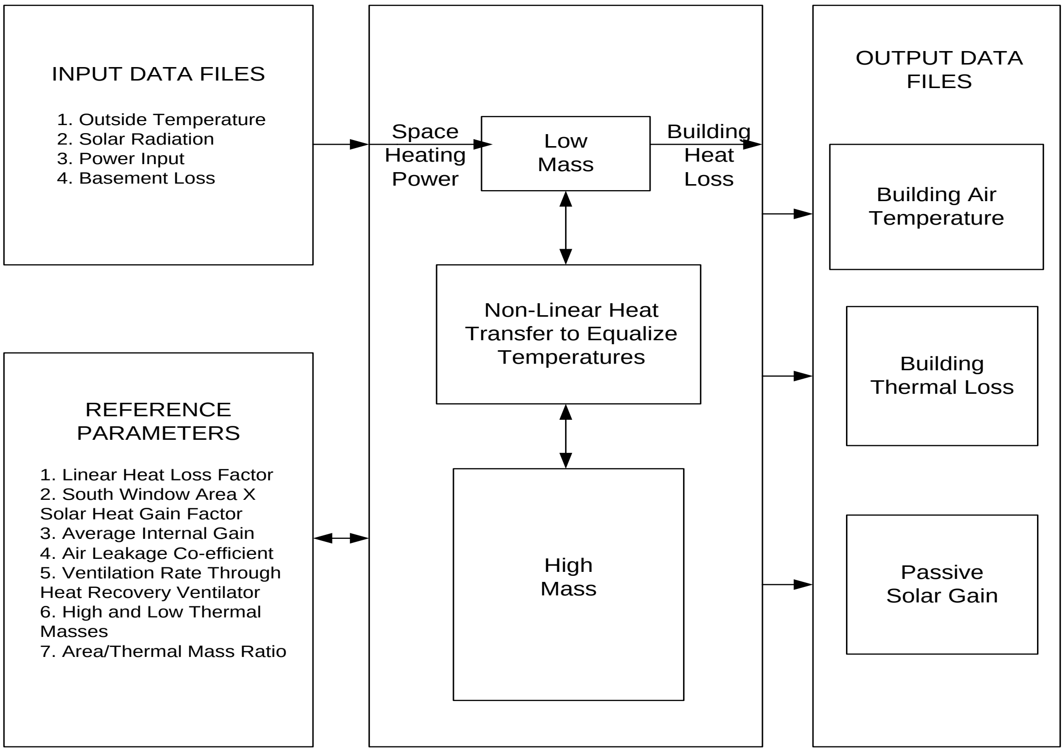

Figure 13: The Block Diagram of the Building Model

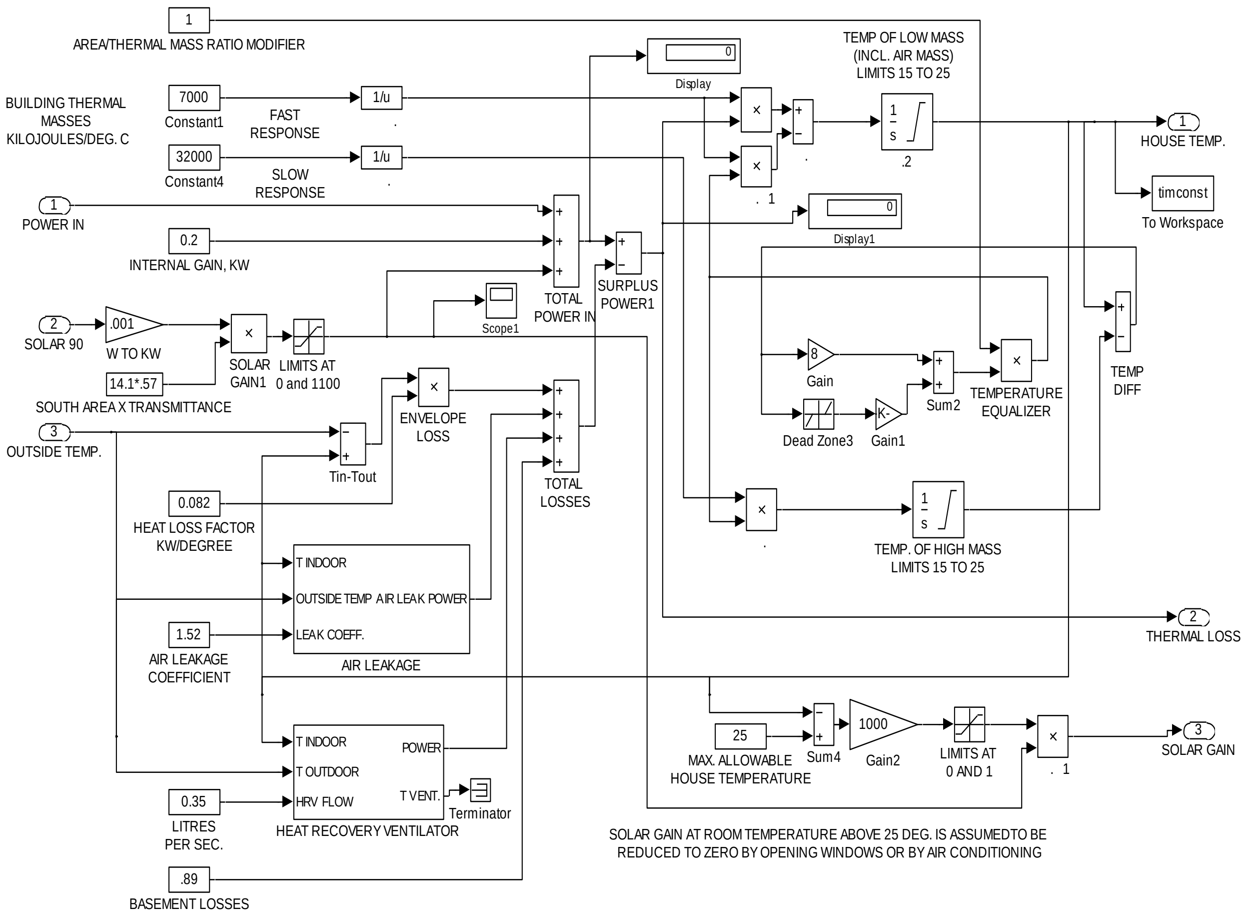

Figure 14: Model for Dumont House

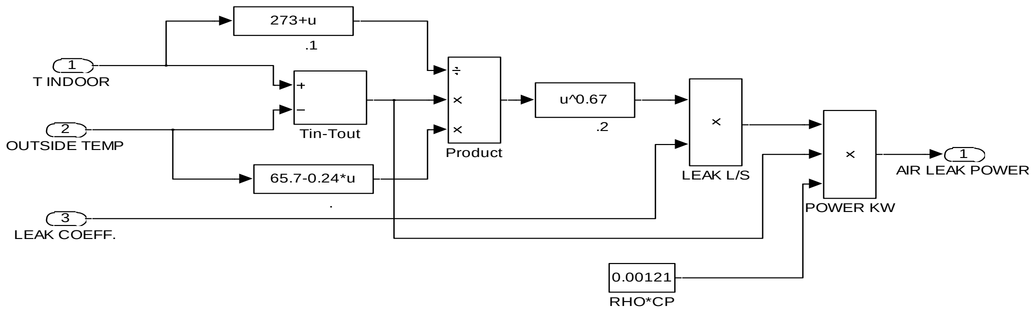

Figure 15: Model for Power Loss due to Air Leakage

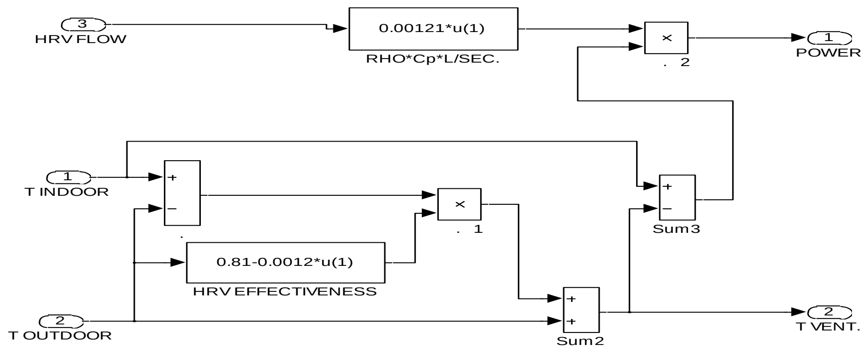

Figure 16: Model for Heat Recovery Ventilator

A number of the paramaters that have been quantized for the Dumont house are shown as constants on the block diagram for illustrative purposes. In practice these would be set in an initialization text file for a more generalized application of the model.

The model is driven by time series, usually hourly, files of outdoor temperature and solar radiation. Output files are building power demand, air temperature and solar gain.

House time constant and low-cost load shedding

The potential for low-cost load shedding is illustrated by tests that were done by setting space heating power to zero under temperature conditions in the range -20°C to -22°C. The normal air circulation was maintained. Temperatures in the three levels of the house were measured and averaged. Testing was done at night to eliminate the effects of solar radiation. Since both the indoor and outdoor temperatures varied slightly during the test period, the derivative of the average indoor temperature was adjusted to normalize the results to a constant temperature difference of 40°C. The normalized derivatives were integrated back to a temperature function.

The simulation parameters in the house model were adjusted to best match the measurement and the result is in Figure 17. The two functions agree within less than 0.05°C over the range of interest for load shedding. Assuming that a drop in temperature of less than 0.7°C will not be noticed by most people it can be concluded that at an outdoor temperature of -20°C the house could use load shedding up to 90 minutes on a routine basis.

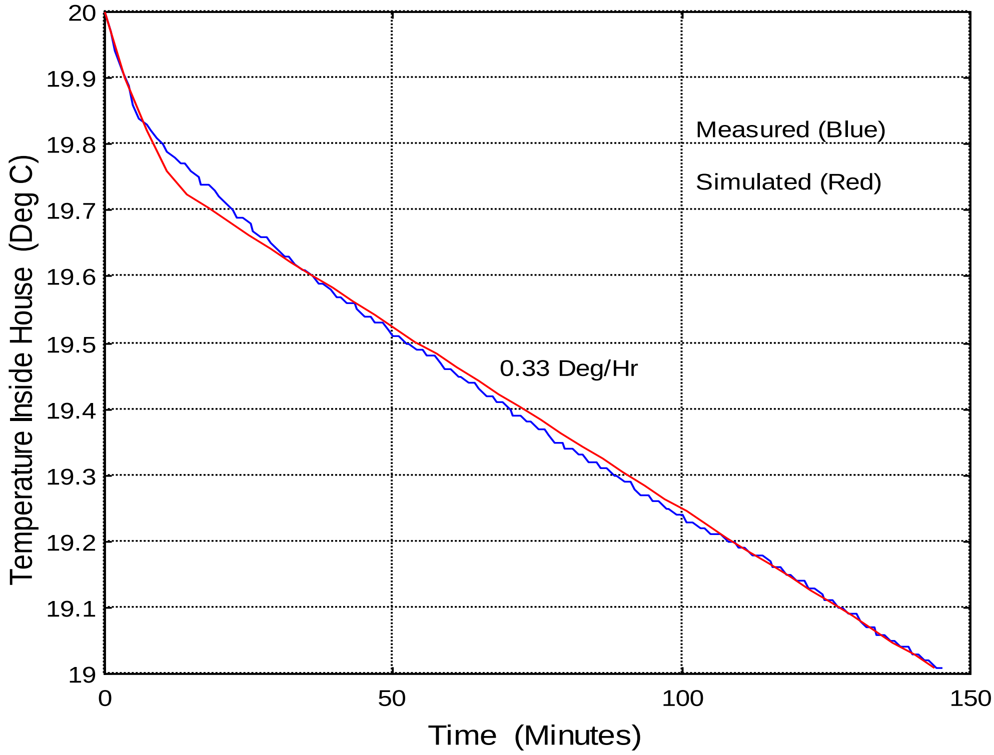

Figure 17: Temperature Drop in Dumont House Normalized to Tin-Tout = 40°C

The only place where the two temperatures deviate by more than a few hundreths of a degree is at the transition where the high thermal mass begins to dominate the rate of temperature drop. It can be seen that instead of a smooth transition between two rates of change, there is an intermediate slope on the measured function, with a maximum difference of 0.05°C. This is partially due to the presence of some components in the house with intermediate heat transfer and thermal capacity parameters. A possibly more significant parameter is the time delay for the buildup of convection air currents to begin to extract energy from the more remote areas of the house, such as the wall panels behind furniture and the interior of cupboards, and in basement areas.

Some evidence of this time delay to build up air convection currents has been seen in measurements taken on a standard house built in the 1970s. This building quickly reached the assumed limit of 0.7°C drop in temperature while still cooling only the air temperature. The transition to extracting energy from the high thermal mass did not occur until the temperature had dropped more than 1.0°C.

This highlights another benefit of the long time constant of the low-energy building. The transition to the low rate of temperature decline begins at around 0.3°C below the starting temperature. This means that most of the transition to 0.7°C below the start occurs during the time that energy is being extracted from the slow time constant at a rate of 0.33°C per hour.

If the building temperature had been 0.33°C above the set point at the time the power was set to zero, the time to reach the 0.7°C drop below the set point would be extended by an hour to 2.5 hours. This extended time is shown in Figure 18. The rates of change are also shown in this figure, indicating a ratio of 1.7/0.33 = 5.1 between the two slopes.

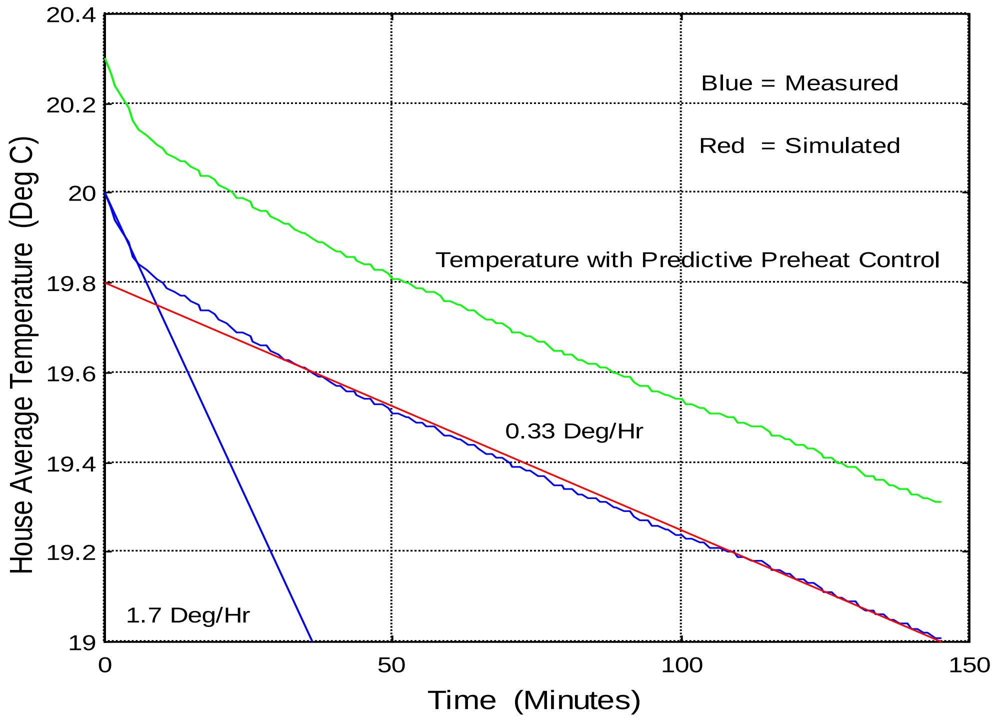

Figure 18: Temperature Changes in Dumont House after Setting the House Space Heating Power to Zero.

The linear blue line showing a 1.7 Deg/hr represents a low mass house with greater heat loss.

The control stratagy for load shedding could take advantage of this transition in the rate of temperature loss to greatly extend the load shedding time if the peak demand can be anticipated. The utility could notify the building temperature controller in advance and the building temperature could be elevated 0.3°C during this time, putting the region of fast temperature loss above the normal temperature set point. This small elevation in temperture would have a very small effect on long-term heat loss but it would increase the level of stored energy. As it can be assumed that the future buildings will have heat metering with two-way communication controls, this type of load shedding is easy to implement. This method is used in one of the low-cost load shedding simulations.

This type of predictive control may only be practical if the utility has accurate knowledge of load in the immediate future. However, as will be seen later, the use of predective control in active thermal storage has no similar considerations since the level of stored energy has no inpact on house temperature and any thermal losses from storage are inside the house.

Validation of low-energy building model

Characteristics during the 3 day building test period:

- The clothes dryer was not used.
- The approximate heat loss characteristic of the house as a function of the indoor-outdoor temperature difference was determined from the spreadsheet of measured power consumption values.
- Electricity used for the DHW was 28.4 kWh (ck) or an average of 0.394 kW, as recorded manually from a utility meter.
- The total electrical energy consumed by the house was 324.38 kWh or an average of 4.5 kW. Peak power consumption was 12.96 kW and likely occurred during cooking episodes. The peak power consumption of the regular electric water heater is 3kW. (There is no other source of conventional energy in the house such as natural gas, oil, propane, etc.)

- The house was occupied by 3 adults most of the time.

Validation of Dumont house model

The method of validation involves recording data over a period of three days under a variety of outdoor temperature conditions during periods of solar radiation. The data is used to drive the model being evaluated. Since a building with low losses is very sensitive to changes in energy stored in the thermal mass of the building, caused by indoor temperature variations, the measured indoor temperature is used to vary the corresponding value in the model.

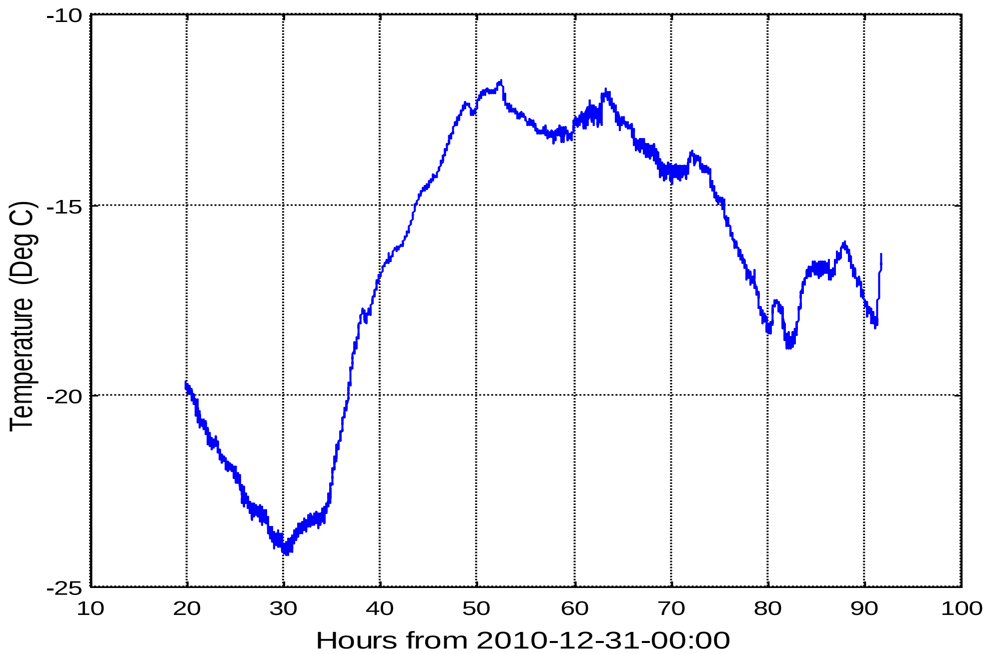

Figure 19: Outdoor Temperature during Model Validation Test

Data was recorded from the evening of December 31 2010 00:00 to the evening of January 3 2011. Figure 19 shows the outdoor temperature and Figure 20 shows the solar radiation.

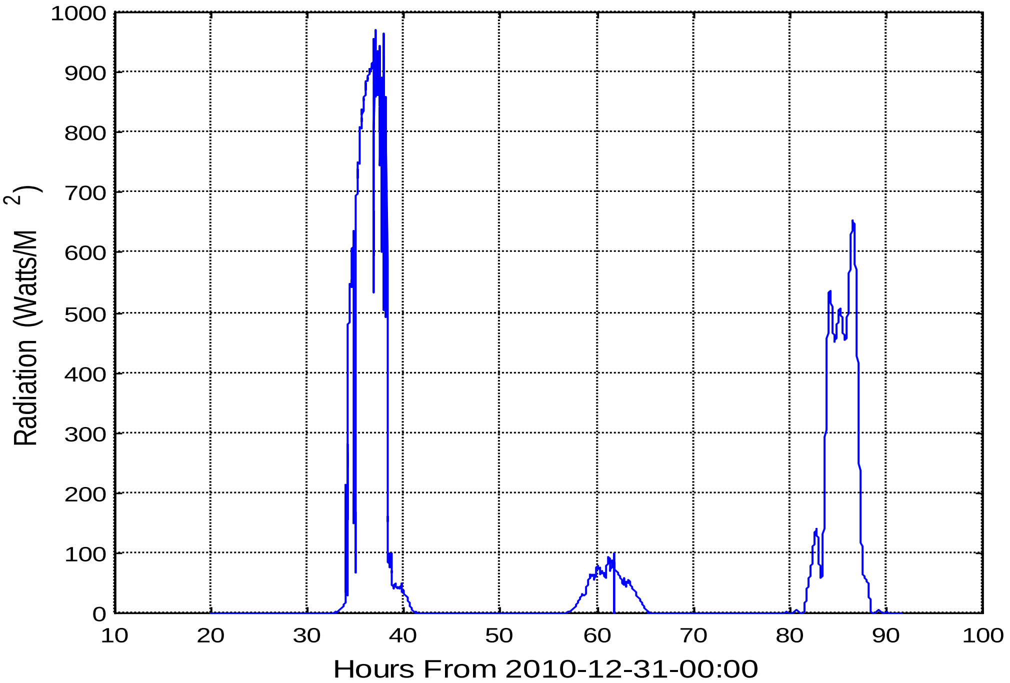

Figure 20: Radiation in Saskatoon on a Vertical South Window

During the third day of the test the solar radiation sensor failed. Data from the local university was used to complete the data set.

The incidence angle modifier was set to the values shown in Figure 21, based on data from ASHRAE tables for triple glazing with two low e coatings and one clear glass. The data was normalized to 1.0 at zero degrees and the solar heat gain factor value was kept separate in the model to enable it to be adjusted.

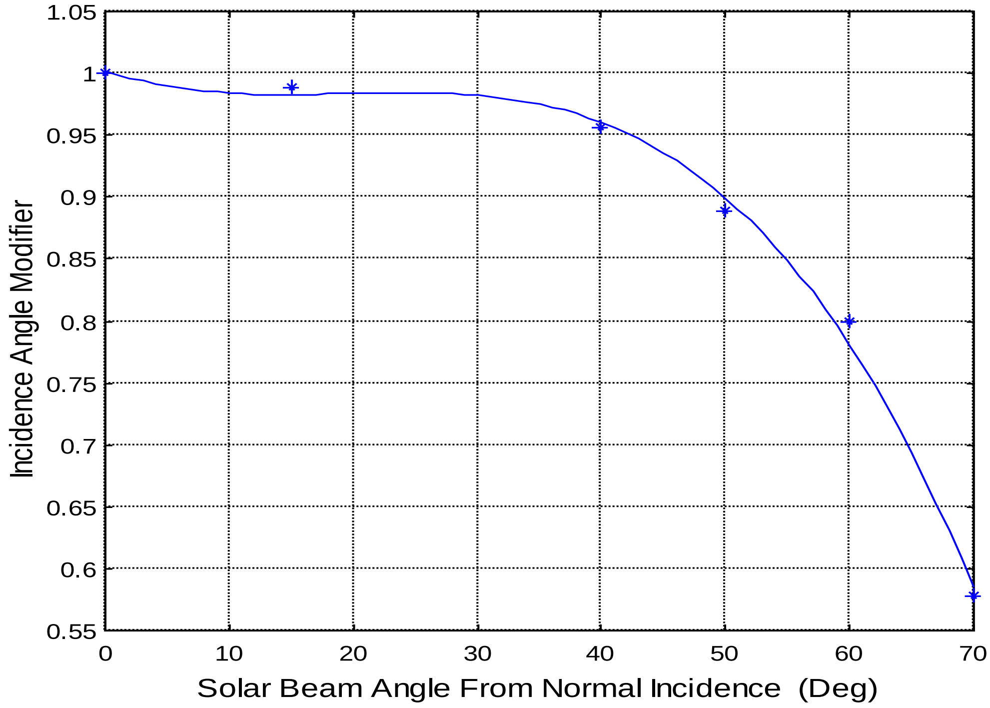

Figure 21: Incidence Angle Modifier for Triple Glazed Window

The measured and simulated indoor temperatures are shown in Figure 22. The simulated temperature has a slight offset from the driving function but this is typically within 0.1°C and has negligible effect on the result.

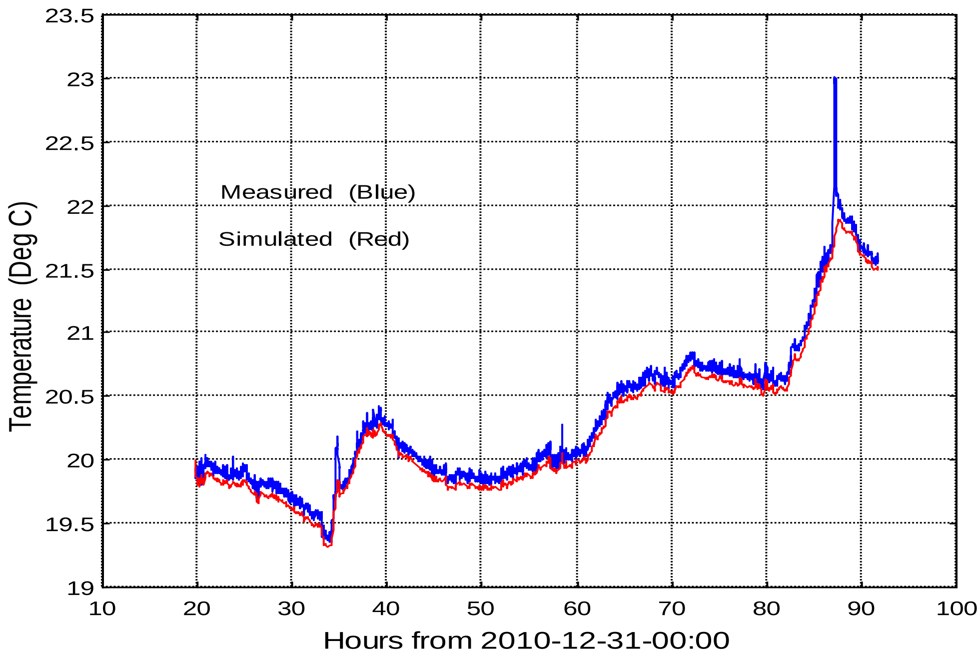

Figure 22: Indoor Temperature during Model Validation Test

The model was initialized with the following parameters:

- Solar heat gain factor: 0.45 (from ASHRAE tables)
- Linear heat loss coefficient of 0.0838 kW/°C
- Basement loss: 0.45 kW

The simulation generated a time series of instantaneous power. This was integrated to energy and plotted in Figure 23. The measured total house energy had the DHW component subtracted and was plotted for comparison. There is a significant divergence starting at 10 am on January 1, with the simulated values going more than 20 kWh below the measured. Since there was strong radiation during that day the conclusion was that the effective passive solar gain was less than predicted. It was found that the windows had some shading.

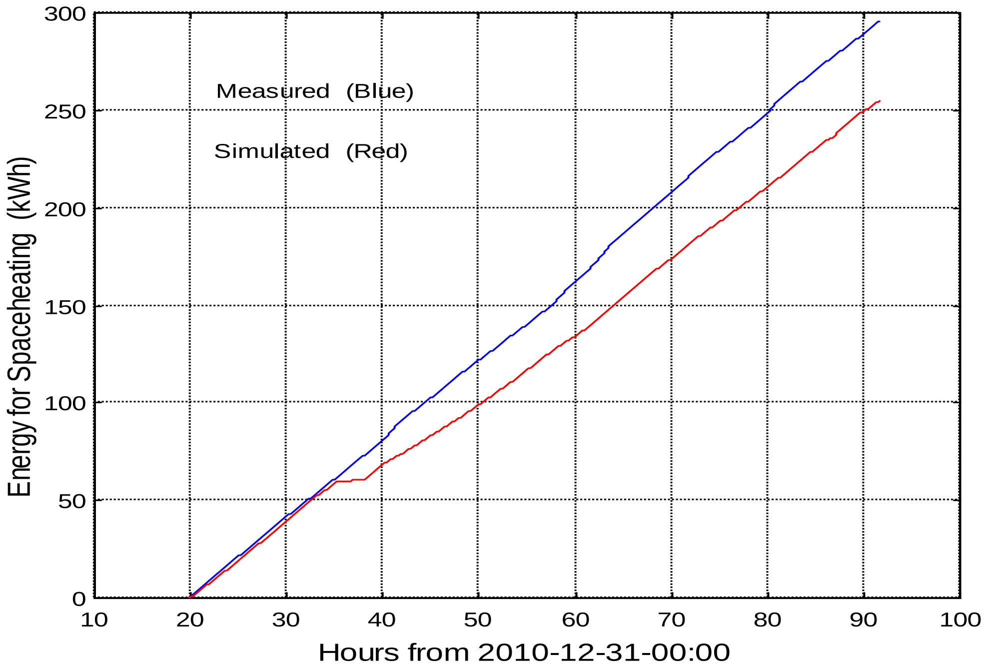

Figure 23: Comparison of Simulated and Measured Space Heat

Two changes were made to the parameters. The window solar heat gain factor was lowered to 0.3. Since the simulated energy function continued at a lower slope even after the radiation went away the heat loss of the building was being simulated at a lower value than the measurements would indicate. The linear component of the heat loss factor was increased to 0.086 kW/°C from its previous value of 0.0838. This resulted in Figure 24.

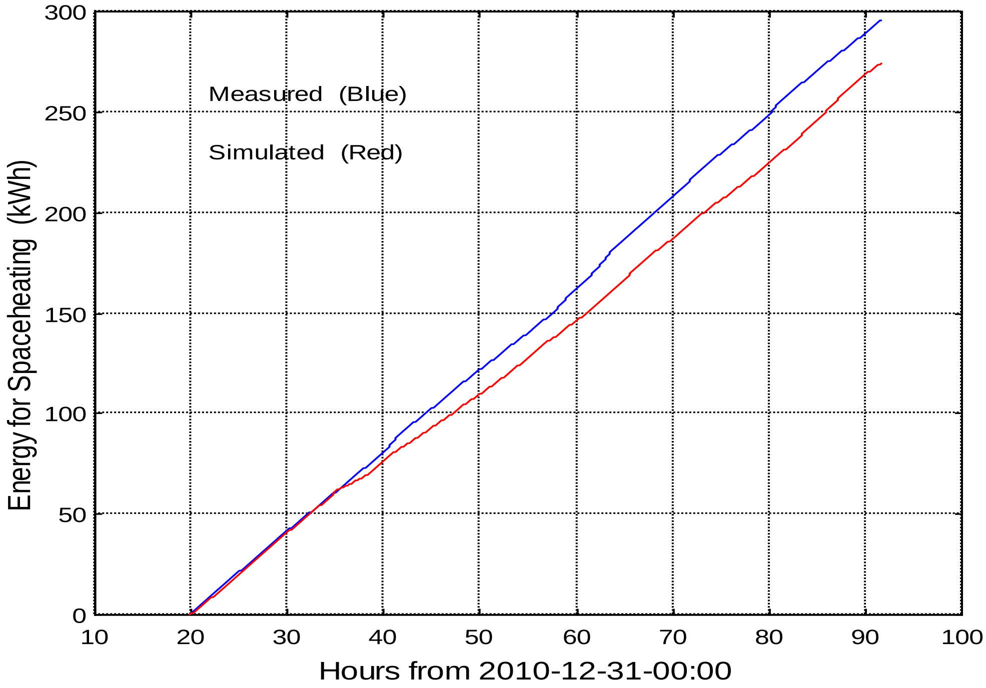

Figure 24: Comparison of Simulated and Measured Space Heat

There is still a steady difference in the slope of the two energy functions after the first day, even though the outdoor temperature had increased by more than 10 degrees. This pointed toward a steady component of heat loss, such as the basement loss. Since the total space heat demand has to meet the original value measured at -20°C, the linear heat loss factor must be decreased as the basement loss is increased.

Various combinations of these were tried and the final parameters that gave the best comparison were:

- Solar heat gain factor: 0.3
- Linear heat loss coefficient: 0.082 kW/°C
- Basement loss: 0.89 kW

Using these parameters resulted in the comparison shown in Figure 25 The simulation and measured energy functions agree within 4% over most of the range.

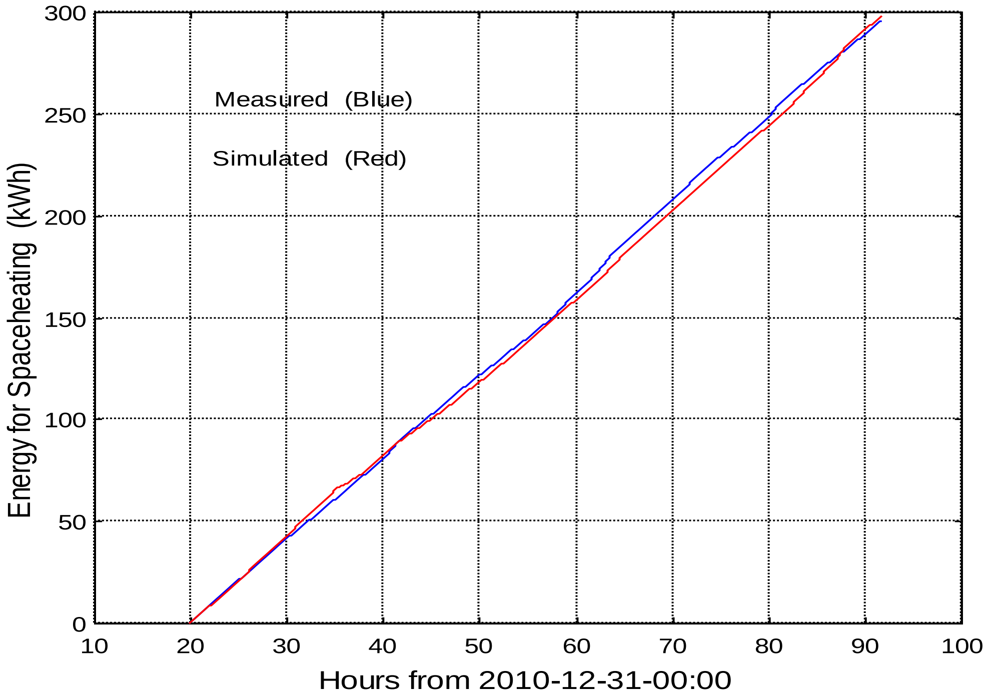

Figure 25: Validation of Dumont House Model with Revised Parameter Set

As previously mentioned, the measured indoor temperature was used to drive the model. However it is difficult to precisely establish temperature in all parts of the building. Since a low-energy house has relatively high energy stored in the building structure the energy balance will be sensitive to small changes in temperature. The effect of these will average over a period of time as the indoor temperature fluctuates about some value.

The conclusion is that to identify all components of heat loss to high precision, it may require more than three days of measurement. If the indoor temperature cannot be held highly stable, which is difficult with high solar gain, it may require more than one temperature measurement at each level of the building. In the case of the main living floor, a temperature measurement at both the north and south side of the building would improve the accuracy.

Another aspect that may need to be considered is the effect of wind. Houses on small lots are sheltered to a considerable extent by neighboring houses but if the winds are strong during a test period they should be measured or compared to periods of low wind.

Similar data was recorded in March but the total building energy did not correspond well with outdoor temperature. The period from 3:00 am to 6:00 am was examined and even though the miscellaneous electrical consumption should have been the least, the lowest consumption for space heat was on the coldest night. There is the possibility that wind effects caused the inconsistency.

Parameters used for case studies of "Future Houses"

Considerable progress has been made in windows in the past decade. Triple-glazed windows are now available with solar heat gain factor of 57%, using low-iron glass. It can be assumed that competition will lower the price of these to be the same as typical triple-glazed units.

For the case studies the parameters were set to:

- Solar heat gain factor: 0.57
- Incidence angle modifier: Same as the ASHRAE data used above
- Linear heat loss coefficient: 0.082 kW/°C
- Basement loss: 0.89 kW

The values give a peak load of 5.87 kW at -32°C. In practice an occupied building will have a few hundred watts of internal gain. Measurements on the Dumont house indicate a loss of less than 5.6 kW at -32°C and this value will be used in the analysis.

Space Heating System

Benefits of low temperature space heating systems

The benefits of operating DE systems at low supply and return temperature have been previously examined[11, 17]. These studies mainly concentrated on cost savings on the distribution network and more efficient use of low cost waste heat.

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

- The branch line to the house can be a smaller diameter, allowing the use of supply and return lines in a common jacket.
- 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 use of low temperature heating makes the system compatible with solar systems, which can be added at a later date. In addition, if a borehole seasonal storage system is used, even a small reduction in water return temperature will have significant improvement 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, cause drafts, etc. These are certainly valid for poorly designed, oversized systems cycling in an on-off mode between 100% and 0 capacity in an older building with high heat demand. Realizing that the Dumont 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 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 high quality 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.

A space heating system with a very low return temperature is shown in Figure 26. This was designed and a prototype constructed under contract in Annex IX[18]. Since the emphasis is on low-energy “future buildings” it is assumed that microprocessor control will be used to optimize the system performance and continually adjust its characteristics to match the operating conditions.

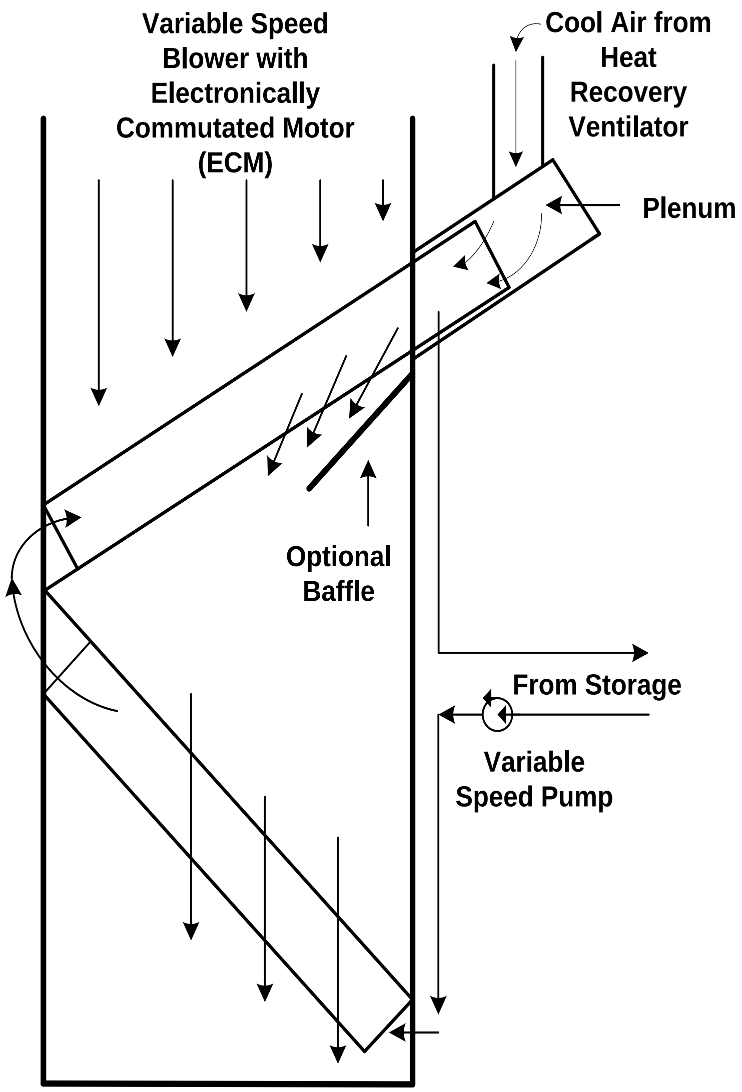

Figure 26: Space Heating System with Single Row Air Coils

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.

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. Even a high efficiency HRV such as the one in the Dumont house 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.

The coils are 61 cm by 76 cm. The cost of the two was a total of $1050 in a single unit purchase.

Testing was done by varying the water flow while keeping the air flow constant at 0.54 m^3 per second. The water temperature was set to 65°C. Power measurements were taken by a heat meter that meets the EN 1434 standard and are accurate to 1.5% at these conditions.

Three cases of ventilation air temperature were measured at a flow of 35 l/sec.

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

The results are shown in Figure 27 and Figure 28.

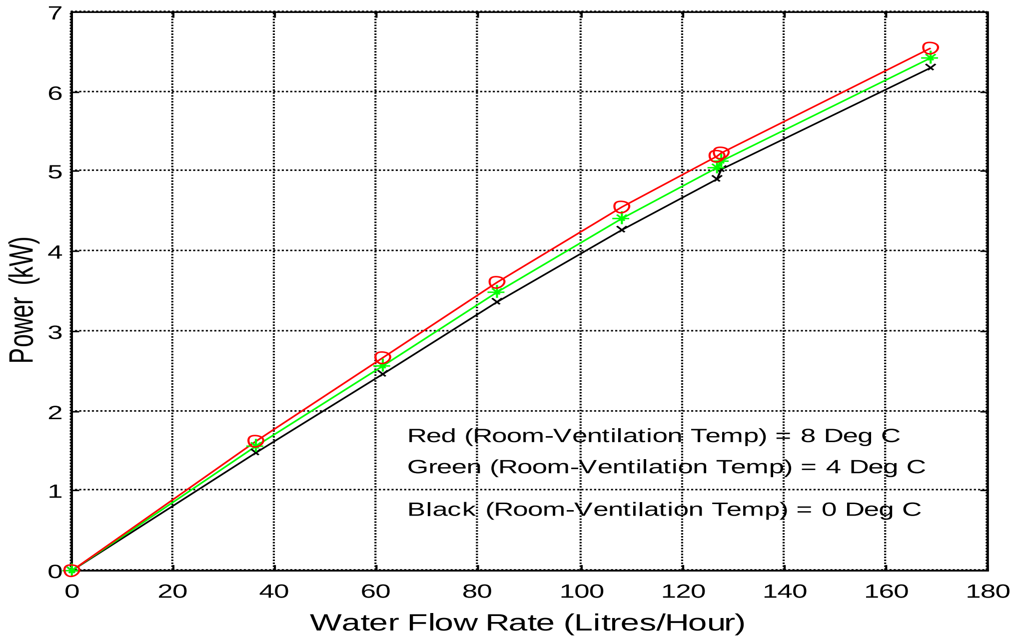

Figure 27: Air Coil Power at Different Ventilation Air Temperatures with Supply Temperature = 65°C

The peak demand of 5.6 kW can be met with a water flow rate of 140 litres per hour at the 65°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.

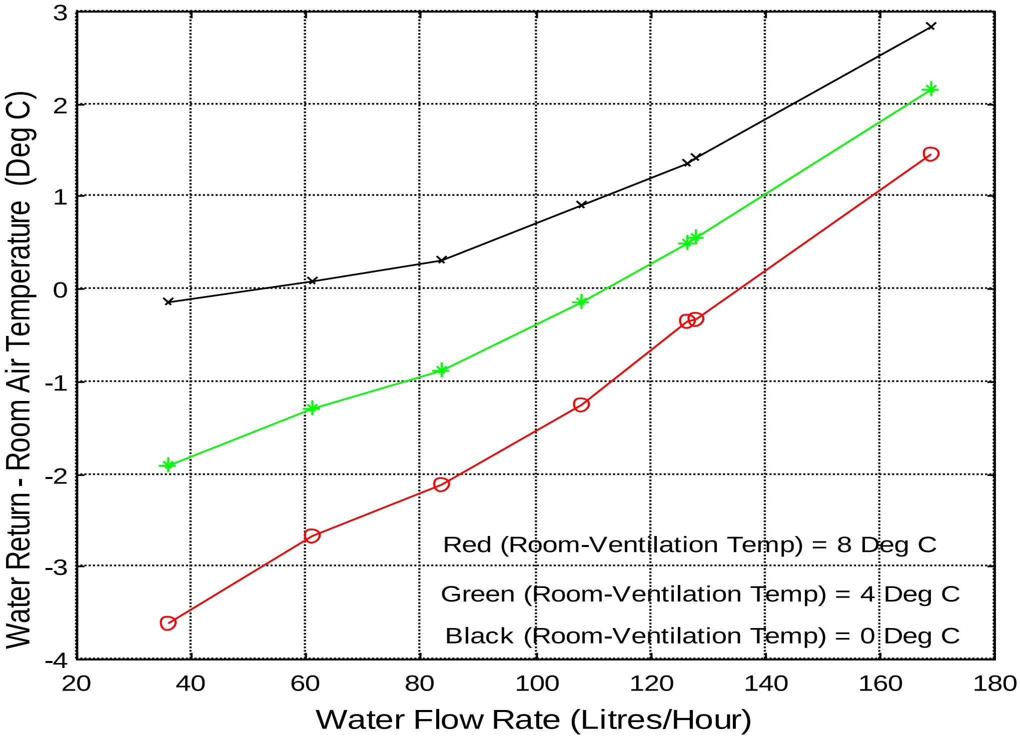

Figure 28: Effect of Ventilation Air Temperature on Water Return Temperature

Figure 28 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 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.

Thermal Storage Systems

For implementation of load shedding in low-energy buildings there are three categories of storage:

- Low cost – using the thermal capacity of the building together with its inherent long time constant
- Medium cost – a DHW storage tank
- Higher cost – active hot water storage for combined space heating and DHW, with provision for solar collectors

The thermal capacity of a medium size house is of the order of 11 kWh per degree. As a result, if a house has a heat loss of 4 kW (corresponding to -20°C in the Dumont house) it can have zero input power and lose less than one degree after two hours even allowing for the fast transient as the room air initially cools.

DHW storage is relatively more important in a low-energy house. A typical DHW consumption of 4,000 kWh per year will be over 30% of total energy consumption.

Combined storage for space heating and DHW storage is effective but expensive. As shown later it has the best payback when combined with active solar energy input. In a non-solar building that uses forced-air heating there may be more economical ways to store intermediate levels of energy by ducting warm air into thermal mass, possibly masonry walls, which has been added to store passive solar energy.

DHW storage

A DHW storage tank can greatly improve the peak shedding capability of the building demand. A once-through heat exchanger can have a peak demand that is ten times higher than the peak demand for space heating. This may require larger diameter pipe on the branch line to the building substation. Even with diversification there still are distinct morning and evening peaks on demand and this will add cost to other parts of the infrastructure. The evening demand will be partially into the period when the cogeneration plant has shut down and there will be extra load on the backup boiler.

Design and maintenance of DHW storage must be done carefully to avoid the risk of Legionella.

The energy to raise the DHW to the required temperature will vary through the year as the ground temperature changes. The municipal water supply is assumed to be equal to the ground temperature.

Configurations of DHW tanks

A common configuration for DHW storage connection to a DE system is to use a coil-in-tank heat exchanger with DE water passing through the coil to heat the DHW. A 280 litre tank of this type can be installed for about $700. These tanks tend to have high return temperature. A full-height coil with some restriction on flow rate will operate at a reasonably low return temperature until it is heating the last section of cold water at the bottom of the tank. Since most plumbing codes now require the entire contents of the tank to be brought to 60°C there will unavoidably be a period when high temperature returns to the DE system. Another problem is that the coil is a small distance from the bottom of the tank and since water has a rather high insulation value there will tend to be lower temperature regions in the bottom edges of the tank.

A configuration that can operate with low return temperature is shown in Figure 29. The substation is similar to a conventional unit with a once-through counterflow heat exchanger. The secondary side operates with a thermosyphon loop and the primary side flow is regulated to limit the power input to about 3.5 kW, similar to the power level in an electric hot water tank. A plate heat exchanger can be used but it may have flow restrictions due to mineral deposit buildup in its narrow channels if the municipal water supply has high mineral content. A better choice would be a tube-in-shell heat exchanger, which is more tolerant of mineral buildup.

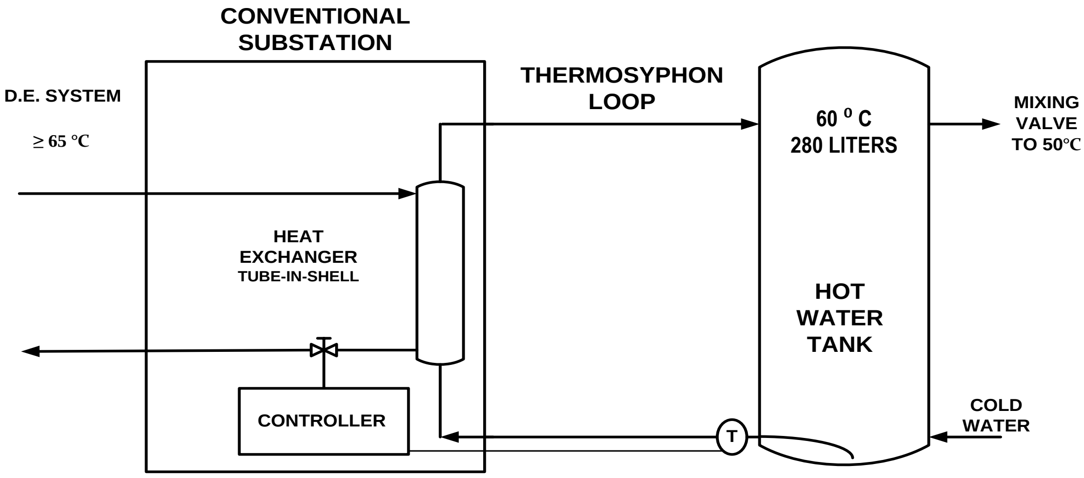

Figure 29: Non-Solar House with Simplified DHW Tank System

The thermosyphon loop has the advantage of reverse flow in the tank, with the cool water from the bottom of the tank being extracted and passed up through the heat exchanger to the top of the tank. This heating and mixing will continue until all the DHW is close to the temperature of the DE supply.

If the control valve modulates the flow from the DES based on the temperature difference between the 60°C set point and the bottom of the tank the flow will stop gradually without significant elevation of the DE return temperature.

There will be increased cost of this system compared to a once-through configuration. The additional cost of $800 is divided in the following manner:

- 280 litre tank installed $400
- Extra cost of heat exchanger $200
- Controller $200

Whatever configuration is used for the DHW storage it must meet local plumbing codes regarding Legionella prevention. Also, some plumbing codes mandate a double wall heat exchanger even if the DE system distribution system pressure levels are much lower than the municipal pressure. This will affect both cost and performance of the system.

Legionella

Legionella are gram negative bacteria found in lakes and streams and man-made water systems. They are responsible for Legionellosis, a sometimes fatal pneumonia or lung infection. In particular, the species Legionella pneumophila appears to be the most likely causative agent with other forms of Legionellae having a more benign nature. Most infections have been caused by inhalation or aspiration of aerosols, smaller than 10 microns in size, containing enough virulent bacteria from water contaminated with Legionella[19]. The bacteria thrive in warm water with temperatures of 25-46°C[20] and are found primarily from cooling towers or evaporative condensers, cooling and ventilation systems, with contamination of the water more strongly located in end runs. People who are immunocompromised, either from treatment for disease, such as cancer or HIV/AIDS or recent organ transplantation are more likely to suffer serious effects, as are people over the age of 70. While patients in the Health Care Sector are most at risk, approximately 2-16%[19]of Legionnaires' disease cases originates in the community (flats, apartments and single family homes). This figure may be an underestimate. Overall, Legionella was responsible for 1.9% to 2.3%[21] of all community acquired pneumonia[22] reported around the year 2000 and 4.9% of hospital acquired pneumonia[22]. The number of cases/year has risen or has been more easily identified since then[23]. 27.3% of cases were community acquired in a European study reported by Helbig in 2002[23]. However, in Ontario, the number of cases in the years 1978-2006 has shown a decrease[24]. Cases of the disease have been found from infection in whirlpools or spas, including at flower shows, decorative fountains and humidifiers. There is disagreement as to whether showers pose a hazard. Several studies indicate this is not so[25] but others believe that it is possible[19]. A study in Quebec indicated that contamination from shower heads and taps appears to come from the growth of Legionellae in the hot water tank which occurred in 39% of households with electric tanks[26].

The virulence of Legionella varies. Above 50°C Legionella can survive, with difficulty but likely do not multiply. At 55°C it takes several hours (from 5 - 10)[27] to kill Legionella, but at 71°C it is killed almost instantly[20 27].

The question then arises as to whether Legionella can grow in solar systems or DHW systems. A study was conducted in Germany comparing Legionella in hot water systems of single-family residences in the suburbs of two cities concerning solar and district heating[28] . While the supplied drinking water was treated, the method was not stated and chlorination was not done. It is uncertain if this biased the results. In Canada, chlorination of the water of public health systems is the gold standard. In the United States the trend is towards the usage of monochloramine as a biocide in municipal water systems and it is more effective than chlorine in preventing transmission of Legionella[29]. The German results indicated that all point-of-use instantaneous water heaters were free of Legionella, probably due to higher water temperatures. Analysis was then done on all systems except those with these water heaters. Legionella was found in 12% of hot water systems of households with a storage tank and recirculation. Factors that did not influence the growth of Legionella included the volume of the storage tank or the use of copper pipes. As in the Quebec study, newer systems grew fewer bacteria than older systems[28].

Contamination by Legionella in the German study[28] was influenced by the type of hot water production. 50% of houses that used heat exchangers from the DE to heat the hot water were contaminated compared to only 5.5% of those with conventional hot water systems. The DE temperature of the water was 47.9°C versus 50.7°C with the conventional system.

There are no published reports of solar heating influencing the growth of Legionella in hot water systems in the German study. Even thought the temperature of the hot water was 47.4°C instead of the conventional hot water temperature of 50.7 °C there were fewer indications of colonization suggesting that high elevations in water temperature in the storage tanks of solar systems inhibits the growth of Legionella. While this may be true in the summertime, it is unlikely to be true on cloudy, winter days.

The conclusion was that the temperature of the hot water is the most important determinate of the presence of Legionella. No Legionellae were isolated from hot water systems with a constant temperature of 60°C or higher.

Other methods to decrease the risk of Legionella in storage tanks include[30]:

- Cold water should be kept to 20°C or less.
- Hot water should ideally be heated to 60°C for one hour per day, preferably at a time of low demand, e.g. early morning and controlled by a time clock.
- However, in the German study[28] raising the temperature of the tank to 60°C on a weekly basis seemed to favour the growth of Legionella.
- Any debris at the base of the storage tanks should be cleaned on a yearly basis.
- Keep water softeners and filters clean to prevent build-up of organic contaminants.
- Filtration devices have proved successful in the Health Care Sector and could be installed in the homes of people at high risk[28].

DHW source water temperature

The ground temperature for the three locations is shown in Figure 30. The winter will have the highest power demand, during the same period when the space heating demand is highest. In the case of Okotoks the DHW needs to be heated from 3°C to 50°C. This will be true in the reference case where it will be heated in one pass through the substation heat exchanger. In the case of a DHW water tank the water temperature must be elevated to 60°C and then mixed down to 50°C via a tempering valve.

The daily volume of DHW in the simulations is set to 225 litres for a typical family of four, with a maximum draw rate of 0.27 l/sec (16 l per min). This is based on a test procedure used by the Canadian Standards Association (CSA). This flow rate will impose a load of over 50 kW on a once-through heat exchanger

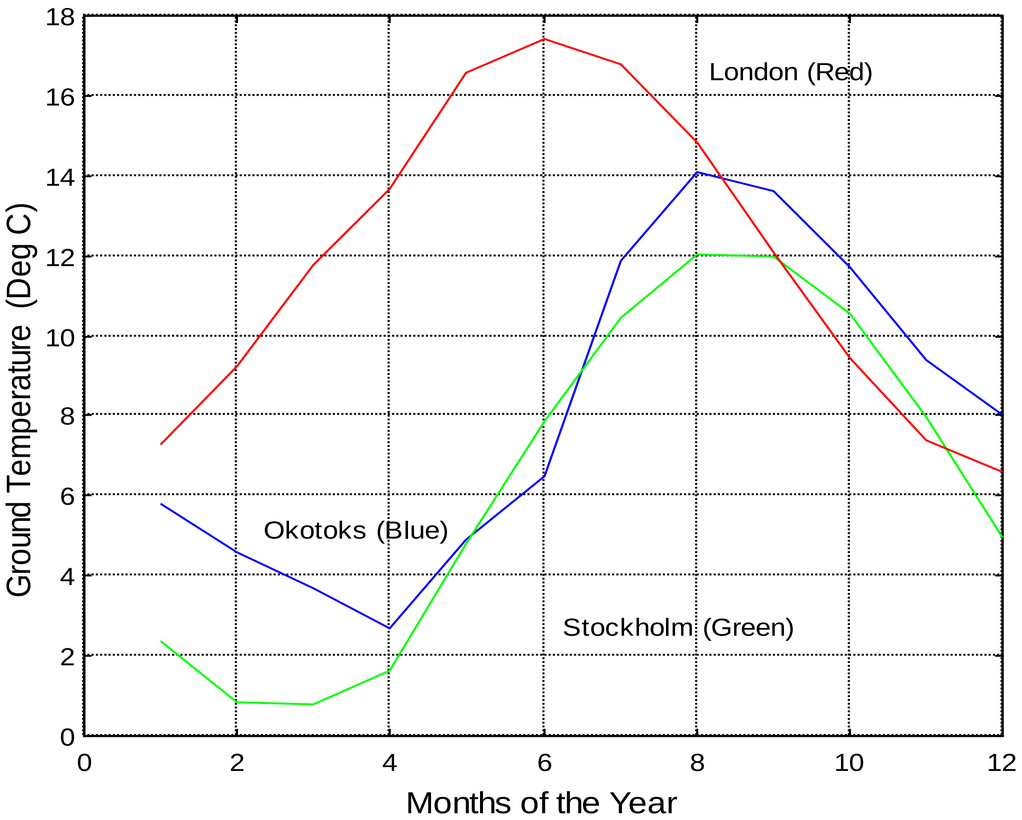

Figure 30: Ground Temperature Variations throughout the Year

The ground temperature variation results in the following power requirements for a once-through system at a flow rate of 16 litres per minute at Okotoks.

50°C delivery temperature:

- Summer = 40.1 kW
- Winter = 52.2 kW

The high value of DHW power required in cold weather emphasizes the importance of buffering the DHW in a storage system at a time when the space heating load is the highest. It also fits in well with the typical operating schedule of the cogeneration plant. Low cost waste heat can be stored at the 5:00 AM startup and used to supply the large morning peak demand. Similarly the energy stored during the early evening can carry the DHW load in the late evening after the 9:00 PM shutdown.

The flow pattern is similar to the one based on measurements from a 24 unit apartment[31]. This level of diversification gave a peak power level of 1.8 kW on a per unit basis. Based on Swedish experience with larger systems[32], the flow pattern was modified to give a per unit peak of 1.2 kW.

The power function is shown in Figure 31 for the three cities at the time when the ground temperature is coldest.

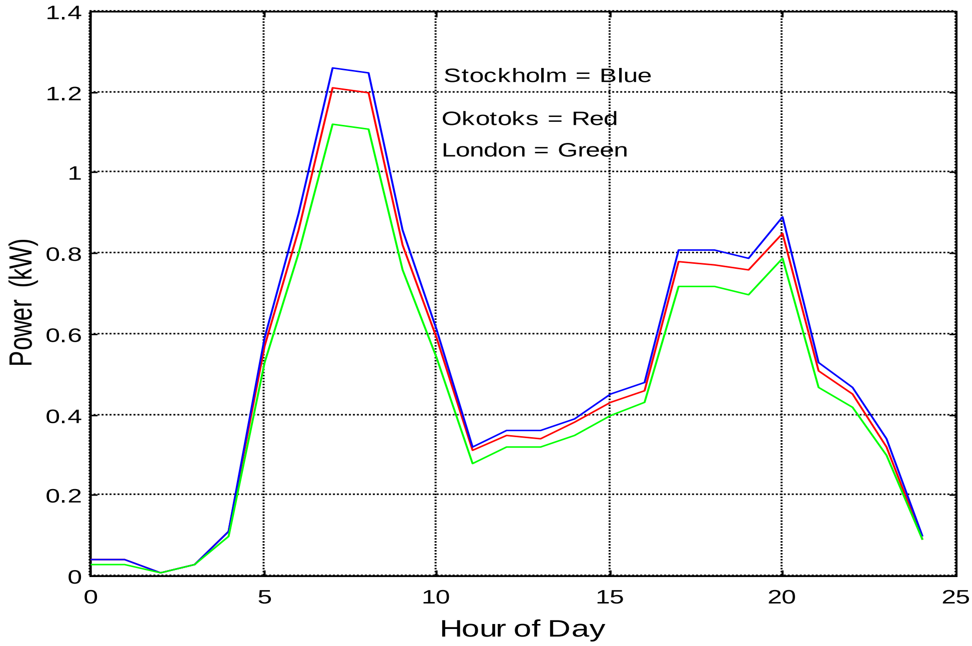

Figure 31: DHW Power per House, Diversified for 240 Houses

This power profile was combined with the yearly ground temperature to generate a time-series of power demand seen by the DE through the year and this data set was used in the simulation case studies.

Storage to combine domestic hot water and space heating

A considerably more effective storage system is one that can supply both space heating and DHW. In a low-energy house even a modest volume, less than 1000 litres will carry the DHW and space heating load through most of the night, during the seven hour period after 9:00 PM when the cogeneration plant is not operational in these case studies. If 1000 litres is discharged from 65°C to 25°C the energy that will be recovered is 46 kWh, assuming well- controlled stratification. The peak space heating load of the Dumont house is 5.6 kW and this energy will last 8.2 hours. Since peak conditions occur so infrequently, in practice a smaller volume can also be very effective in reducing the yearly consumption of fossil fuel in a backup boiler.

Testing was done in both two tank and three tank configurations. One tank has a volume of 450 litres and contains an almost full-height coil heat exchanger of 25 mm diameter pipe with a length of 26 meters and surface area of 2.1 m^2. One or two 280 litre tanks made up the rest of the volume.

The volume available in the configurations was:

- Two tank system 730 litres
- Three tank system 1010 litres.

The 730 litre system is shown in Figure 32.

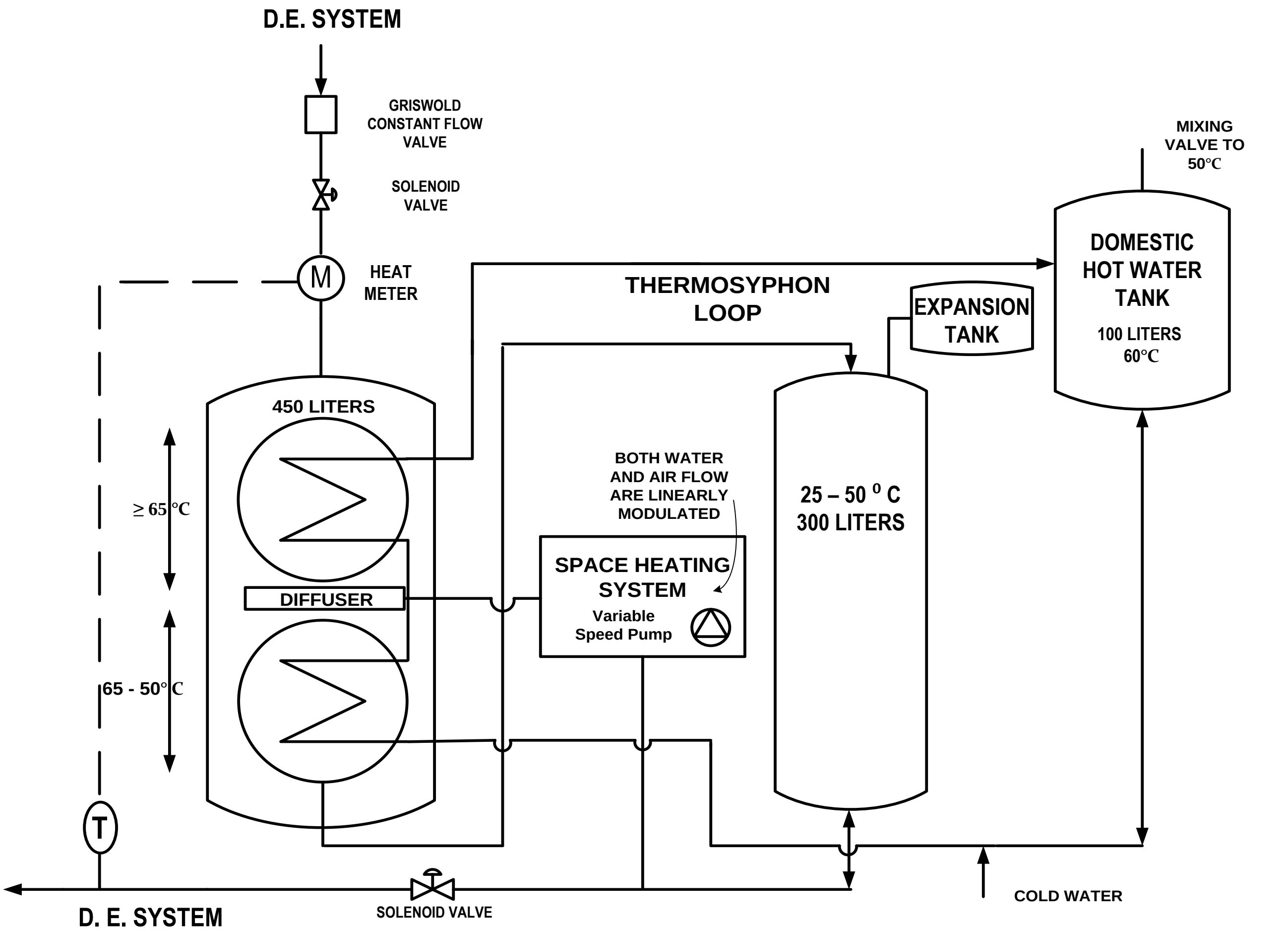

Figure 32: Combined DHW and Building Thermal Storage (Two Tank System)

The tanks are in series to enhance stratification. Diffusers were constructed and installed in all connection points except the bottom of the tanks. The bottom connection has a short curved pipe that directs the inflow of water to the bottom to mix with cool water at that location. As a result it was not possible to install diffusers at the bottom of the tanks.

The space heating system extracts water from a point at about 65 % of the height of the 450 litre tank, reducing the effective volume by about 150 litres. This was done to ensure that the upper part of the volume is always at 65°C to maintain the DHW tank at the required 60°C through the thermosyphon loop that connects the two tanks. It also is the best connection point for a solar system if one is added later.

The cool water from the space heating system is returned to the bottom of the smaller tank. When this tank is filled with cool water it is connected to the DE system and transferred to the return line while the storage is partly recharged. The costs for the two tank storage system and space heating system are found in Table 6.

Cost of two tank storage system and space heating system

ITEM	**COST** (Canadian dollars)	**SUBTOTAL** (Canadian dollars)
300 litre tank	$505	
450 litre tank	$1,780	
Variable speed pump and controller	$550	
Charging flow restrictor, solenoid valve and controller	$300	$3,135
Liquid-to-air coils	$850	
Air handler	$600	
DHW storage tank	$300	
Installation	$600	$2,350
Total		**$5,485**

Table 6: Cost of Two Tank Storage System and Space Heating System

The installation of the air ducts is considered part of the house construction.

The storage tanks for space heating adds $3435 if half of the installation cost is allocated to it. The remainder of the cost is for the required heating system.

After testing it was concluded that this configuration was too expensive to justify without solar capability.

The three tank system is a similar arrangement with the additional tank located between the other two.

Supply of DHW from storage

The transfer to the DHW tank is done by a thermosyphon loop through the heat exchanger in the 450 litre tank. This heat exchanger also acts as a partial one-pass path during a draw of DHW. The other path is directly to the bottom of the DHW storage tank. This tank is 100 litres, equal to about half of the daily water consumption, after mixing down to 50°C.

The thermosyphon system has the inherent advantage of self-regulation of flow based on temperature difference. This enables good control of stratification without complex control systems. Testing done on solar DHW systems at the Canadian National Research Council[33] indicated the benefits of thermosyphon flow in systems where stratification control is important. Side-by-side comparisons between solar collector drain back systems and a glycol thermosyphon collector loop indicated higher performance in the thermosyphon system even though it had an extra heat exchanger.

Testing done on the 450 litre tank thermosyphon system indicated fast response and high heat transfer. The flow settles close to peak value in less than 15 seconds and the heat transfer was about 3.8 kW, equal to an electric heater.

The recovery of the DHW tank is shown in Figure 33. Prior to opening the thermosyphon loop valve the tank was depleted to 23°C.

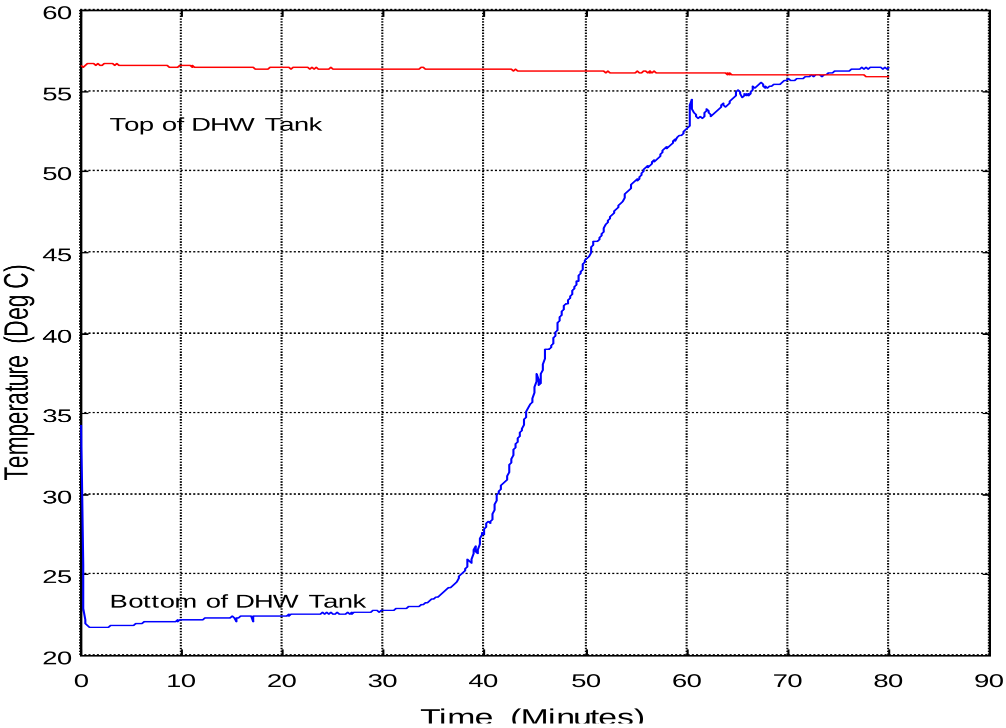

Figure 33: DHW Tank Recovery from 23°C

Multiple DHW charge/discharge cycles of two tank storage system

In order to establish the capability of the DHW system to meet the 225 l/day demand a series of five DHW draws totaling 155 litres were done over a period of 2.3 hours.

Test conditions:

- Flow rate 7.0 litres per minute
- Each draw 31 litres

The 450 litre storage tank was recharged within 10 minutes of a draw cycle. The DE supply temperature was close to 66°C.

The thermosyphon loop output to the DHW tank was in the range 56 to 57°C. Since the entire DHW tank is above the highest point of the thermosyphon coil its coldest section would be driven to 60°C even if the lower section of the 450 litre tank is below 50°C, so long as this tank is well stratified. The DHW delivered temperature was close to 51°C, indicating some mixing in the DHW tank, as the partially preheated water enters. The height of the 100 litre

DHW tank is 70 cm. A larger tank would have less mixing.

The charging was controlled manually, stopping when the exit temperature from the bottom of the 450 litre tank reached temperatures in the range of 47 to 51°C. In practice the DE system return temperature would be well below these values. During the heating season the bottom of the last tank would be filled with 23°C return water from the space heating system. Since this storage system will typically be connected to a medium size solar system there would be few occasions to purchase DE system energy during warm weather. If an automatic charge control sensor were located near the middle of the tank a compromise could be established between low DE return temperature and DHW recovery time.

The test proved that 155 litres could be withdrawn over a 2.3 hour period without the supply delivery temperature dropping below 51°C.

Stratification test of three tank system

The space heating system was operated at a flow rate of 178 litres/hour, which corresponds to a power level of 8.9 kW at 65°C of supply water. For testing purposes the supply temperature was reduced to 48°C. This should have negligible effect on stratification. The results are shown in Figure 34. Since the diffuser is located at about 60% of the height of the 450 litre tank the effective volume of the tanks is approximately 870 litres.

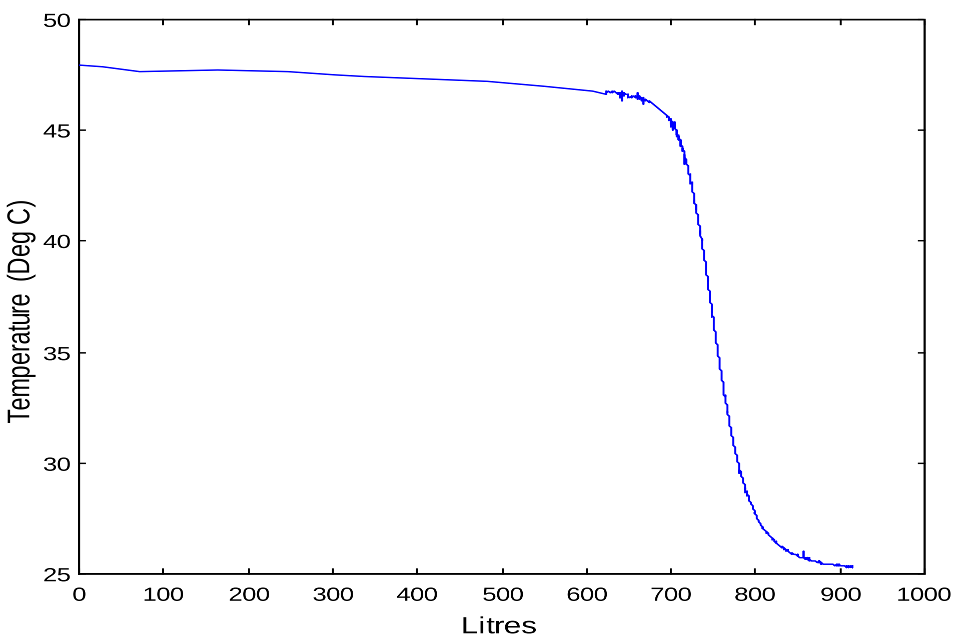

Figure 34: Stratification Performance of Three Tank System at 178 Litres/Hour

There is a small loss of stratification during the five hour duration of the test. The supply temperature stays fairly constant for about 700 litres and then falls rapidly. Assuming the space heating requirement is not too high when the temperature begins to fall, by lowering the air flow rate the supply temperature could be operated to below 40°C without causing discomfort in a house with a long time constant. This has the advantage of improving the stratification profile, which will tend to deteriorate with repeated charge/discharge cycles.

Off-peak charging of thermal storage

As shown in Appendix A, a test was done on the Dumont house in which the 4,000 litre storage tank was charged to 50°C by an electric tank that emulated the connection to a DE system. The DE source was disconnected and the space heating system was only operated from storage. With an outdoor temperature of -15°C, with some passive solar gain, the system operated in this mode for 22 hours before the indoor temperature had a significant drop and the electrical tank was reconnected to the storage tank.

The house was equipped with a large storage system to be compatible with the solar collector array input. If thermal storage is charged to 65°C and the temperature drop through the heating system is 40°C, a smaller storage could be used. An 800 litre tank could supply the space heating of the house on the coldest night during the seven hours when no energy is available from the cogeneration plant. This assumes that the storage is highly stratified.

Use of load shedding and charging of storage to minimize backup boiler cycling

Thermal storage, in addition to enabling more efficient use of waste heat, can also stabilize the supply temperature in a DE system. This is especially true in a small system with only a single boiler supplying the entire load.

There can be stability problems when the system load is at an intermediate level.

The typical startup procedure for some small to medium-size gas boilers is to start with a high firing rate to purge unburned gases from the combustion chamber and bring the boiler up to capacity quickly. After a few minutes of operation at a high firing rate this can be reduced if a lower heat output is sufficient. The temperature rise through the boiler is a function of the water flow rate through it. At the initial high firing rate under intermediate levels of heat load in a system with no storage the boiler exit temperature can rise rapidly. If it reaches the cutoff temperature before the high firing rate startup cycle is complete the boiler will shut down. Under some load conditions, this can lead to a continuous on-off cycling if a single boiler with limited modulation capability is used. This has been observed in two DE systems in the one-to-five MW range. This cycling, if it lasts over extended periods, can induce fatigue stresses in steel distribution pipes. There are design recommendations for the maximum rate of change that should be part of normal operation. One system in Ontario was observed to exceed this recommendation by a factor of eight for hours at a time. The cycling also puts stress on the boiler and its control systems.

An example of boiler cycling is shown in Figure 35.

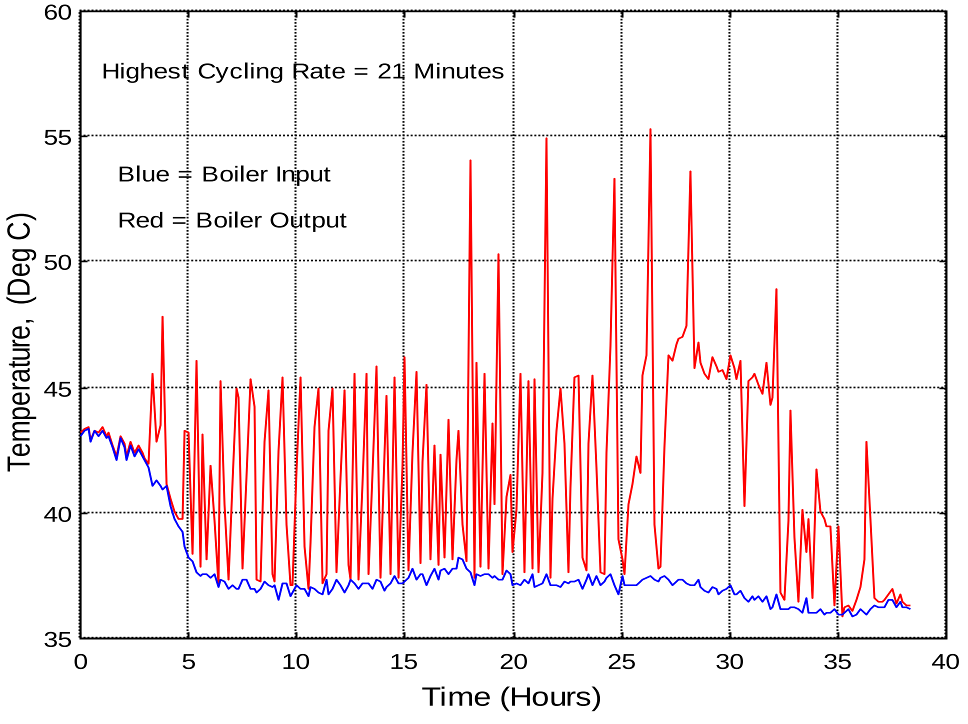

Figure 35: Cycling in a Backup Boiler on a Small DE System

The recycle rate in the fastest section is about 21 minutes.

The strategy to control the boiler system would be to avoid startup when possible. A request would be issued to the building control systems to go into load shedding mode. If the system demand keeps increasing to the level where a boiler startup is mandatory a request would be issued to store energy for the few minutes required to get the boiler through the start transient and operating at a lower level. At that time the request to store energy would be removed. In this situation the utility may choose to offer this energy at a reduced price, or even free, for a few minutes.

Case Studies 1-5

Case studies of low-cost load shedding methods

The primary objective of the load shedding energy management options is to time-shift loads as much as possible to periods when waste heat is available from a cogeneration plant. This will increase the sale of low-cost energy that can be utilized from the cogeneration plant and sold to additional loads. It also minimizes the consumption of fossil fuels.

Load shedding can be used to either reduce the percentage of energy from a backup boiler for a given load or to increase the total amount of energy that can be sold in the new future sub-division for the same percentage of backup boiler energy. Since increasing total sales increases the profit of the DE utility the latter is used in this analysis.

The basic approach in the simulation case studies is to compute the dynamic time-series yearly power demand and the cumulative fraction of this being supplied from a backup boiler. As the total DE system load is increased the backup boiler meets more of the load along a complex function of the statistics of hourly weather, space heating and DHW demand. The reference case is the low-energy building based on the Dumont house but with no upgraded energy management. Then similar buildings with improved energy management are compared to this, with simulations done to some upper limit of backup boiler energy usage, perhaps 30% of total yearly energy.

The first group of simulations was done with elementary load shedding using the thermal mass and long time constant of low-energy buildings, plus the use of a DHW storage tank. The cases are described below.

Any load shedding needs to be either based on direct control by the DE utility or on-line information regarding peak rates that are about to be applied due to an impending peak that will require operation of the backup boiler. In all cases of automatic control the building owner would be able to over-ride the load-shedding commands.

Load shedding has the effect of flattening the load duration curve, making more energy available from a source with limited capacity. Then additional houses could be connected to the same cogeneration source. However, this complicates the analysis since it implies a subdivision covering a larger area, with different distribution requirements for each case study.

To simplify the analysis with variations in total load without changes to the distribution system a large load such as an apartment building was assumed to be at a location on the main supply line. For the simulations this single load was varied in size. This load was increased in units of "equivalent house loads". As more surplus energy becomes available due to load management this building was assumed to be increased in size to absorb all the extra energy.

This apartment building was assumed to have approximately the same thermal time constant as the low-energy houses.

Analysis was done on the following case studies:

- Case 1: This is the Reference case – with low-energy buildings, similar to the Dumont house, which has a wood frame construction and a small addition to the thermal mass. It is operated with a constant indoor temperature and standard substation with a one pass DHW heat exchanger.

- Case 2: Same as Case 1 with utility controlled shedding of space heat, down to 0.7°C below set point when no power is available from the cogeneration plant.

- Case 2.1: Same as Case 2 except set point is elevated 1°C from 17h to 21h.

- Case 2 with NSB: Same as Case 1 using night setback of 2.0°C between 22 hours and 5h, corresponding to the times when the cogeneration plant is shut down as well as controlled shedding of space heat, down to 0.7°C below set point

- Case 3: Same as Case 2 with a doubling of the building thermal mass.

- Case 3.1: Same as Case 2.1 with a doubling of the building thermal mass.

- Case 3NSB: Same as Case 1 NSB with a doubling of building thermal mass as well as controlled shedding of space heat, down to 0.7°C below the set point

- Case 4: Same as Case 3 with a 280 litre DHW tank with a configuration such as the tube-in-shell heat exchanger of Figure 29 to maintain a low return temperature to DE system.

- Case 4.1: Same as Case 3.1 with a 280 litre DHW tank with the heat exchanger configuration of Case 4.

- Case 4NSB: Same as Case 3NSB with 280 litre DHW tank with the heat exchanger configuration of Case 4 as well as controlled shedding of space heat, down to 0.7°C below set point.

- Case 5: Case 5 combines DHW and thermal storage for space heating. It uses the two tank thermal storage as shown in Figure 32 and has a volume of 750 litres.

Procedure for case studies

The dynamics of the thermal energy available from the cogeneration plant are a function of how large the thermal load is in the old DE system and the yearly percentage of energy from its own backup boiler. If the local load absorbs too much of the cogeneration thermal energy there will only be intermittent times when energy can be supplied to the new subdivision. Preliminary simulations indicated that if the old DE system was requiring more than 15 or 20% backup boiler to meet its own demand the potential to sell more energy via load shedding was falling off. Since the objective was to identify any system configurations of low-energy houses that had potential for economic payback the simulations were restricted to the case where the cogeneration plant required 10% backup boiler energy to meet the demand of the old DE system. Since each case of load shedding configuration required multiple simulation runs this kept the number of simulations to a manageable level.

Even at this relatively low ratio of backup boiler on the old system the simulation results showed some periods of low temperature where there was no cogeneration energy available to the new subdivision for a few days in a row and there was insufficient passive solar energy to raise the temperature during the day. In this situation the control logic would let the temperature drop and stay down at 0.7°C below the set point until the outside temperature became warmer. The occupants have the option of raising the set point manually or dressing more warmly. Since they will see an indicator that the system is running on more expensive backup boiler power it is assumed for this analysis that they will choose to keep the lower temperature set point. The results of the simulations are shown in Figures 36-41.

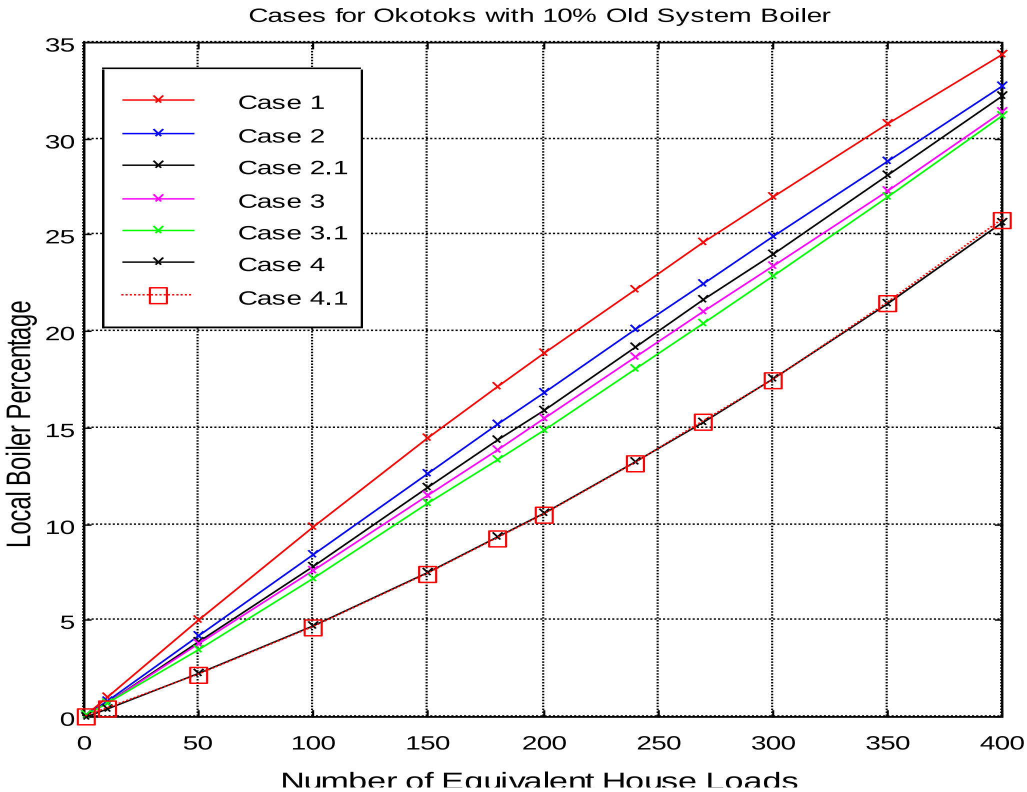

Figure 36: Cases for Okotoks with 10% Old System Boiler

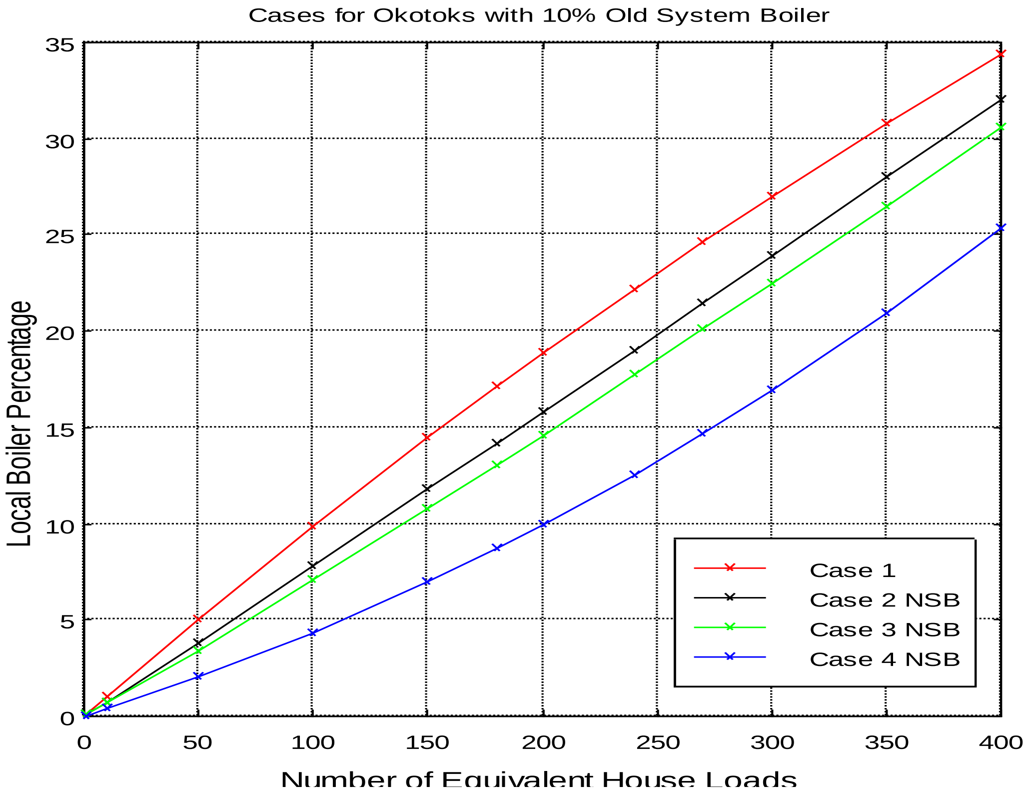

Figure 37: Cases for Okotoks with 10% Old System Boiler using NSB

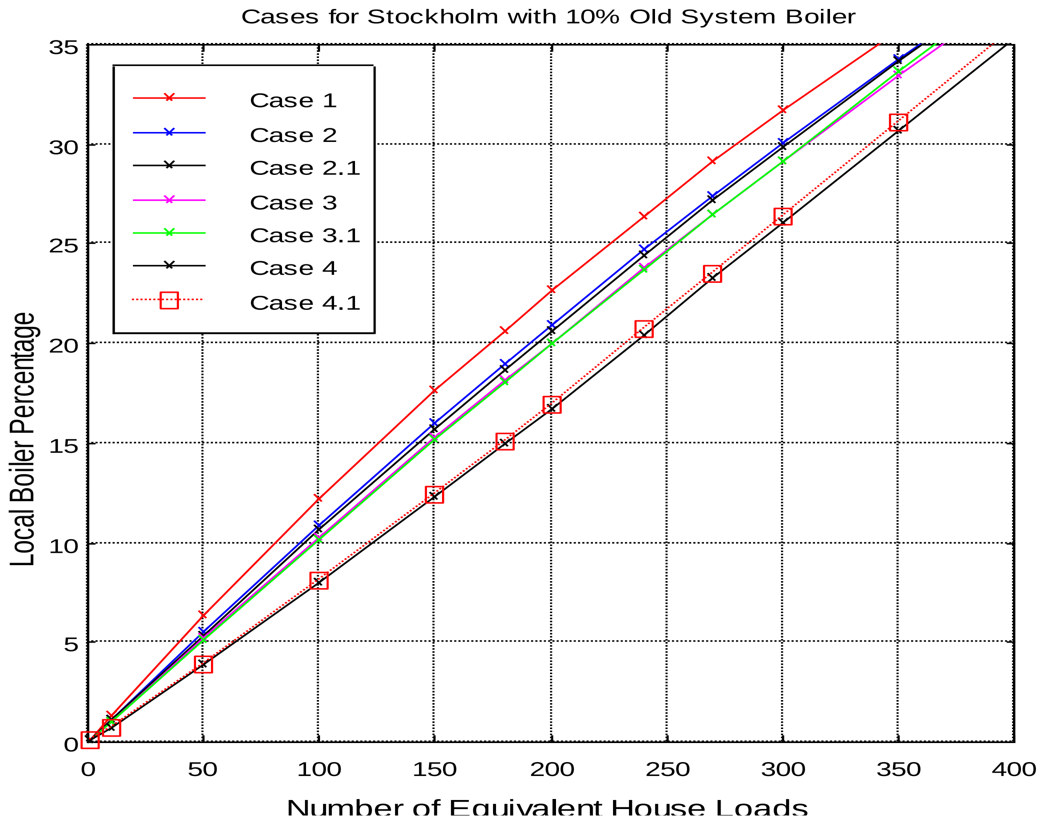

Figure 38: Cases for Stockholm with 10% Old System Boiler

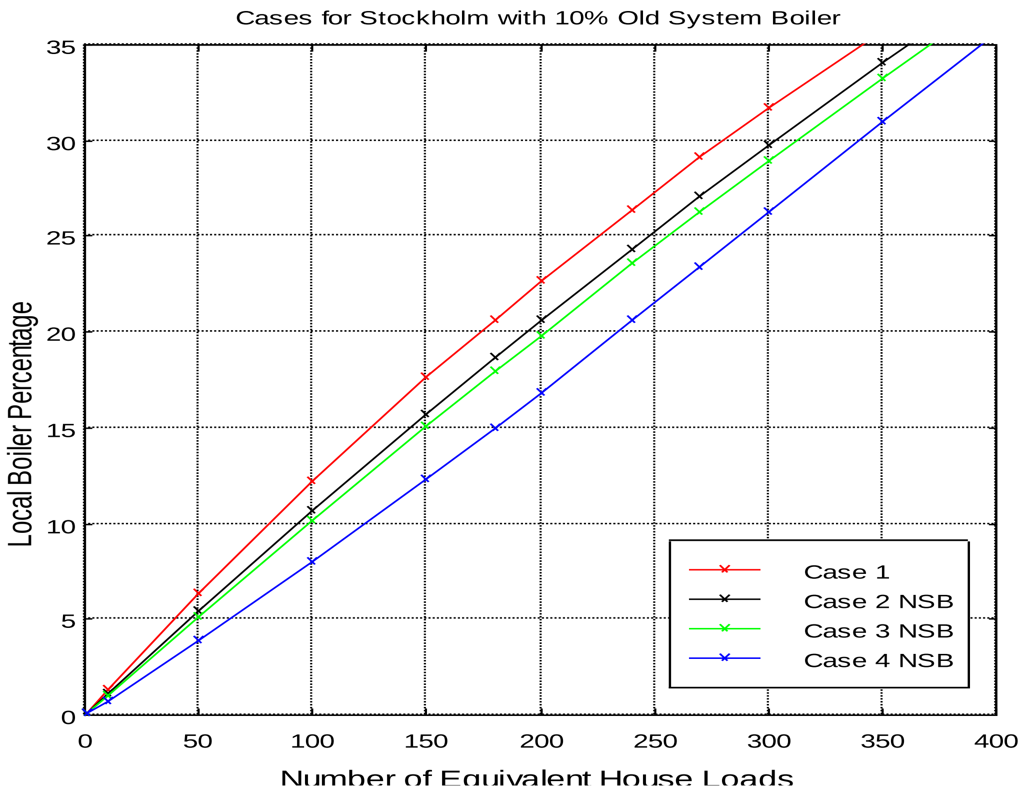

Figure 39: Cases for Stockholm with 10% Old System Boiler using NSB

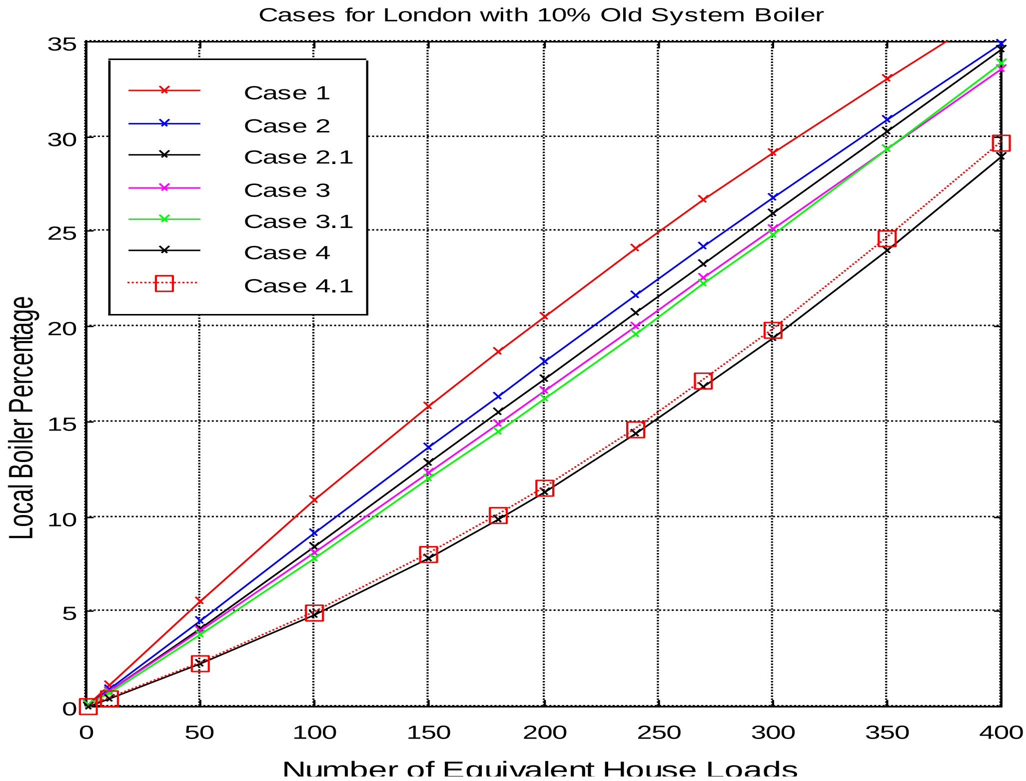

Figure 40: Cases for London with 10% Old System Boiler

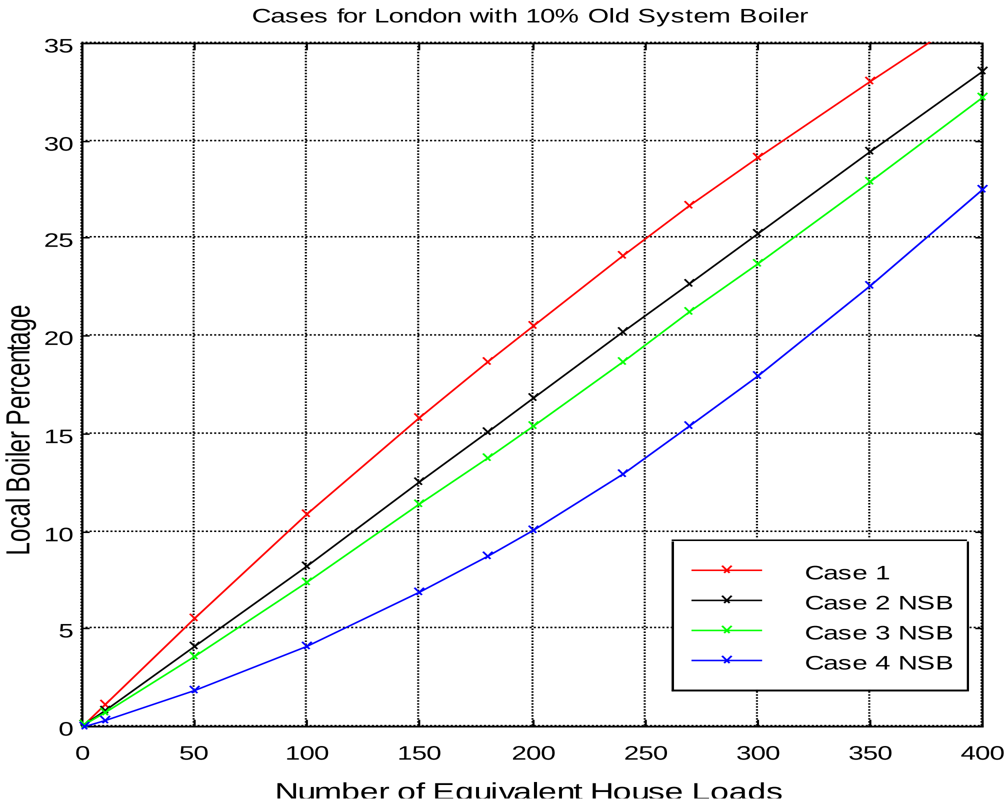

Figure 41: Cases for London with 10% Old System Boiler

Definition of equivalent house loads

For each case, in order to accurately compute the increased energy that can be sold for a given percentage of a backup boiler, a correction must be applied to compensate for the small variation in total yearly energy consumption for a particular house configuration. For example, a night setback of 2.0°C typically has a yearly reduction of total energy consumption, including DHW, of three percent.

The case studies from each of the three cities: Okotoks, Stockholm and London have been normalized to have approximately the same kWh yearly usage for comparison. This was done by adjusting the linear part of the heat loss factor in the houses and running simulations for the year until the energy consumptions for the three locations were within a few percent of each other. Figure 42 demonstrates this and Figure 43 shows the load duration curves for one house. (Calgary and Okotoks weather are the same.)

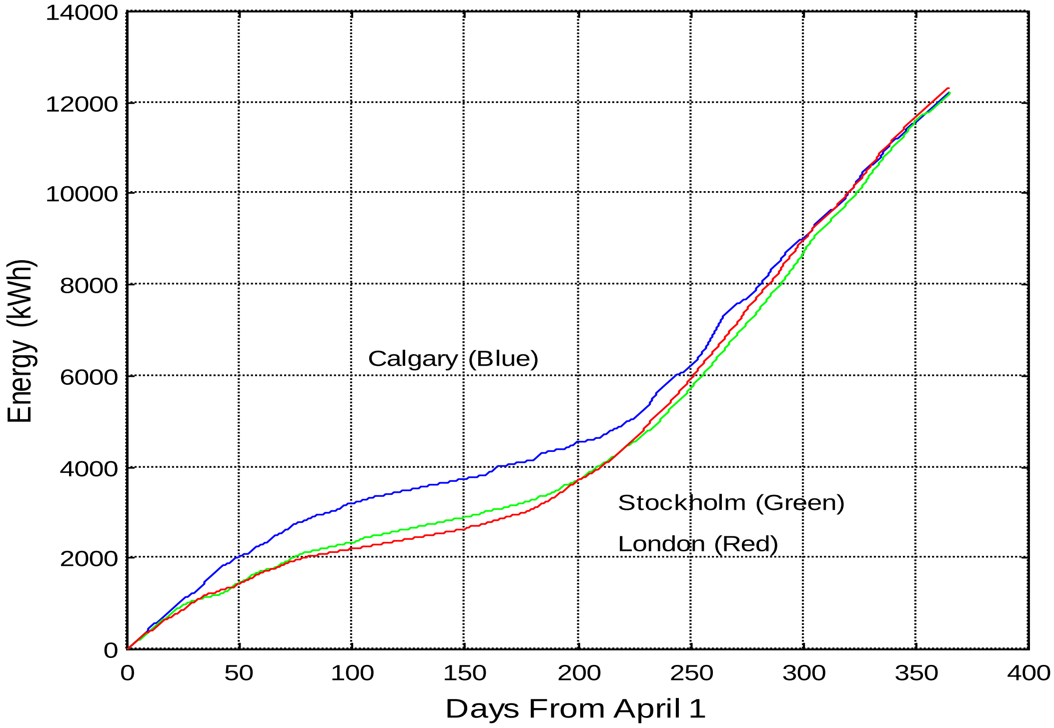

Figure 42: Space Heating plus DHW Energy Integrals

Keeping air leakage, ventilation and basement losses constant, the linear heat loss factors (HLF) were:

- Okotoks = 0.082
- Stockholm = 0.069
- London = 0.118

Peak power (kW) follows:

- Okotoks = 5.8
- Stockholm = 4.6
- London = 4.4

The peak power varies by 27% between the three cities even though the yearly energy has been adjusted to be the same. This indicates the differences in climate. Okotoks has a colder spring and the fluctuations in the graph during the winter illustrate the temperature swing in the winter.

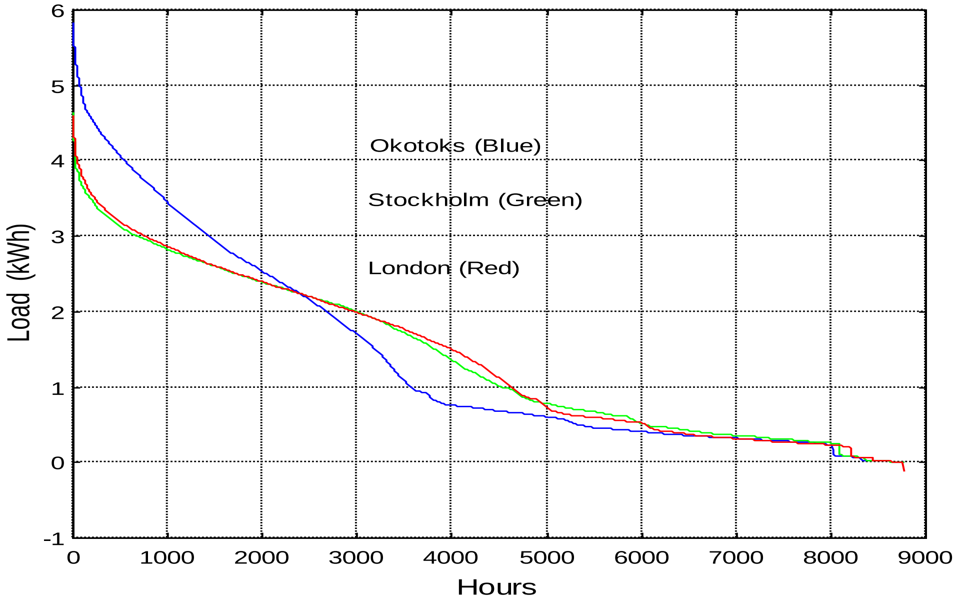

Figure 43: Load Duration Curves for One House

Figure 44 shows the large variation in passive solar gain in the three cities. Okotoks has a much larger gain during the winter.

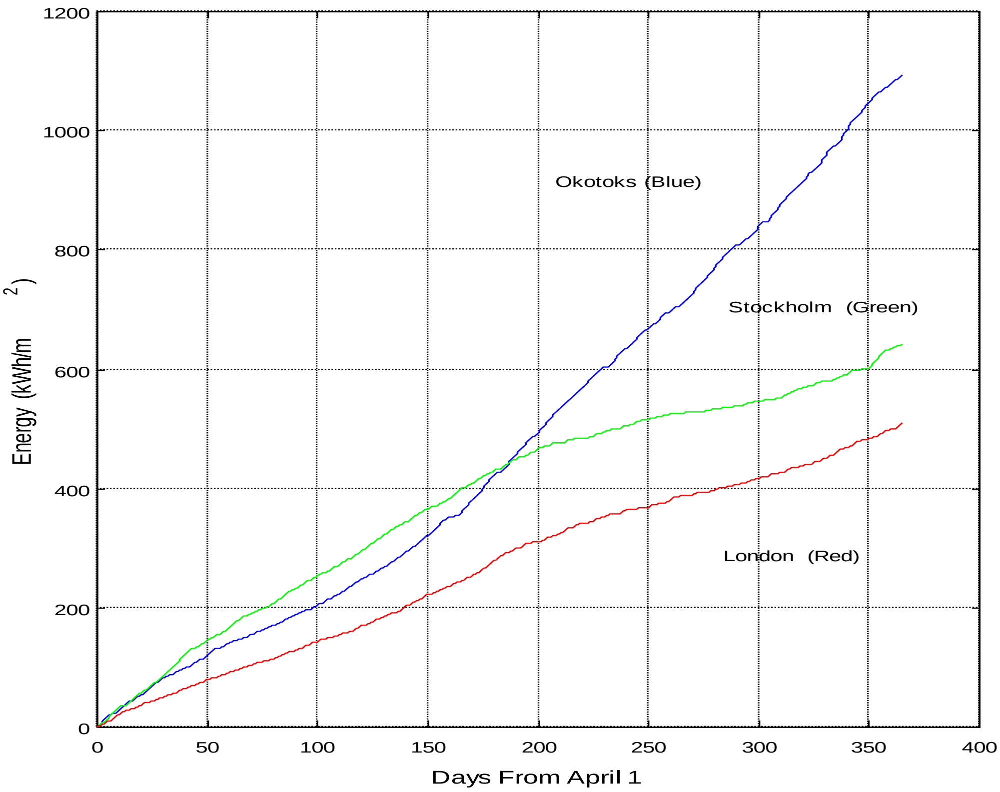

Figure 44: Solar Gain through Window/m²

For each of the case studies shown in the graphs the "number of equivalent house loads" was multiplied by the adjusted yearly energy consumption to obtain the actual energy sold by the utility. These energy consumption quantities are shown in Tables 7-9.

Case Number	kWh	% Energy Savings With Respect to Case 1
1	12207	
2	12013	1.6
2.1	12127	0.7
2 NSB	11887	2.6
3	11805	3.3
3.1	11992	1.8
3 NSB	11716	4.0
4	11816	3.2
4.1	12005	1.7
4 NSB	11727	3.9

Table 7: Okotoks Case Studies

Case Number	kWh	% Energy Savings With Respect to Case 1
1	12222	
2	12017	1.7
2.1	12140	0.7
2NSB	11922	2.5
3	11904	2.6
3.1	12078	1.2
3 NSB	11846	3.1
4	11904	2.6
4.1	12069	1.3
4 NSB	11849	3.1

Table 8: Stockholm Case Studies

Case Number	kWh	% Energy With Respect to Case 1
1	12293	
2	11999	2.4
2.1	12243	0.4
2NSB	11853	3.6
3	11924	3.0
3.1	12225	0.5
3 NSB	11839	3.7
4	11935	2.9
4.1	12238	0.5
4 NSB	11850	3.6

Table 9: London Case Studies

The detailed analysis to establish increased sales of energy was done by establishing the percent backup boiler required for the Case 1 house. Then the number of equivalent house loads at this percentage was read from the graph for each case. The total kWh consumed and increased sales for each of the three cities under study was recorded in Table 10. The part of increased sales from the cogeneration plant was then calculated. This is waste heat that would normally be dumped if there were no load shedding.

The Reference Load is with 22.2 % backup boiler.							
OKOTOKS	**1**	**2**	**2.1**	**3**	**3.1**	**4**	**4.1**
No. Houses	240.0	266.0	277.1	285.3	291.6	358.9	358.2
KWh/House	12207	12013	12127	11805	11992	11816	12005
TOTAL MWh	2929.7	3195.6	3360.1	3367.4	3496.3	4240.8	4300.2
Extra Sales (MWh)		265.9	430.5	437.7	566.6	1311.1	1370.5
% Extra Sales		9.1	14.7	14.9	19.3	44.8	46.8
Increased Cogen							
Heat (MWh)		206.9	334.9	340.5	440.8	1020.0	1066.3
The Reference Load is with 26.4% backup boiler.							
STOCKHOLM	**1**	**2**	**2.1**	**3**	**3.1**	**4**	**4.1**
No. Houses	240.0	258.6	261.7	269.0	268.9	303.6	300.3
KWh/House	12222	12017	12140	11904	12078	11904	12069
TOTAL MWh	2933.3	3107.6	3177.0	3202.2	3247.8	3613.7	3624.3
Extra Sales (MWh)		174.3	243.8	268.9	314.5	680.4	691.0
% Extra Sales		5.9	8.3	9.2	10.7	23.2	23.6
Increased Cogen							
Heat (MWh)		128.3	179.4	197.9	231.5	500.8	508.6
The Reference Load is with 24.1% backup boiler.							
LONDON	**1**	**2**	**2.1**	**3**	**3.1**	**4**	**4.1**
No. Houses	240.0	268.7	279.1	287.7	291.5	344.8	350.3
KWh/House	12293	11999	12243	11924	12225	11935	12238
TOTAL MWh	2950.3	3224.1	3417.0	3430.5	3563.3	4115.2	4287.0
Extra Sales (MWh)		273.8	466.7	480.2	613.0	1164.9	1336.7
% Extra Sales		9.3	15.8	16.3	20.8	39.5	45.3
Increased Cogen							
Heat (MWh)		207.8	354.2	364.4	465.2	884.0	1014.4

Table 10: Load Shedding: Potential Extra Sales of Cogeneration Energy

This Table 11 compares three night set-back cases with the reference case for each of the three cities.

The Reference Load is with 22.2% backup boiler.				
OKOTOKS	**1**	**2NSB**	**3NSB**	**4NSB**
No. Houses	240.0	279.3	297.0	364.2
KWh/House	12207	11887	11716	11727
TOTAL MWh	2929.7	3320.0	3479.7	4271.0
Extra Sales (MWh)		390.4	550.0	1341.3
% Extra Sales		13.3	18.8	45.8
Increased Cogen				
Heat (MWh)		303.7	427.9	1043.5
The Reference Load is with 26.4% backup boiler.				
STOCKHOLM	**1**	**2NSB**	**3NSB**	**4NSB**
No. Houses	240.0	262.3	271.1	301.4
KWh/House	12222	11922	11846	11849
TOTAL MWh	2933.3	3127.1	3211.5	3571.3
Extra Sales (MWh)		193.9	278.2	638.0
% Extra Sales		6.6	9.5	21.8
Increased Cogen				
Heat (MWh)		142.7	278.2	638.0
The Reference Load is with 24.1% backup boiler.				
LONDON	**1**	**2NSB**	**3NSB**	**4NSB**
No. Houses	240.0	286.3	304.4	365.3
KWh/House	12293	11853	11839	11850
TOTAL MWh	2950.3	3393.5	3603.8	4328.8
Extra Sales (MWh)		443.2	653.5	1378.5
% Extra Sales		15.0	22.1	46.7
Increased Cogen				
Heat (MWh)		336.3	653.5	1378.5

Table 11: Load Shedding: Potential Extra Sales of Cogeneration Energy with NSB

Based on Table 10 and 11, detailed costs are given for each of the 10 cases in Table 12.

CASE	1	2	2.1	2 NSB	3	3.1	3NSB	4	4.1	4NSB
c/kWh	5.47	5.22	5.00	5.06	5.00	4.84	4.86	4.57	4.51	4.50

Table 12: Canadian Heat Costs Cents/kWh (20 yr)

Discussion of Phase I case studies

Both London and Okotoks had the largest increase in performance due to load shedding, with each city being ahead in some of the categories. London requires slightly more backup boiler energy to supply the original 240 Case 1 houses with no load management, 24.1% vs. 22.2% for Okotoks.

Case 2

The elementary, almost zero cost, load shedding by permitting 0.7°C droop in house temperature when waste heat is not available has a potential increase in sales of 9.3% at London and 9.1% at Okotoks. Stockholm is considerably lower at 5.9%.

Increase in sales of waste heat:

- Okotoks 206.9 MWh
- London 207.8 MWh
- Stockholm 128.3 MWh

These numbers indicate that by taking advantage of the long cool-down time constant of these houses considerable extra income can be earned by the DE utility by being able to utilize cogeneration energy that would normally be dumped. The intermittent drop in temperature of 0.7°C would hardly be noticed and can always be overridden if required. The slight reduction in yearly consumption is due to the lower average temperature. The average drop for the three cities is 1.9%.

Case 2.1

A variation on the elementary load shedding is to elevate the house temperature by 1.0°C for four hours (at 17 to 21h) before the cogeneration plant shuts down for the night. The slightly higher yearly average temperature raises the total yearly energy to within 0.7% for Okotoks and Stockholm and 0.4% for London. As discussed previously, raising the temperature slightly means that the initial fast temperature of the fast time constant (air and furniture) occurs above the set point and all subsequent loss of temperature will be at the rate of 0.33°C (for -20°C), controlled by the large thermal mass. As a result, a few hours will be gained before the backup heat is required. This raised the use of waste heat by about 15% for Okotoks and London, with Stockholm being lower, at 8.3%

There is some increase in comfort level by slightly elevating the temperature at the end of the day. In a house with high passive solar gain the house will feel slightly cooler after sunset, even if the air temperature stays the same, due to radiant gains and losses. The one degree rise in temperature will counter this.

Cases 3 and 3.1

These cases were simulated with double the building thermal mass, using 64 MJ/°C. Increasing the thermal mass in passive solar houses is fairly common practice to avoid overheating but does get into more specialized design and construction, plus extra cost. It does raise the use of waste heat by about 20% for Okotoks and London, with Stockholm at 10.7%.

One rather simple possibility is to use part of the thermal mass of the building for storing elevated temperatures generated by the air heating system. If a passive solar house has been designed to incorporate extra thermal mass in the form of masonry or some other suitable material it may be practical to direct part of the warm air (35°C) from the space heating system into this thermal mass. An example would be two concrete wall panels with a narrow air gap between them. If a cold night is anticipated energy could be transferred to the panels from cogeneration heat during the afternoon and evening period. As long as the time constant of the panels is more than half a day it should not cause overheating during the day. Then when heat is required at night a thermostatically controlled fan could extract energy from the panels.

The principal is similar to the traditional Scandinavian masonry wall heated by a wood stove.

Warning: Even though most houses have a concrete floor slab that could act as a ready-made thermal storage, room air should not be passed through it. Even with thick insulation under this slab it will tend to be cool during the summer and during periods of high humidity mould could form in the ducts. An interior wall panel in normal room areas will not have this problem.

Cases 4 and 4.1

One characteristic of low-energy houses is that the DHW load becomes a relatively large part of the yearly load, typically 30%. This load can be time shifted by use of a storage tank, with a large impact on the amount of waste heat that can be used.

The two best cities were in the range of 40% to 45% increase in the amount of waste heat that could be used, with Stockholm in the 23-24% range.

As previously discussed, a storage tank has benefits in the peak flow requirements in the branch line. On the coldest day the flow corresponds to a total load of about six kilowatts, instead of around 60 kW for a once-through heat exchanger plus space heating load. With the storage tank a small size branch line (16 mm) can be used, with twin pipes in one jacket, resulting in cost saving.

Cases 2NSB, 3NSB and 4NSB

In the case of 2.0°C night setback there is a significant benefit after the cogeneration plant shuts down. The rate of temperature loss is 0.33°C per hour at -20°C. Under this condition the heating system would not come on for 6.1 hours, within less than an hour of the cogeneration plant startup.

In practice, if a large percentage of buildings are using night setback the morning recovery can overload the available low-cost heat source. In this case the price structure can be used to motivate some homeowners to delay the startup or bring up the temperature on a slow ramp, at lower power level.

Stockholm

It is not clear why Stockholm consistently shows lower levels of performance improvement compared to both Okotoks and London. It is at considerably higher latitude, with very short daylight hours in the winter, so that passive solar gain is lower. This can be seen in Figure 44 which gives passive solar gain through triple-glazed windows. Okotoks has very high yearly solar gain. This can be expected to raise room temperature above the thermostat set point quite often in the winter, storing extra energy in the building structure and enabling the house to accommodate longer periods of load shedding. Stockholm has the lowest passive solar gain of the three cities and will be limited in thermal energy storage. London has the lowest yearly solar gain but most of the deficiency appears to be due to fog conditions in the warm weather. London has higher gain in the winter compared to Stockholm.

Conclusions from Case Studies 1-4

Based on the results of low-cost load shedding using the thermal mass of low-energy buildings there is considerable potential for increasing the sale of waste heat from cogeneration plants. Increased sales in the order of 30% appear feasible, compensating for the relatively low-energy density of these buildings.

Case 5: Two tank space heating/DHW storage of 730 litres

The use of active, water-based storage can effectively load-shift power demand to times of the day when low cost waste heat is available. In low-energy houses about 800 litres of well stratified storage will carry the house through peak load conditions for about seven hours. The cogeneration plant would charge storage during the daytime operation and the storage would supply energy during the night. If the source of waste heat is sufficiently large during its operating periods the system can be 100% supplied by this if each house has storage similar to the two tank system shown previously.

There is a cost associated with this, approximately $3,435 after the air coils and air handler are subtracted from Table 6. The control of the space heating system is more complex than a simple once-through air coil and the return temperature of a storage system tends to be higher than a once-through system.

One conclusion is that if there is to be sizable storage in the house it will have the best payback if linked to a solar system. Then the storage can serve two purposes, to buffer the solar collector output and to load-shift the usage of energy.

The Borehole Model

The model

The modeling of the borehole for this project is based on experience gained from the Drake Landing Solar Community in the Town of Okotoks as shown schematically in Figure 45[34]. The goal of the first phase was to develop a certain sized model and validate it against 3.75 years of actual measured data at Okotoks. Building on this validated methodology the next phase is to expand it by a factor of 2.5, moving forward to a larger, hopefully, more economic system than shown here.

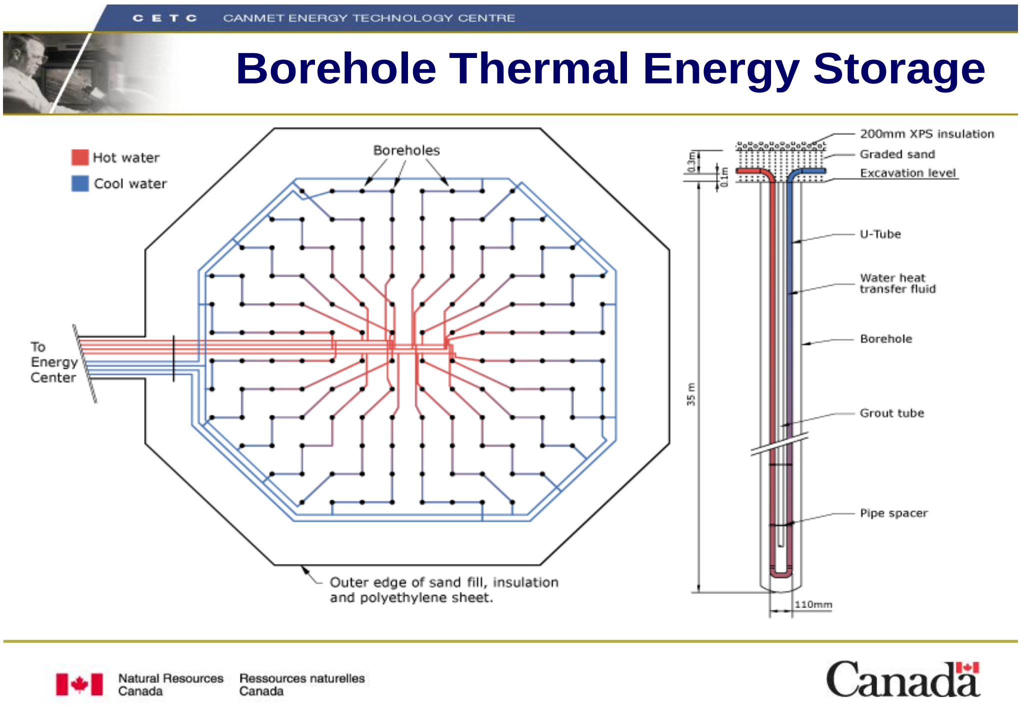

Figure 45: Schematic Diagram of the Okotoks Borehole Thermal Energy Storage

Excavation of the soil and layout of the boreholes at the Okotoks project is shown below in Figure 46[34]. Note the colored markers that indicate placement of each borehole.

Figure 46: Excavation for the Boreholes at Okotoks

In order to understand the workings of the Okotoks borehole more closely, it is necessary to design a model to analyze what is happening in specific areas of the borehole. The following method is used.

Grid-based thermal modeling

The simulations of thermal distributions in solids by using electrical analogies are well known, with temperature being the analogue of voltage, with thermal capacitance and resistance corresponding to their electrical counterparts. For modeling the thermal behavior, we divide the region into a uniform grid[35]. Each square on the grid is modeled as a lumped element, with a heat source at its centre and thermal resistances connecting it to its neighbors, as well as to the top and bottom of the region, as shown in Figure 47.

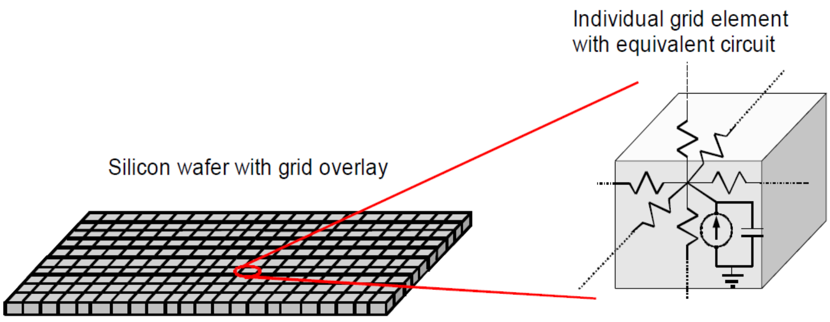

Figure 47: Example of Grid Based Thermal Modeling for Semiconductor Design[35].

In our application, there are no internal thermal sources except for the borehole which behaves as a voltage source at a cell boundary. Further, the simulation is carried out in a two-dimensional region representing an average one-metre layer of the borehole field, with added sparsely distributed vertical elements to simulate the vertical thermal flux due to bottom losses. Compared to physical finite-element analysis (FEA) systems, this approach suffers from complexity in obtaining array thermal distributions and requires individual connections to each element. It has the advantage of running more quickly than a true FEA package and is easier to incorporate into a full system analysis.

Matlab was employed with its graphics-oriented system simulation module SIMULINK™ instead of a dedicated circuit simulator, with a grid elements implemented as shown in Figure 48. The inputs are connected to the outputs of adjacent elements or thermal sources; correspondingly, the outputs are connected to adjacent inputs. The C4 gain blocks represent the cell conductances, in effect the total effective conductances between the centres of adjacent cells, with the thermal flux being calculated as the product of the conductance and the temperature difference of the two cells. The currents are summed, divided by the thermal capacity, and integrated to produce the temperature. An admitted inefficiency of this implementation is that each current is calculated in each of a pair of adjacent cells while providing the advantage of strict regularity of interconnections.

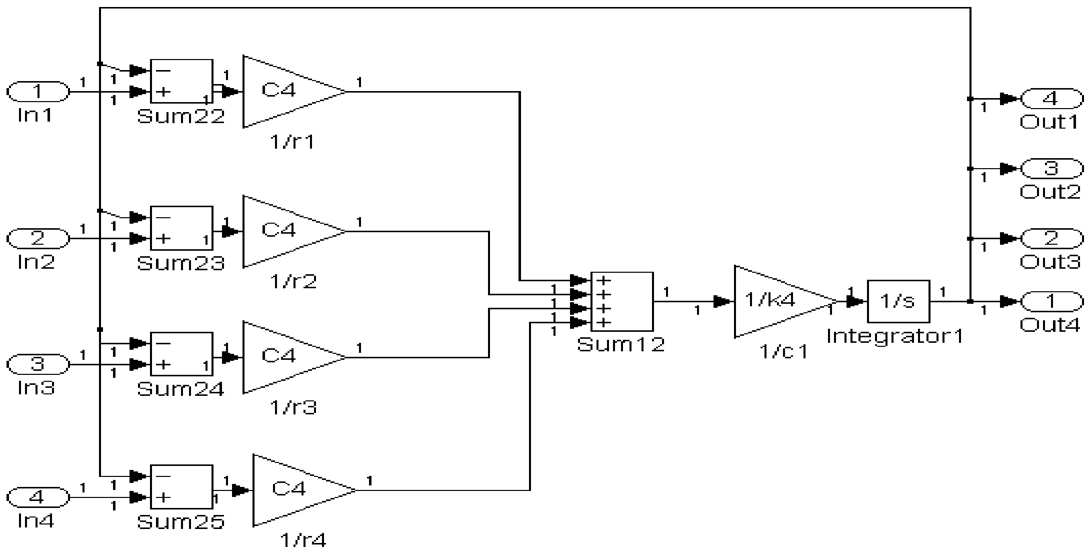

Figure 48: Schematic Representation of One Element of the Borehole Model in SIMULINK™

The vertical loss element is an extra input with the loss conductance being an adjustable parameter used to match measured energy transfers. At thermal walls representing insulated boundaries or symmetry planes, the corresponding input is connected to the cell's output, thus resulting in no flux at that port.

While the conductances of a square cell are independent of its horizontal size, the capacitance is proportional to its area. In this work, its value represents a square of one-sixteenth of 2.25-metre borehole spacing, 0.141 metre on a side. The array used draws its arrangement from the Okotoks borehole field, with six blocks of sixteen cells deep and eight wide having half a borehole in the middle of one side with a thermal wall on each side as well as at the end corresponding to the centre of the field as shown in Figures 49 and 50.

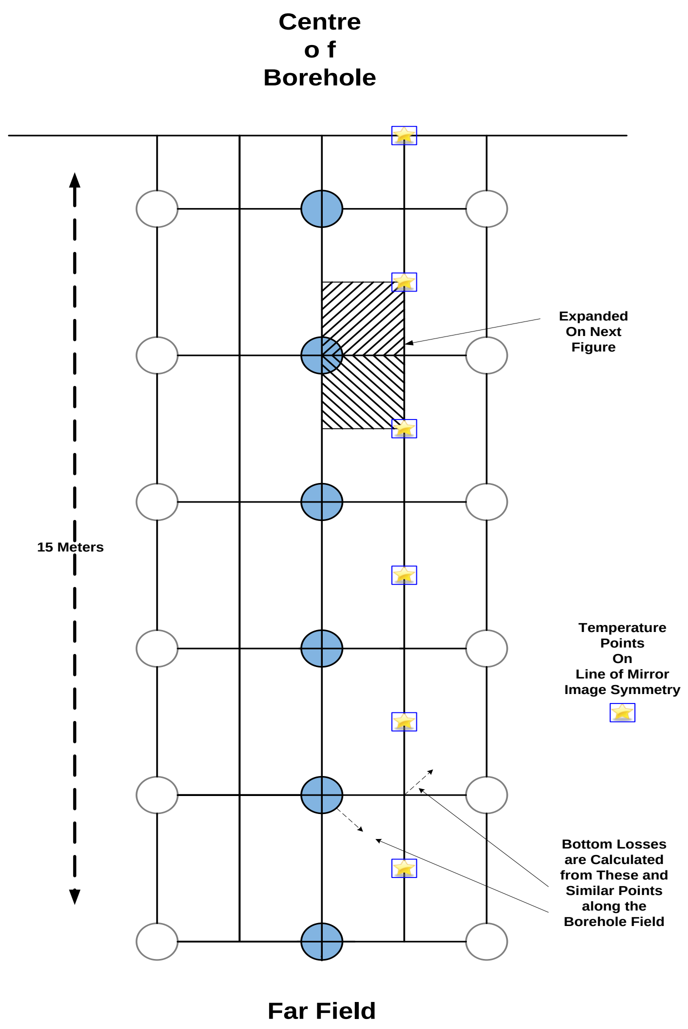

Figure 49: Schematic Drawing of Borehole and Far Field

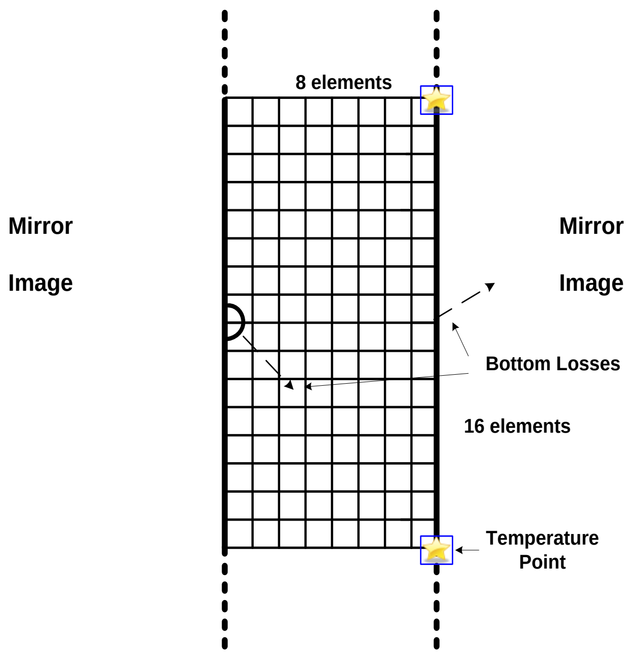

Figure 50: Expanded Schematic of Borehole Grid

This represents 1/48 of a 144-borehole square array, with admittedly with some geometric distortion. The total number of cells is 2597, representing that many simultaneous first-order differential equations which are driven from input-output temperature and flow rate data from

Okotoks over a forty-five month period (July 1, 2007 - March 31, 2011). To run the simulation takes 5 hours on a medium fast computer.

The "outside" end continues to a 7.5-degree one-sided taper connected to earth temperature of 6 degrees C as shown in Figure 51.

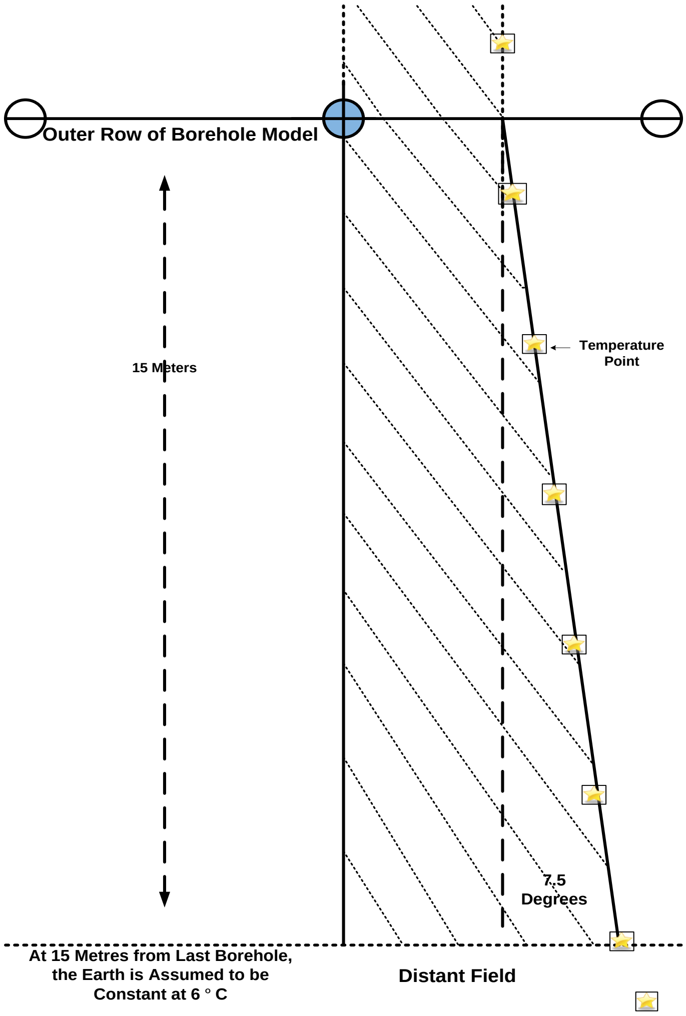

Figure 51: Distant Field outside the Borehole

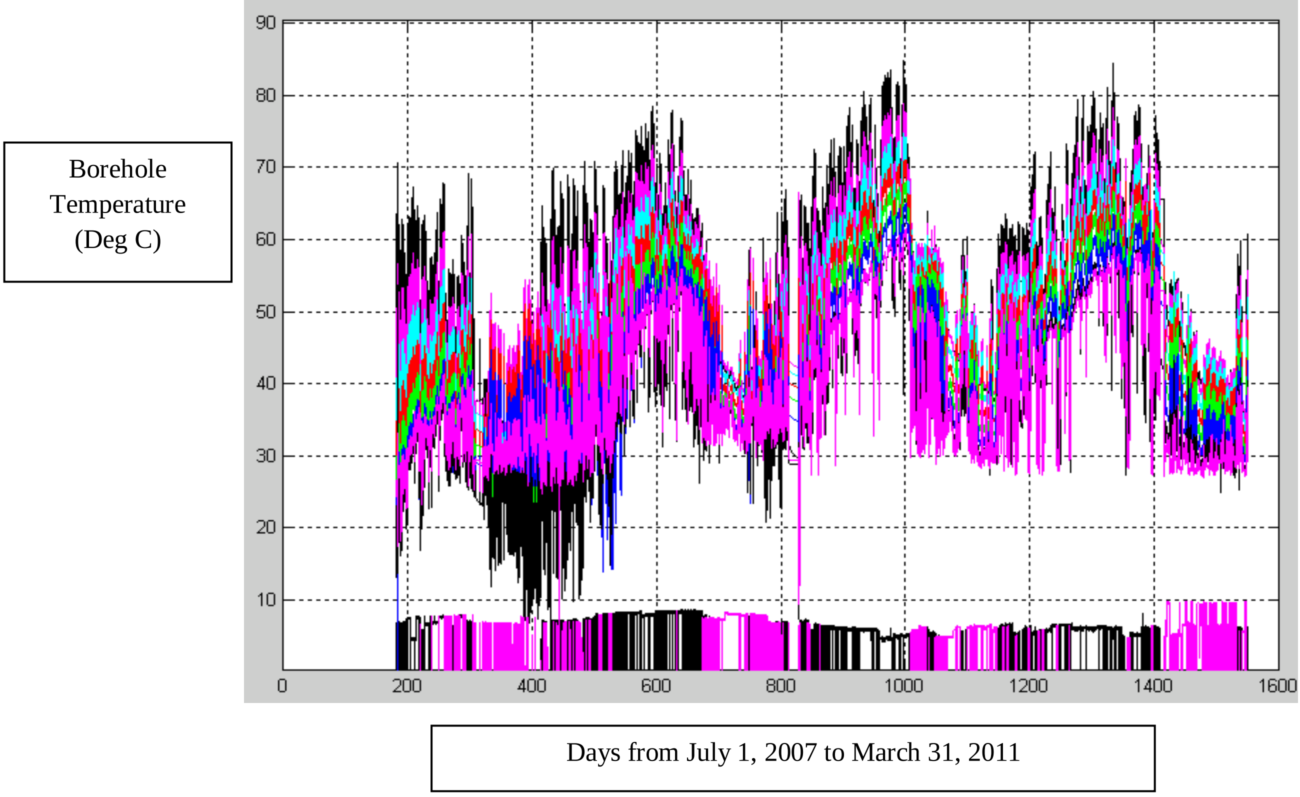

Figure 52: Simulated and Measured Borehole Temperatures at Okotoks[1]

Figure 52 displays simulated fluid temperatures at the boreholes along with those measured for injected and extracted fluid every ten minutes during the July 1, 2007 to March 31, 2011 period. Superimposed at the bottom are fluid flow rate measurements, color-coded according to charge and discharge. Simulated temperatures are computed from the injection temperature and flow rate and direction for all the intermediate boreholes as well as the extracted fluid. Spurious measured temperatures during zero flow are omitted to avoid confusion whereas the simulated temperatures reflect those of the interface elements.

The fluid temperature used to calculate the energy transfer is the average of the input-output temperatures along the full length of the borehole pipe. This assumption represents a reasonable estimate and is supported by the good agreement between measured and simulated extraction temperatures during both charge and discharge.

Temperatures over the 45 months every 2.25 metres along the line of symmetry halfway between the boreholes are shown in Figure 53 with the 6-degree ground reference at the bottom. These are calculated from 13 data points radiating from each centre of the borehole field to the distant fields. The unheated far field earth temperature has been assumed to be uniform at 6°C. Because the Okotoks system had been in partial operation a few months prior to data recording, all temperatures were assumed to start at 12 degrees. Since we have no data for the initial period of operation, the temperature represents a guess for best fit to early data.

[1] The days are calculated from January 1, 2007 however the data from Okotoks starts on July 1, 2007. This is day 182 on the data points.

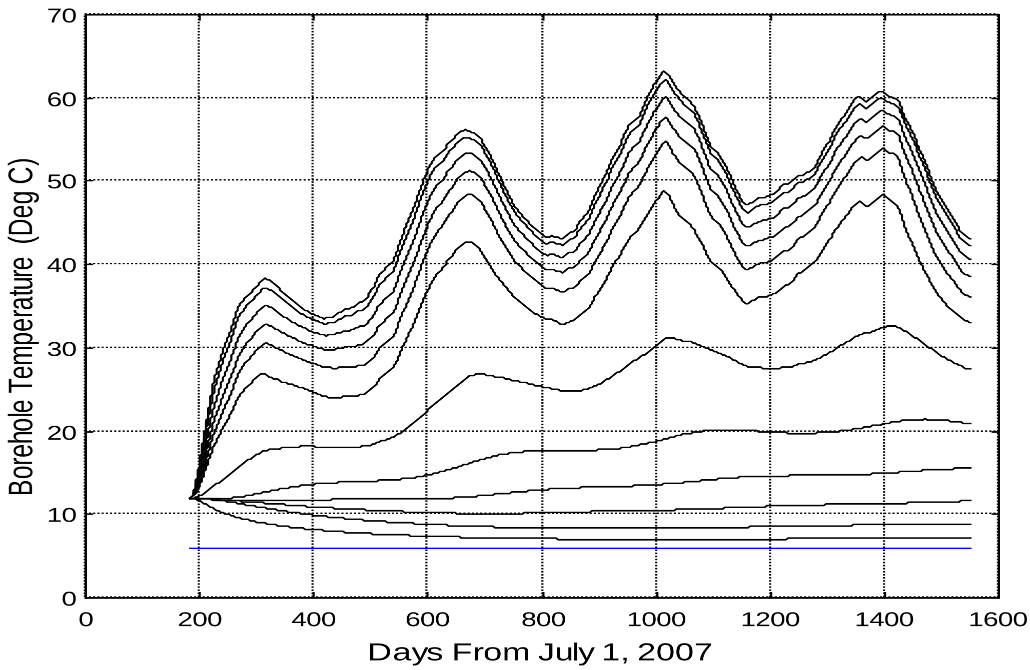

Figure 53: Simulated Temperatures along Line between Boreholes

A more quantitative indication of the simulation accuracy is given by comparing measured and simulated energy transfer integrals shown in Figure 54 and as seen in Table 13 in which annual increments from April 1, 2009 to March 31, 2011 during charge and discharge are compared between measurement and simulation. Summing the individual cell temperatures and peripheral losses also allows an estimate of bottom losses. Two significant differences may be noted between the two years. The charge energy in October 2009 is markedly higher than in the next year, mostly due to an unusual amount of extra energy stored in March as reflected in the Stored Simulated numbers. This led to an unusual amount of extra energy made available during the second year, augmented further by the drop in return temperature and increase in flow rate toward the end of the spring.

While the input-output behavior of the borehole model appears sufficiently accurate for incorporation in simulating a DE system, adjustment of the loss components in order to minimize the discrepancies of both the charge and discharge simulated energies from the measured values introduces some uncertainty in the losses to the surrounding earth. To obtain a more reliable estimate of those losses, a three-dimensional finite-element simulation using FlexPDE from PDE Solutions Inc. was carried out for a buried axisymmetric cylinder approximating the geometry represented by the two-dimensional Simulink^{TM} model. The simulation region extended 12.4 metres beyond the cylinder radius of 14.6 metres and below the bottom depth of 35 with the underground boundary held at 6°C. The thermal flux was integrated over the region boundary. The bottom temperature of the cylinder was driven by those plotted by the top seven traces in Figure 54 with the vertical surface being driven by the lowest of those. The year-to-year increases in the values obtained would suggest that the model had not yet reached equilibrium and the loss numbers are likely to be somewhat lower than the near-steady-state values.

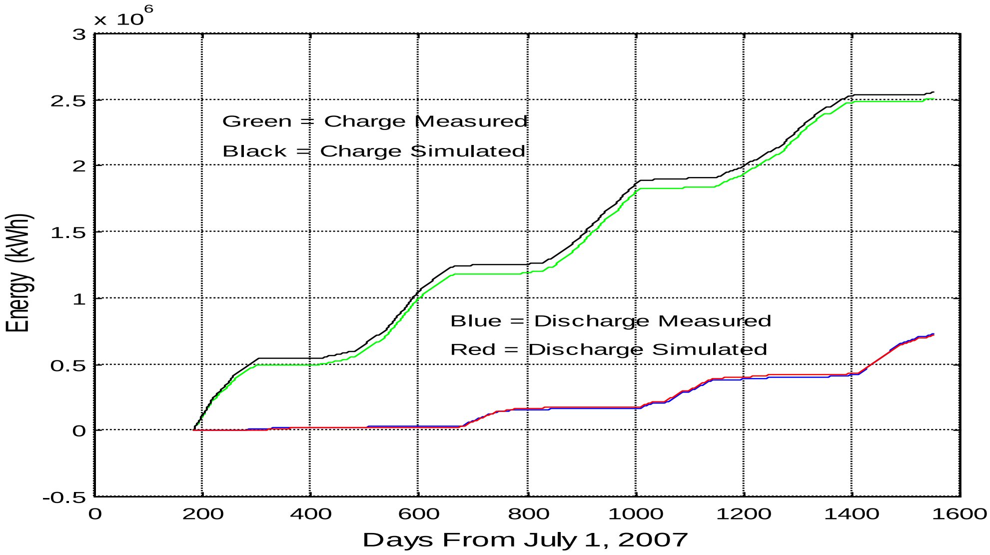

Figure 54: Energy Transfer Integrals

Table 13 follows:

	Apr 1 2009	Apr 1 2010	Apr 1 2011
	Cumulative Energies in GJ		
Charge Measured	4340	6869	9044
Discharge Measured	578	1390	2624
Charge Simulated	4571	7096	9215
Discharge Simulated	618	1447	2588
Peripheral Loss Simulated	420	506	598
Stored Simulated	2028	2515	2245
	Simulation Errors		
Charge Simulated		-3.3%	-1.9%
Discharge Simulated		-4.2%	1.4%
	Year-to-year Changes		
Charge Measured		2528	2175
Discharge Measured		812	1235
Charge Simulated		2526	2119
Discharge Simulated		829	1140
Stored Simulated		487	-270
FEA Peripheral Loss		182	286
FEA Vertical Loss		52	80
	Simulation Errors		
Charge Simulated		0.1%	2.6%
Discharge Simulated		-2.1%	7.7%

Table 13: Comparison of Measured and Simulated Energy Integrals

Comparison of simulated and measured temperatures at the boreholes

In order to validate the transient performance of the model it was driven with measured flow and temperature and the exit temperature was compared to the measured exit temperature. This was done for both charge and discharge cycles. The model also simulated the temperature at the exit side of each borehole in the interior of the field.

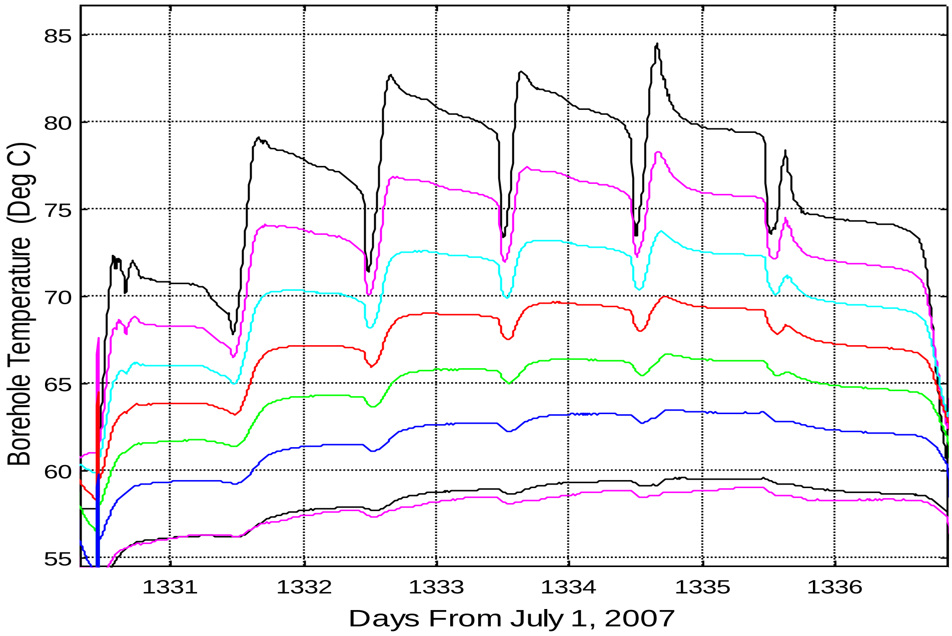

Figure 55: Simulated and Measured Temperatures during the Charge Cycle

Figure 55 shows the charge cycle at the end of summer 2010, when the storage was close to peak temperature. The black trace near the bottom is the simulated temperature and the magenta line is measured. The agreement is within less than one degree and the maximum error relative to the total temperature across the six boreholes is approximately 3.7%. It can be seen that the simulated temperatures track the transients of the measured values.

The agreement on discharge is not as close as can be seen in Figures 56 and 57, due to the complex paths by which the energy is extracted from the field. The simulated output is below the measured but becomes closer as the field is depleted.

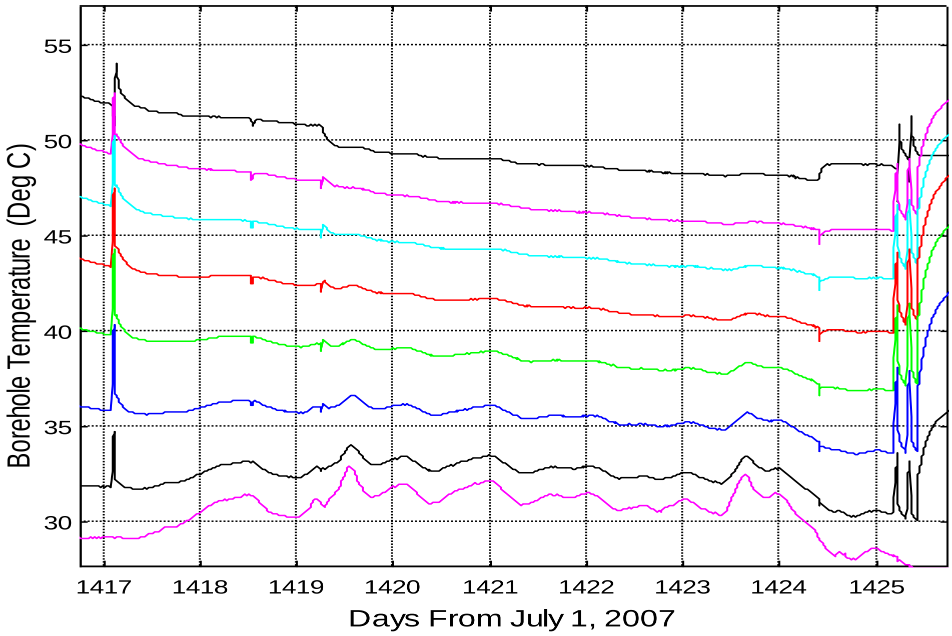

Figure 56: Borehole Simulated and Measured Temperatures at the Start of the Discharge Cycle

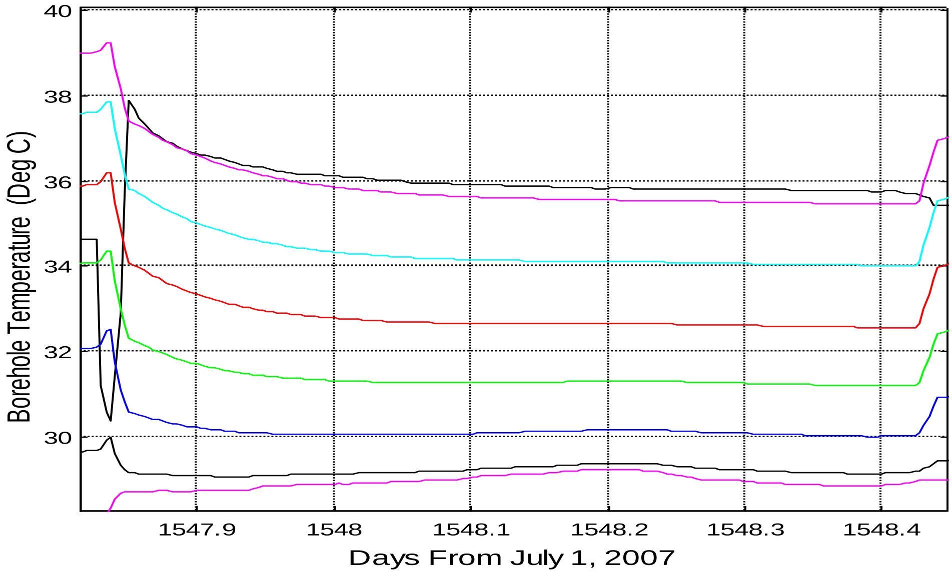

Figure 57: Borehole Simulated and Measured Temperatures at the End of the Discharge Cycle

Solar Systems

At current natural gas prices in North America it is difficult for solar energy to compete unless there are subsidies to reflect its renewable nature.

It is necessary, in the short term, to search for applications where solar is closest to being competitive. This can still lead to a significant market and, with increased field experience, will lower cost and aid the development of more reliable components.

As the future price of fossil fuel escalates the two cost functions will cross.

There may be potential for cost reduction of solar energy by involving the private sector in selling solar energy to the DE system. This is an approach that the electrical utilities have taken in many countries with the "feed in tariffs" (FIT). These agreements typically have a guaranteed purchase rate for a period of about 20 years.

The DE systems are limited in their ability to absorb large amounts of solar energy. This was discussed with a senior engineer from one of the larger Swedish DE companies. His position was that their system has large quantities of surplus energy during warm weather from cogeneration and incineration plants. As a result they would not purchase any energy during these periods, when solar energy is readily available. The most promising application of solar energy linked to DE is to have all the thermal energy from a boiler fired by fossil fuel.

Contact with a number of DE utilities has failed to supply any information on the amount the utilities might be willing to pay for private generation of thermal energy. As a result the approach taken in the present study is to compute the minimum selling price the solar system owner would need to receive in order to recover the capital investment required for the solar system.

The seasonal variation of solar availability can be countered by long-term storage of surplus summer energy. This is the approach taken with the experimental solar seasonal storage system at Okotoks. While long-term storage has potential, it has to be analyzed carefully since the seasonal storage adds a large cost to the DE infrastructure. The cost problem is compounded by the large heat loss of seasonal storage over the months that it needs to retain the heat. This is most severe in the smaller size borehole storages and sets a lower limit for practical storage capacity.

Solar seasonal storage is a useful field of research since large volume borehole storage has the potential to reduce both per unit cost and thermal losses.

In order for solar energy, at the building level, to be competitive with fossil fuel many of the following components are required:

- An energy supply temperature in the 65 to 75 °C range.
- Long-term agreements, e.g. 20 years, with the DE utility to purchase a minimum amount of energy at a guaranteed price.
- All capital cost and maintenance of the solar system is covered by the building owner.
- An optimized subdivision layout, as in Figure 2, that enables half of the houses to have guaranteed long-term solar access.
- Small lot sizes to maximize energy density.
- Houses are constructed in a "solar-ready" form for economical addition of solar components.
- Availability of mass-produced solar modules to match the size of installations on

the "solar-ready" houses.

- Non-solar buildings located near solar ones, as in Figure 2, for efficient direct transfer of energy, with buying and selling controlled by the utility.

Solar system connections to DE systems

There are two methods of transferring solar energy to a DE system:

- Direct transfer to loads synchronized with solar availability as in Case 6.
- Direct transfer plus storage of summer surplus energy in seasonal storage, to be used during cold weather as in Case 7.

The direct transfer configuration, as in Case 6, will have the best payback since the transfer is efficient, without the losses from the seasonal storage. The best scenario is one where a decision has been made by the building owner to install a medium size system to supply most of the local DHW demand and part of the space heating load. A typical system might have four or five collectors, twice the size of a DHW preheater system. Then another five collectors plus extra storage could be added and have the surplus thermal energy available for sale. Only the incremented cost needs to be included in the economic analysis, as well as the cost of a pump and controls for the transfer of energy to the DE system, as the initial costs are for personal usage. This is a limited market since only some of the houses can be equipped with solar collectors. As there is no extra storage in the non-solar building, other than the thermal mass of the building and possibly DHW storage, the ability to absorb solar energy is limited.

For this study, in a future subdivision of 240 houses, the houses on the south side of the subdivision layout of Figure 2 are optimized for access to solar radiation and are constructed to be "solar-ready". In order to supply the demand of the house itself for most of its DHW and part of its space heating about 14 m^2 of absorber area would be installed. This is similar to the collector area of the Dumont house.

The solar house can supply some energy directly to the non-solar ones if supply and demand happens to be synchronized. The houses are connected to a distribution line at the back boundary of the lot. At this location there is also a direct connection to the houses on the north side of the back lot. If the collector area and storage volume of the first house is increased it would be able to supply significant amounts of energy to other houses. The DE utility would purchase energy from the privately owned solar system and sell it at a profit to the other houses. The transfer would be very efficient, since the pumping power and thermal losses on this short connection (typically less than 30 metres) would be very small. The control strategy has many options and needs careful planning.

The heating equipment in the non-solar house would be conventional but with the various load shedding options examined previously.

For Case 7, if seasonal storage is available, all 120 of the solar-ready houses could be equipped with high temperature solar collectors and all surplus energy purchased by the utility. Since extensive data and operating experience is now available from the Okotoks borehole seasonal storage the analysis will be limited to storage in this size range. Only the length of the borehole pipes has been increased, resulting in 2 times the volume of the Okotoks system. Even though a larger system would be more cost effective, analysis of a smaller one will supply information to optimize various options. As the future subdivision has a total of 240 homes, with half of them not having solar systems, the solar fraction will be relatively low.

The main limitation with seasonal storage is the reduced amount that the utility would be willing to pay for energy - likely no more than for the energy into storage multiplied by the storage recovery fraction.

Control strategy for energy transfer from the solar systems to the DE system

The optimization of energy transfer can be quite complex but some general rules can be stated:

- The solar system would supply the requirements of its own house first.
- The amount of energy retained in local storage is ideally a function of the expected load for the next day, which is a function of the known DHW load and the weather. A rough approximation can be based on the previous day's load and this is the method used for the simulations.
- During cold weather conditions the transfer of any surplus energy would be based on requests from the DE control system. This could be based on a price offered by the DE for its purchase.
- If seasonal storage is being used any surplus would be transferred to this, with flow at a low rate extending into the night to optimize heat transfer.

The control system requires a computer with medium capability and fairly sophisticated software to enable optimum use of available energy.

Three tank system for solar collection

The storage and control system configuration for bi-directional transfer of energy is shown in Figure 58. This system is an expansion of the two tank system examined previously. A third tank is added, bringing the total volume to 1,050 litres.

The main additions are related to the components for two-way energy transfer between the building and the DE system. A gear pump can transfer water to the supply line independent of the line pressure. Hot water transfer in both directions is at a nominally constant flow rate. This gives best control of stratification. It also enables the use of heat meters with a more limited range of operation.

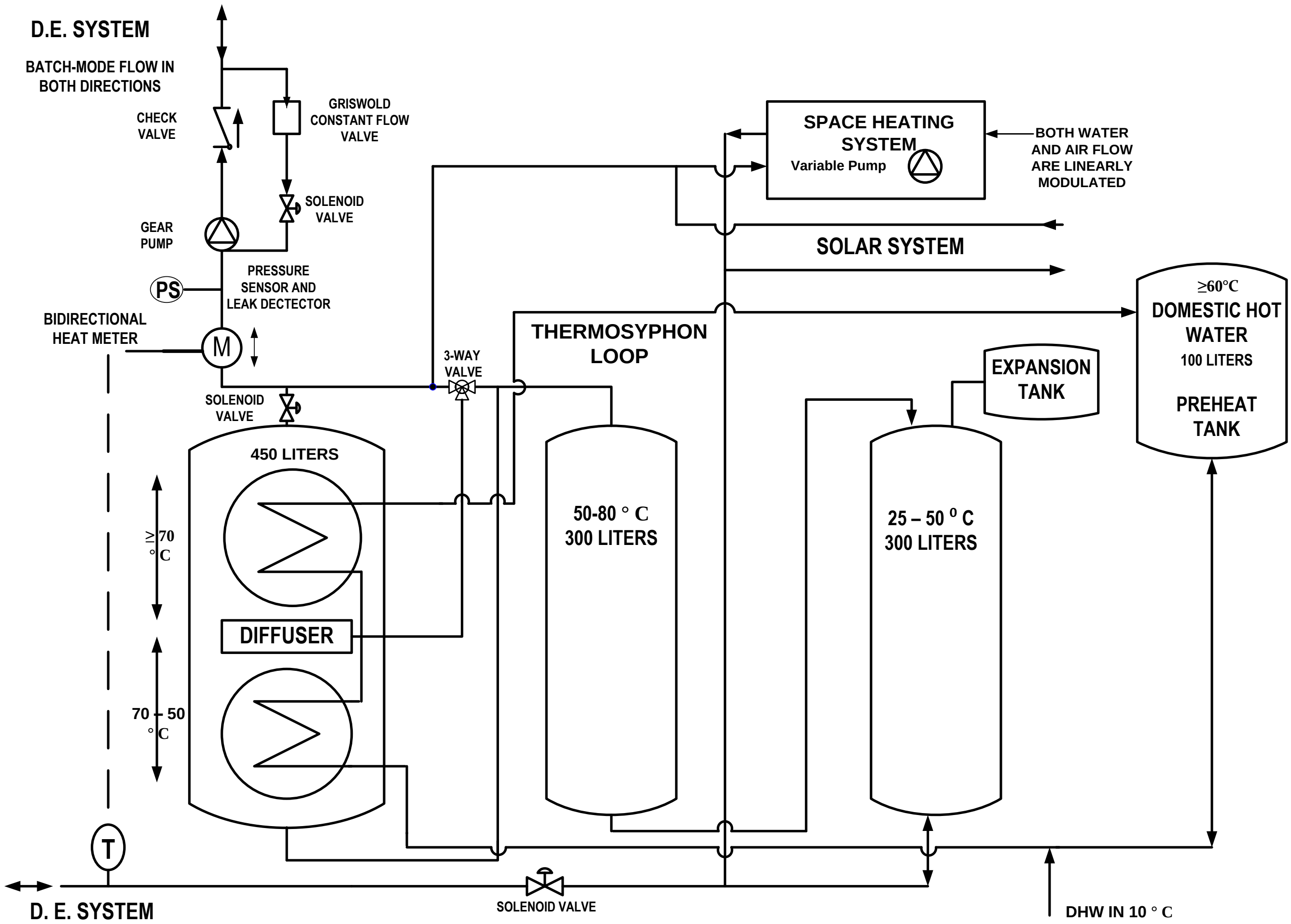

Figure 58: Three Tank Thermal Storage with Solar Connection

A bidirectional "smart" heat meter is required with communication to the DE management system. This will have dual registers for different tariff rates for buying and selling energy. The three tanks operate in series, giving the best isolation between the supply and return temperature.

As the tanks go through multiple charge/discharge cycles the stratification between high and low temperatures will gradually be lost. This has the effect of reducing the effective volume, assuming that only the lowest temperatures (below 23°C) should be returned to the DE system.

Since the low-energy building has broad tolerance on the power level required during any short period of time the heating system can be used to "absorb" the region of broad temperature gradient. If the water is passed through the air coil at low flow and a medium air velocity is used the return water will be near room temperature. By having a three-way valve between the 450 litre tank and the middle tank the water to the air coil can be mixed to any required temperature. Since the peak heating demand can be met by 55°C water, the load can often be filled mostly by the two smaller tanks, especially if some solar energy has been collected. During periods of high solar availability and low demand most of the high temperature energy in the 450 litre tank can be reserved to supply local DHW and the surplus sold to the DE system.

Evacuated solar collectors

Since the distribution system requires a minimum of 65°C in order to supply the DHW load the evacuated-tube solar collector is the best choice due to its high efficiency at elevated temperatures. Most of the energy generated in this manner is of a quality the utility would be willing to purchase. This type of collector occupies more area than a flat plate unit, due to the spacing of the evacuated tubes. Doubling the absorber area to 27 m^2 would require around 40 m^2 of roof area. Assuming about 2.7 m^2 of absorber area ten collectors would be required. If the house has two stories, half of the collectors could be installed on the roof and the other five installed similar to the Dumont house, on an overhang that shades the first floor windows in the summer.

The collector array is assumed to be configured in a water-based drain back system. This is usually not practical in a large array because of the danger of freeze-up, which is compounded by the long pipe runs. At the residential level a drain back system can be considered if care is taken in the design. The evacuated-tube collector based on heat pipes lends itself to drain back operation since it only has the top manifold pipe to transport water, in comparison to a flat-plate collector with its small-diameter distributed pipes. The automatic air vents that are used to avoid air-locks can be a problem, since under cold conditions they can freeze and fail to open. One possible solution is to seal the system from outside air and have a third pipe to transport air from inside directly to the highest point in the collector array. The third pipe should be next to the hot return pipe to avoid frost buildup.

A drain back system will require higher pumping power compared with a glycol loop since there will be air in the return line. As the electrical consumption is relatively low, and is mainly recovered in the water, the difference will be small. To minimize the risk of leaks on the DE system the collectors should be isolated via a heat exchanger and equipped with its own drain back system.

The evacuated-tube collector is relatively insensitive to variations in inlet temperature. The efficiency characteristic is shown in Figure 59. The performance of the solar array was initially evaluated with an inlet temperature of 30°C. During the heating season it will operate at a lower temperature. The space heating system has a return temperature below 23°C. If a sufficiently large heat exchanger is used on the DHW system with its storage well stratified, it will also have return temperatures below this value. If a borehole seasonal storage is being charged during the summer its exit temperature will go above 30°C. This is fed to the collector inlet but since the ambient temperature is warm will have only a small effect on the collector efficiency. In order to speed up the simulations a constant 23°C is used on the collector input during the heating season. During charging of the borehole storage the actual return temperature from the storage is used for collector input.

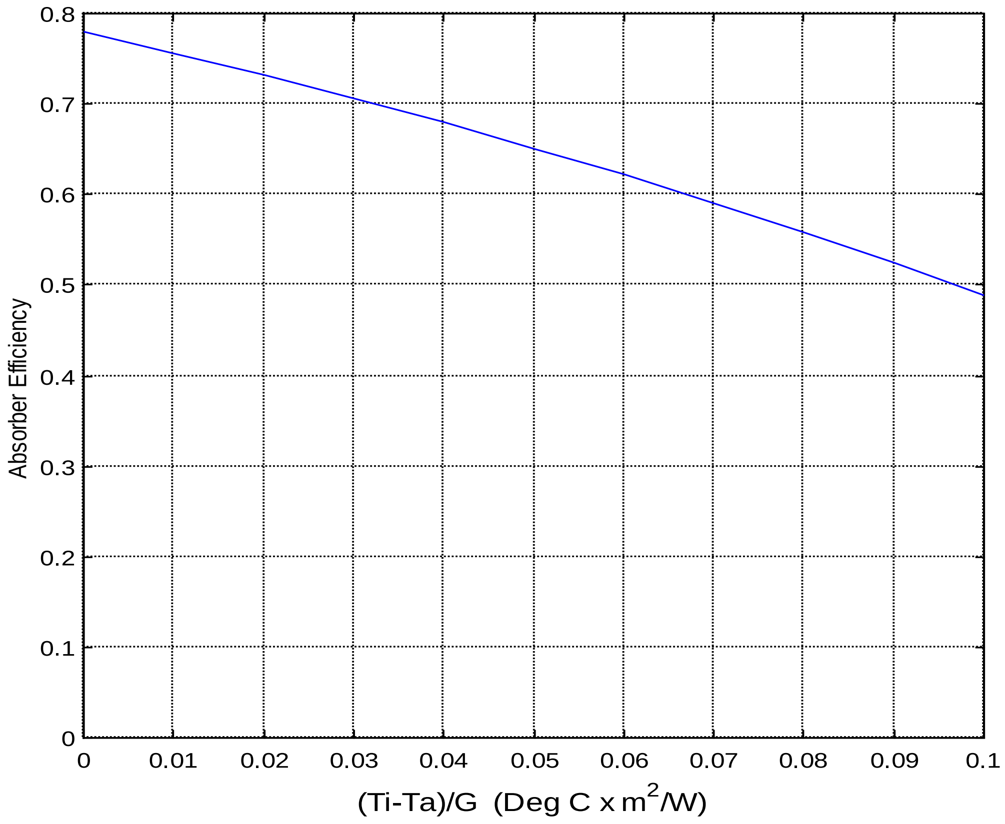

Figure 59: Typical Absorber Efficiency of an Evacuated Tube Collector

Ti = Inlet water temperature
Ta = Ambient air temperature
G = Radiation in Watts/m^2

Absorber area = 2.7m^2

The efficiency equation is:

$$\textbf{Efficiency} = \mathbf{0.78 - 2.24\,(Ti - Ta)/G - 0.0067(Ti - Ta)^2/G}$$

The Simulink^{TM} function for this equation is shown in Figure 60. In the actual model the efficiency parameters are set as variable names.

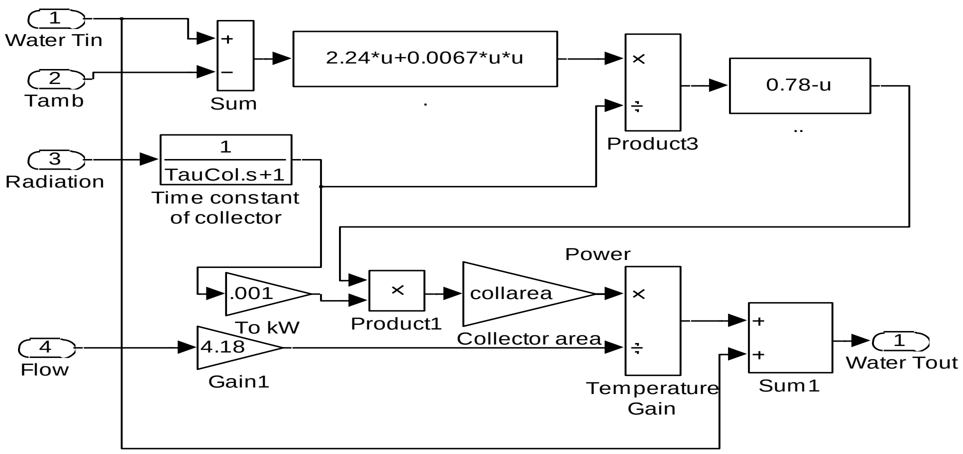

Figure 60: Efficiency and Power Function for a Typical Evacuated-Tube Collector

Ten of these modules were placed in series to form the array shown in Figure 61.

Control functions were added to limit the output temperature to a preset limit by increasing the flow. The array is capable of giving output temperatures above 100°C but for this application the maximum temperature was set to 65°C for Case 6 and 75°C for Case 7.

The flow is restricted to a range of 0.03 to 0.14 litres/sec.

In order to speed up the simulation the incidence angle modifier is pre-computed in the hourly radiation function.

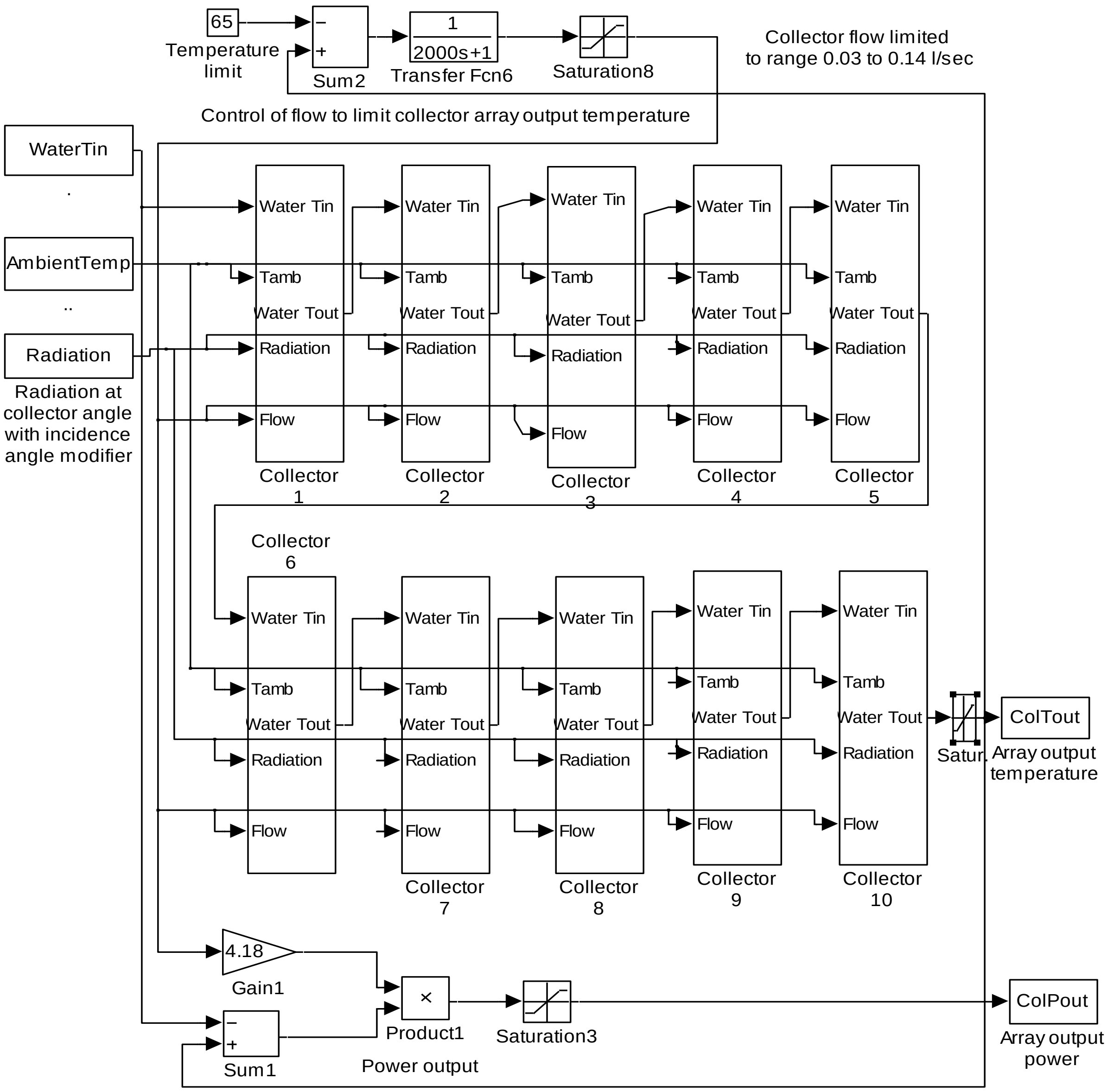

Figure 61: Solar Array with 10 Collectors

Initial testing of the model was done with a temperature limit of 75°C to evaluate its performance at the highest temperature that is likely to be required in this type of system.

The results are shown in Figure 62. The input water temperature was held constant at 30°C. With the output temperature feedback loop controlling its temperature level, above radiation levels of 545 W/m^2 the output temperature stays constant at 75°C as the ambient temperature is reduced to -25°C.

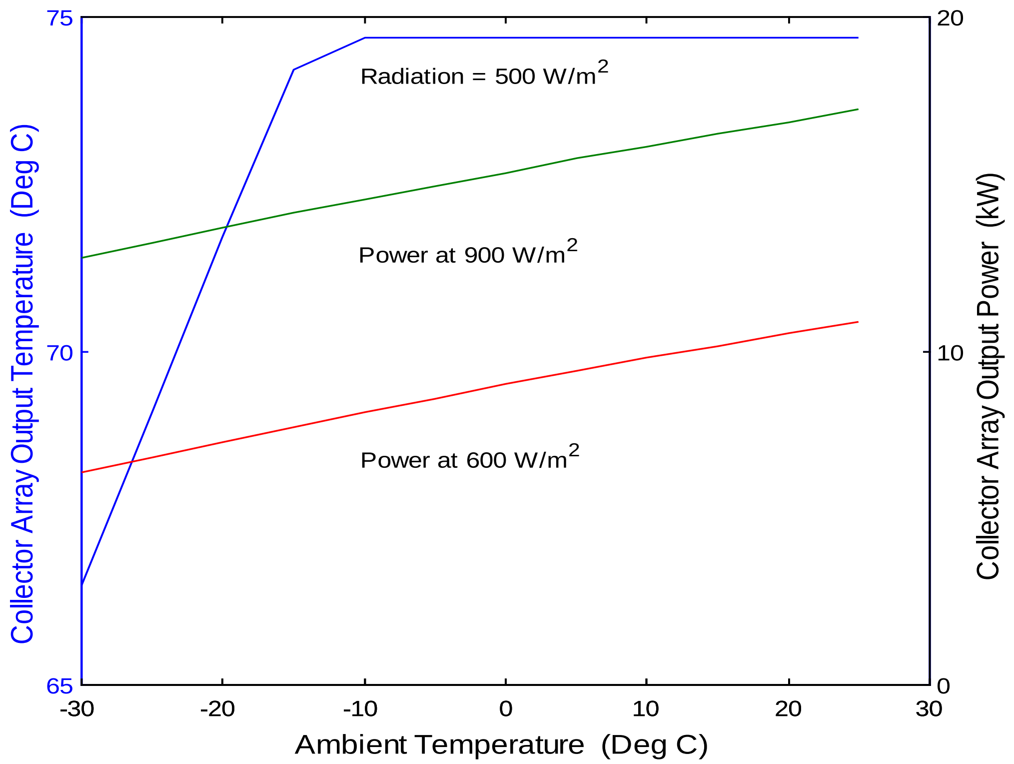

Figure 62: Performance of 10 Collector Array with Okotoks Weather, Tin = 30°C

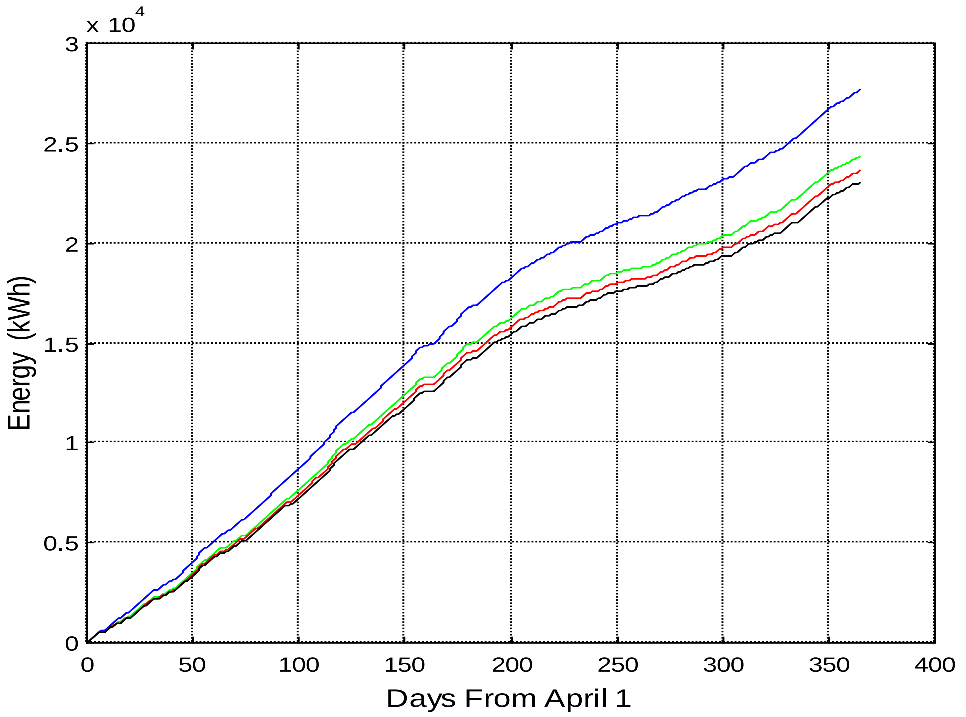

Figure 63: Collector Array Output with Okotoks Weather

The collector array output with the Okotoks weather is shown in Figure 63 with the yearly energy (kWh) values collected and the different operating temperatures shown in Table 14.

Total Energy Collected (kWh)			
Graph Color	**Tin Deg C**	**Temperature Range Deg C**	**kWh**
Blue	23	24-65	27,700
Green	23	64-65	24,397
Red	23	64-75	23,646
Black	43	64-75	23,081

Table 14: Total Yearly Energy Values Collected (kWh)

Energy collected in the range of 64°C to 65°C = 88% of total.

Optimization of collector output temperature levels

There is a trade-off between the collector array maximum operating temperature and collector efficiency. Even with high performance collectors the efficiency will be reduced, especially under lower radiation levels. For locations such as Stockholm and London the radiation levels are much lower than at Okotoks, as shown below. These are yearly values on the plane of the collector.

Cities	Latitude	Collector Angle	Yearly Radiation
Okotoks	50.7°	45°	1772 kW/m^2
Stockholm	59.3°	54°	1070 kW/m^2
London	51.3°	45°	994 kW/m^2

Table 15: Yearly Values on the Plane of the Collector

Figure 64 and Table 16 show the energy that can be collected by the solar array in the temperature range of 64-65°C to 64-75°C.

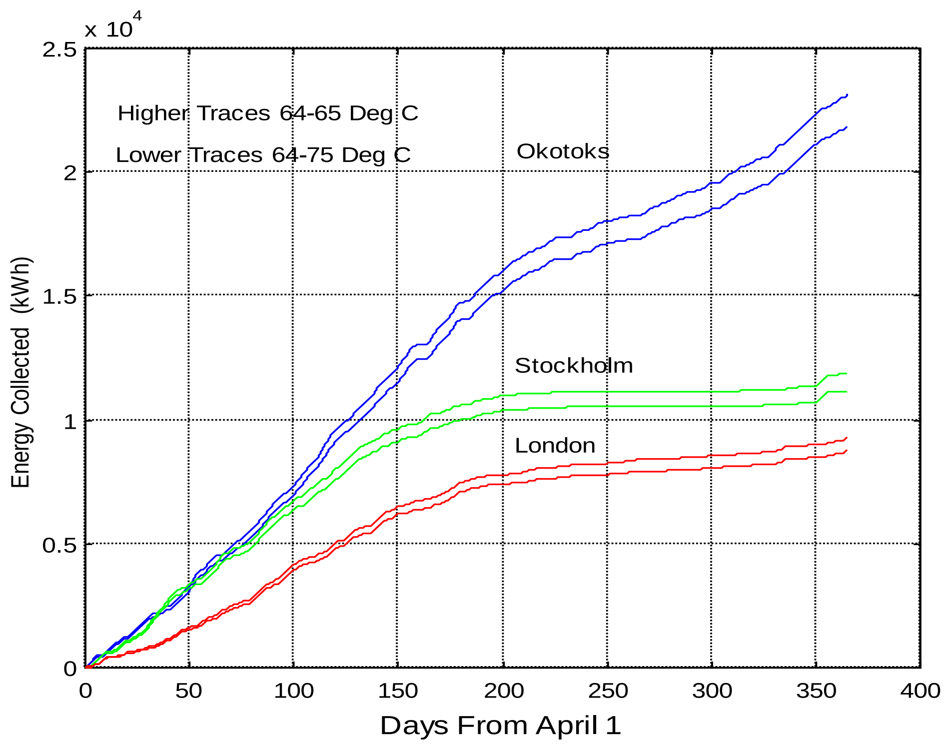

Figure 64: Energy Collected between 64-65 °C and 64-75°C by Collector Array, Tin = 23°C

. City	Okotoks	Stockholm	London
Energy collected (kWh) High	24397	12348	9854
Energy collected (kWh) Low	23646	11936	9530
% Difference	-3.1	-3.3	-3.3

Table 16: Energy Collected between 64-65°C and 64-75°C by Collector Array, Tin = 23°C

Both Stockholm and London show energy collection far below that of Okotoks. The data for Stockholm has very little collection through the winter months. This city is at much higher latitude compared to the others. This results in very short days in the winter and increased atmospheric attenuation of radiation due to the low solar angle. Also, there is probably more moisture in the air, compared to Okotoks, due to the proximity to the Baltic Sea.

It should be noted that the solar system has been designed based on experience and measurements at Okotoks, which has exceptionally high values of solar radiation, only slightly lower than Arizona[36].

The configuration has not been optimized for the other two cities. For example, the Okotoks collector angle offset from latitude was selected to maximize the yearly collection of energy based on the high solar radiation available throughout the year. The same offset was used in the other two cities.

For Stockholm it may be possible to collect more energy by biasing the collector angle towards summer conditions. This approach would be important if seasonal storage is being used. This may result in flat plate collectors having a slight cost-performance advantage over the evacuated tube ones. Flat plate collectors also have an advantage in the area required for installation because of the continuous absorber plate. The evacuated tube collectors require about 80% more space.

London has the opposite situation compared to Stockholm. It collects considerably less energy through the summer, probably due to moisture in the air. In the winter it collects somewhat more, possibly due to the higher solar angle.

Detailed optimization of solar systems in the European cities is beyond the scope of this project.

Case Studies 6,7:

Case 6: Direct transfer of surplus solar energy to non-solar houses

The solar house with ten high performance collectors will have considerable surplus energy at various times of the year, especially during the summer period. If the building owner and the DE utility can agree on the value of this surplus energy the utility can purchase it and sell it at a profit as part of the main supply. In a future subdivision of 240 houses the non-solar ones can absorb the entire surplus if the number of solar systems is not too large. Beyond this number the amount of solar energy that will need to be dumped will increase.

Simulations were done with an increasing number of solar systems, with the houses configured in the Case 1 mode. The collector output temperature control was set for the range 64 to 65°C. For the other cases with load shedding the number of solar houses will be increased but the income per house will stay the same. The results are in Figure 65 and Table 17.

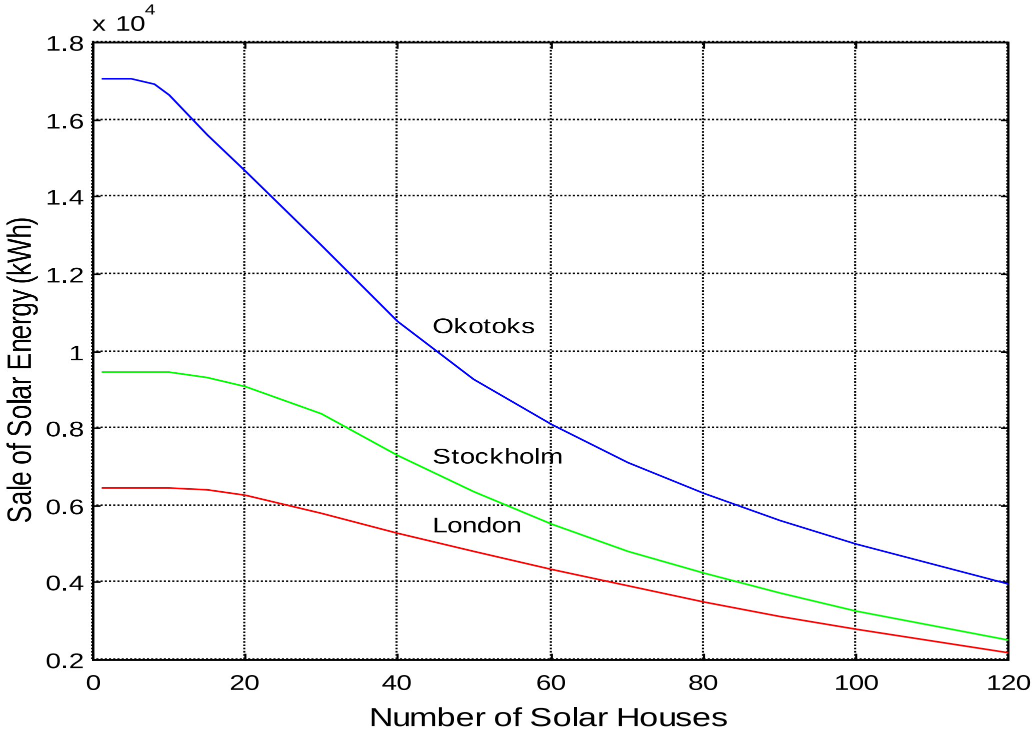

Figure 65: Solar Energy Transferred Directly to Non-Solar Houses

City	Okotoks	Stockholm	London
No. of Houses for 90% Sale of Surplus Energy	16	28	30
Total Solar Collected (kWh)	24661	12826	10544
Solar Sold to DE System (kWh)	17066	9467	6460
Solar Used in Solar House (kWh)	7595	3359	4084
Purchased by Solar House (kWh)	4430	8732	7664
% Solar in Solar House	63	28	35
% Solar of DE System with 90% Surplus Sales	13	12	11

Table 17: Energy Transferred Directly to Non-Solar Houses

With the annual heat sales of 17,066 kWh, at Okotoks the cost to recoup the investment for the homeowner is 4.0 $ct/kWh if only the cost for the collectors ($6,500) and storage with controls ($2,000) needs to be recovered and 5.15 $ct/kWh if an addition to the branch line is needed

($2,451).

The required payback prices are not too high in the Okotoks case. Since the operation is basically in a fuel saving mode the utility may choose to only pay the avoided cost of fuel. At the current price of natural gas this is less than two cents/kWh and the utility can choose to not pay any more unless it is subsidized.

If the investment expense for the extra five collectors and storage (total incremental cost = $8,500) is not covered by the payback, the building owner is likely not to make the investment and restrict the system size to five collectors or less. In the smaller configuration there will still be periods of surplus energy, but the cost of the pump and controls for reverse flow, plus the bidirectional heat meter may not be justified.

Case 7: Borehole seasonal storage system to store solar energy.

Case studies were done with the same collector configuration as Case 6 but with the addition of a borehole seasonal storage system. This was designed to be similar to the Okotoks storage in the number of pipes and the top surface area but with longer pipes. The length was doubled to 70 metres. The collector array temperature output control was set to the range of 64 - 75°C.

As before, the owner of the solar building meets the local need first. Then if there is a surplus of energy being collected the following scenario is used:

- Energy is placed in storage equal to the previous day's consumption.
- If energy is still being collected it is made available to the DE system.
- Any energy that is not directly absorbed by the non-solar houses is transferred to the seasonal storage system.

Since the recovery ratio from seasonal storage is not much better than 50% in this size of storage the utility offer to purchase would be at a lower price to reflect the losses. As long as the owner receives sufficient income during the year to pay for the capital investment of the five extra collectors and additional 1,000 litres of storage, the lower return during the charging of the borehole will be acceptable, since overheating of the collectors will be avoided.

The seasonal storage can accept large quantities of energy so that all 120 of the "solar-ready" houses will be supplying renewable energy to the network. The energy flow is shown in detail in Table 18.

City	Okotoks	Stockholm	London
	kWh/house	kWh/house	kWh/house
Total solar collected	24855	12886	10394
Total solar to DE system	18009	9897	6468
Solar directly to loads	1756	867	448
Solar to seasonal storage	16253	9030	6020
% seasonal storage recovery	46	55	54
Useful solar energy sold	9184	5861	3693
Solar used in solar house	6846	2989	3926
Purchased by solar house	5160	9103	7805
% solar in solar house	57	25	34
% solar of complete system	66	36	32

Table 18: Solar Energy Transfers with a Borehole System for Case 7

The energy flow in the solar houses is similar in Cases 6 and 7.

There are small differences between what the solar energy delivered to the network in Case 6 by a single house and the similar quantity for 120 houses in Case 7. These vary between 1% and 5% for the three cities. Part of this variation is due to slight changes in storage control strategy and slightly different collector output temperature range of operation. Another reason is different error tolerances that needed to be set for the much more complex combined borehole and solar system simulations to speed the simulations that require about 16 hours on a fast computer.

Similar to the results in Case 6, both Stockholm and London have performance much below that using Okotoks data. The cost of energy will be considerably higher than the above figures, though this will also depend on the construction costs in these cities.

Compared to Stockholm, London has a higher solar fraction in the solar house itself, even though the solar fraction for the overall system is higher in Stockholm. This is because of the very low solar radiation during the winter months in Stockholm. Conversely, the solar radiation in London is lower in the summer, with less energy available to charge the seasonal storage.

Stockholm has higher energy going directly to the non-solar buildings. This indicates the higher component of domestic hot water supplied in Stockholm during the summer months.

Detailed information about Case 7 follows in Tables 19, 20, 21 and 22. The total cost for the utility and private owner for a 20 yr lifetime is 17.9 $ c/kWh and for a 30 yr lifetime it is 15.1 $c/kWh. Costs for the 30 year life span are not much lower because the pumps and boilers in the energy centre have been replaced after 15 years and 50% of the installation cost is added to the purchased-equipment cost to remove the old ones and connect the new ones. Operation and maintenance costs remain the same.

IEA Economic Project Summary Results	Case 7	20 yr lifetime
Case description - 240 houses		
Main results:		
Total capital cost 240 home community	$4,118,969	
Total capital cost per home	$17,162	
Cost of heat	**$0.179**	**/kWh**
Main dimensions:		
Solar collector area per home	7	m^2
Energy centre heat exchanger capacity	0.0	l/s
Distribution pump power capacity	5.0	kW
Number of distribution pumps	2	-
Total peak/back-up boiler capacity (excl. spares)	1,700	kW
Spare peak/back-up boiler capacity	625	kW
Primary buried distribution pipe type	Single PEX	
Primary buried distribution pipe diameter 80 homes	63	mm (DN)
Total primary buried distribution pipe length	2,120	m
Secondary buried distribution pipe type	Twin PEX	
Secondary buried distribution pipe diameter	16	mm (DN)
Total secondary buried distribution pipe length	3,360	m

Table 19: Description of Cost Items for a 240 Low-Energy House Project with Case 7

Capital cost summary - 240 homes						
-	**Purchased equipment cost in $**	**Fraction total purchased equipment cost**	**Installation cost in $**	**Fraction total installation cost**	**Total installed cost in $**	**Fraction total installed cost**
Solar collectors	346,667	30.9%	433,333	18.7%	780,000	22.7%
Buried piping remote collectors to energy centre	0	0.0%	0	0.0%	0	0.0%
Energy centre (heat exchanger, pumps, boilers)	74,040	6.6%	124,040	5.4%	198,081	5.8%
Heat exchangers	0	0.0%				
Pumps	6,755	0.6%				
Peak/back up boilers	67,285	6.0%				
Buried piping energy centre to homes	292,545	26.1%	944,933	40.9%	1,237,478	36.1%
Primary distribution piping	220,352	19.7%				
Secondary distribution piping	72,193	6.4%				
Heat users	120,000	10.7%	120,000	5.2%	240,000	7.0%
(Paid by Utility) Substations	0	0.0%				
Hot water tanks	120,000	10.7%				
DHW tanks	0	0.0%				
Pumps	0	0.0%				
Buried piping energy centre to seasonal storage	0	0.0%	0	0.0%	0	0.0%
Seasonal storage	287,328	25.6%	689,587	29.8%	976,915	28.5%
Totals:	1,120,580	100.0%	2,311,894	100.0%	3,432,474	100.0%
Engineering, supervision & commissioning	343,247					
Contingency	343,247					
Grand total investment cost	$4,118,969					

Table 20: Capital Costs for a 240 Low-Energy House Project with Case 7

Economic assumptions cash-flow analysis (per home where applicable):		
Annual heat consumption space heating	5,772	kWh (heated air)
Annual heat consumption DHW	2,811	kWh (heated water)
Natural gas consumption	5,982	kWh (NG heating value)
Natural gas cost in year 0	$0.010	/kWh (NG heating value)
Annual real natural gas cost escalation	2.0%	
Annual O&M expenses as fraction of total capital cost	0.5%	
Lump sum payment by owner/government grant in year 0	$0	
Real discount rate (corrected for inflation)	5.0%	
Project lifetime	20	years
Carbon tax	$0	/tonne CO_{2eq}

Table 21: Economic Assumptions: Cash Flow Analysis (per home, where applicable) for Case 7

Cash flows year 1 (for 240 homes):	
Carbon taxes paid	$0
Electricity and natural gas expenses	$14,643
O&M expenses	$20,595
Revenues	$368,343
Net cash flow to utility	$333,105

Table 22: Cash Flow in Year 1 for 240 Homes for Case 7

Discussion of Cases 6 and 7

The results for Case 6 show promise of economic viability in optimized future housing developments. For this to be successful the building owner must be committed to having solar energy available and is willing to take full responsibility for the system.

The percentage of solar buildings in a group of houses will be limited to not much over 10% but this can still be a major industry in a fast growing country such as Canada.

The outlook is most promising in areas of central Canada that have a weather profile similar to the Okotoks region. There are many locations that have comparable high radiation levels combined with minimum temperatures below -30°C.

If the cost of natural gas rises to equal that of oil, and some reasonable carbon tax is applied, the solar industry could grow rapidly in these locations.

Case 7 indicates rather poor cost/performance in the smaller sizes of borehole storage. In the larger size storage systems there is considerable potential for improvement in the energy recovery factor. The surface area to volume is improved. With a larger number of boreholes it may be practical to have multiple flow paths in the circulation system. Multiple paths can optimize the temperature distribution in the storage volume and minimize the temperature rise in the outer ring during the charging period.

Conclusions

Future low-energy houses are well suited to demand-side management (DSM) because of increased thermal mass and long time constant, plus high percentage of domestic hot water (DHW) load. Elementary DSM can be low cost, approximately $200. Assuming heat meters have two-way communication with the DE utility, only a microprocessor-controlled thermostat is required to interface with the heat meter.

DSM can compensate for low-energy density by increasing the quantity of cogeneration energy that can be sold to additional loads. If a group of low-energy buildings is linked to a DE system with a cogeneration plant that is only requires 10% of yearly energy on its backup boiler, up to 47% increase in sales within the low-energy subdivision is possible with DSM.

Using various elementary load shedding strategies and allowing the house temperature to drop no more than 0.7°C when the cogeneration plant cannot supply the full load, the cost of energy for a group of 240 similar future houses in the Okotoks area would be about $0.052/kWh

DHW tanks are effective at peak shedding. They must be well designed for low return temperature and the risk from Legionella bacteria growth managed.

The cost of supplying energy with DSM can be as low as $0.046/kWh using DHW storage.

With increased thermal mass and using night setback of 2.0°C the cost of energy was $0.049/kWh, assuming that the cogeneration plant does not operate at night.

Water based thermal storage may not be cost-effective beyond the DHW size unless combined with solar collectors.

With the exceptionally high solar radiation at Okotoks, solar energy can be supplied to the network at a cost of $0.040/kWh ($0.052 if a branch line must be added to connect the solar building). Above a penetration level of about 9% of yearly total system energy load the solar systems are not fully loaded and the payback is reduced. The available solar energy in Stockholm and London is much lower than in Okotoks.

Seasonal storage is expensive in smaller sizes. Using a seasonal storage configuration similar to the Okotoks system but with a lower solar fraction the total cost of energy, adding both utility and private investment costs, is $0.179 for a 20 year life and $0.151 for a 30 year life.

Forced-air heating is well suited to low-energy houses, since air-tight buildings have legally mandated continuous mechanical ventilation requirements to all occupied rooms. As the space heat requirements are below half of conventional housing the reduced air flow and continuous operation has low impact in the form of drafts and noise.

It is possible to construct high performance liquid-to-air heating systems at reasonable cost.

The layout design of future low-energy houses in a subdivision needs to be carefully considered on the system level. When this is done, many benefits are available for both the owner and the DE system operator.

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Appendix A

Dumont Residence Energy Efficiency Features

At the time it was constructed in 1992, the house was referred to as having “the lowest heat loss coefficient per square metre of floor area of any house in the world.”

The house is located in Saskatoon, Saskatchewan, Canada at 52 degrees N latitude. The average annual heating degree days in Saskatoon are 5950 ^{o}C-days (base 18^{o}C). Annual solar radiation on a horizontal surface is 5.1 GJ/m^{2}. The outdoor design temperature for heating systems is -35^{o}C, and the cooling season design temperature is + 31^{o}C. The average outdoor temperature in January is -17^{o}C

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A view of the south side of the house is shown in Figure 1.

Figure 1. South side of the Dumont Residence

A view of the north side of the house is shown in Figure 2. Solar thermal collectors are mounted at a 70 degree tilt angle to the horizontal in a band just below the upper windows.

Figure 2. North side of the Dumont Residence

The primary energy efficiency features of the house are as follows:

1. Very high levels of thermal insulation.
   The ceiling has a U value of 0.071 W/m^2-K, the walls have a U value of 0.095 W/m^2-K, and the basement floor has a value of 0.16 W/m^2-K. The insulating material for the ceiling, walls, and floor is cellulose insulation. Approximately 8 tonnes of cellulose insulation were used. A cross-section of the house wall is shown in Figure 3.

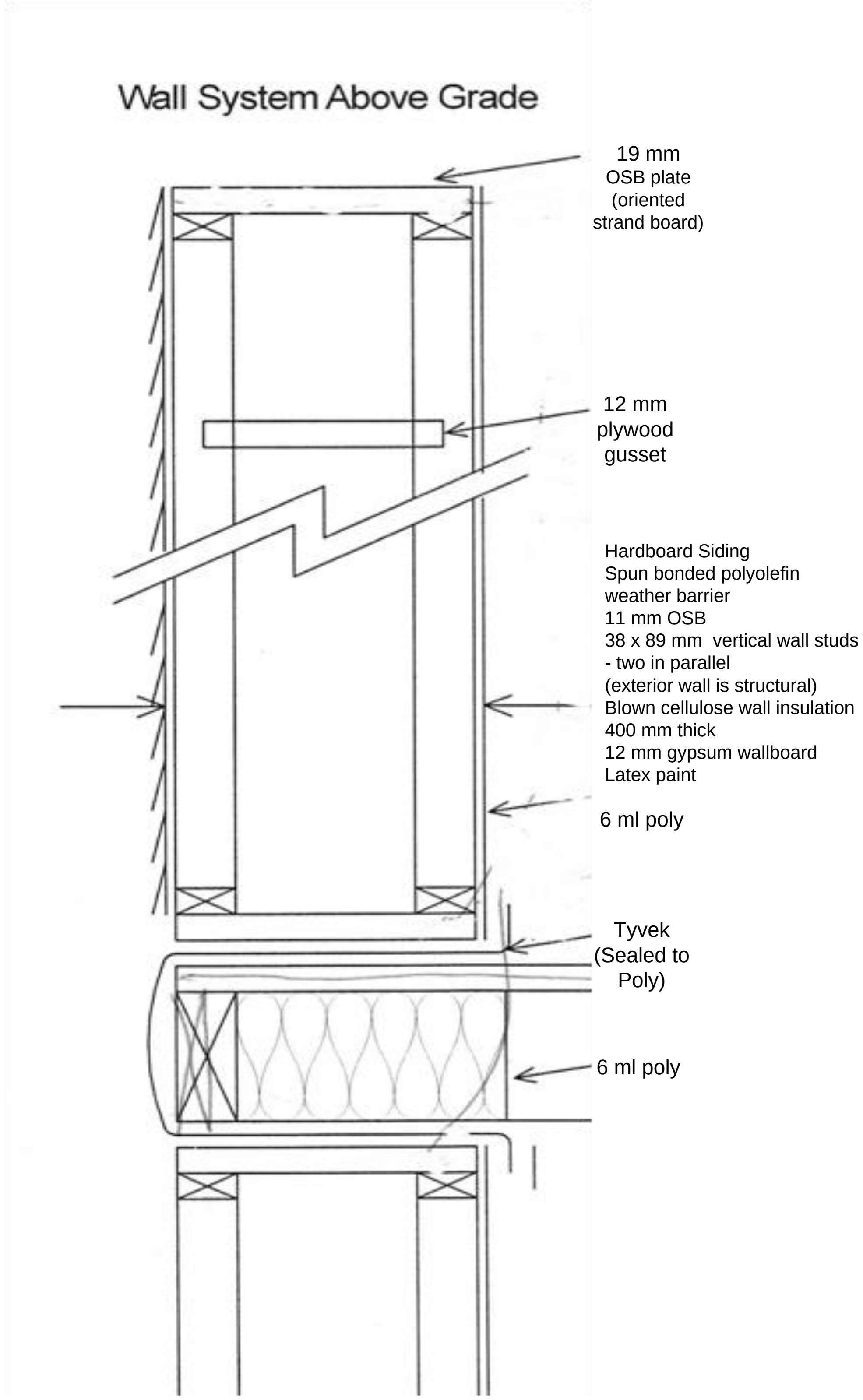

Figure 3: Double wall system - Dumont Residence

2. Triple glazed windows with two low e coatings, argon gas fills, low conductivity spacer bars, and wood frames.

The U value of the windows is about 1.1 W/m^2-K and the solar heat gain coefficient is about 0.4 Windows on the East and West exposures are minimized, and the majority of the windows are on the south side of the house.

3. A well sealed building envelope.
The measured air leakage rate of the building using a blower door apparatus is 0.47 air changes per hour at 50 pascals.

4. A heat recovery ventilator.
The double core heat recovery ventilator (fixed plate air to air heat exchanger) has a sensible heat recovery efficiency of 0.8 at 0 degrees C.

5. Some additional thermal mass.
The house has some additional thermal mass in the form of scrap gypsum board that has been placed in the interior wall cavities. Some areas of the house—kitchen and bathrooms—have ceramic tile as the finished floor, although most of the house has 12 mm thick oak flooring.

A cross section through the house is shown in Figure 4.

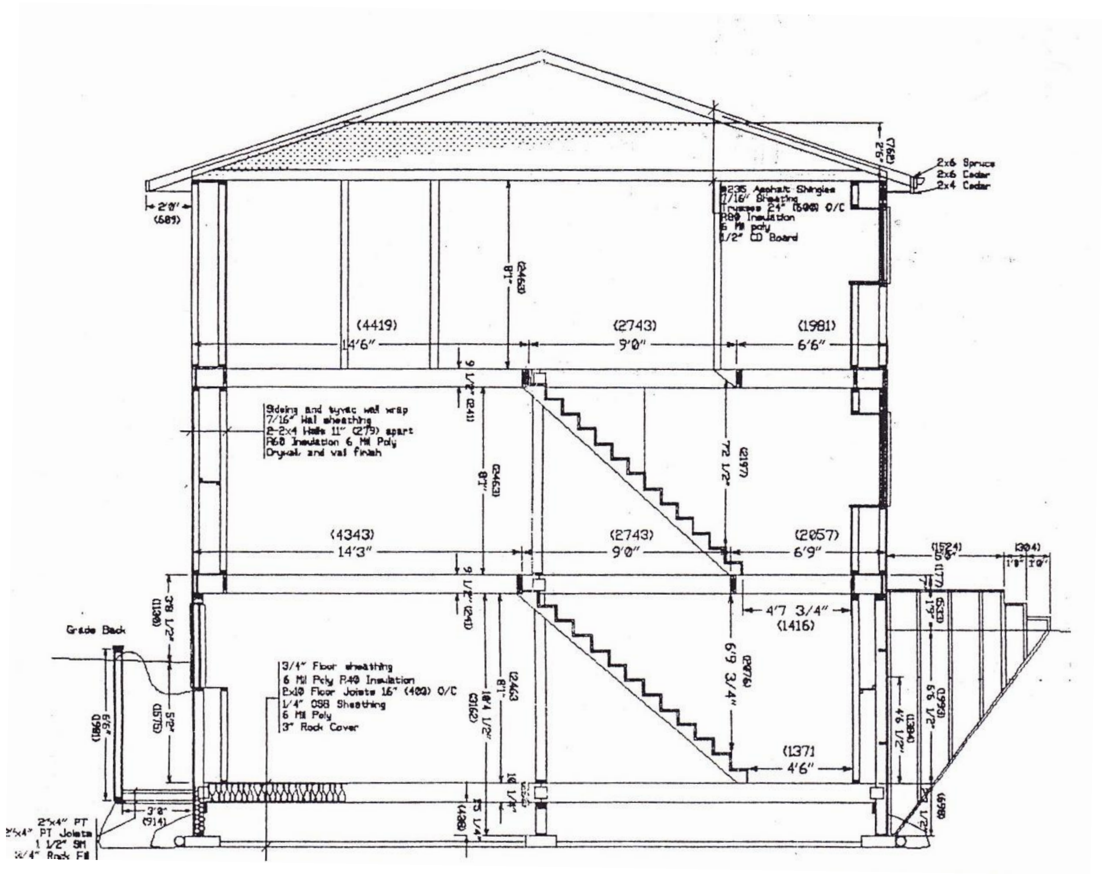

Figure 4. Cross Section through the Dumont Residence

6. Solar thermal collectors.
15.6 square metres of single glazed selective surface solar thermal panels are mounted on the south wall of the house as shown in Figure 5. A propylene glycol and water mixture is used to transfer heat from the collectors to a 4 cubic metre storage tank located in the basement of the house.

The solar thermal collectors provide some, but not all, of the domestic water heating and space heating for the house. For the purposes of the experiments detailed in this report, the solar thermal collectors were physically removed.

A schematic of the solar collection and heat distribution system is shown in Figure 5.

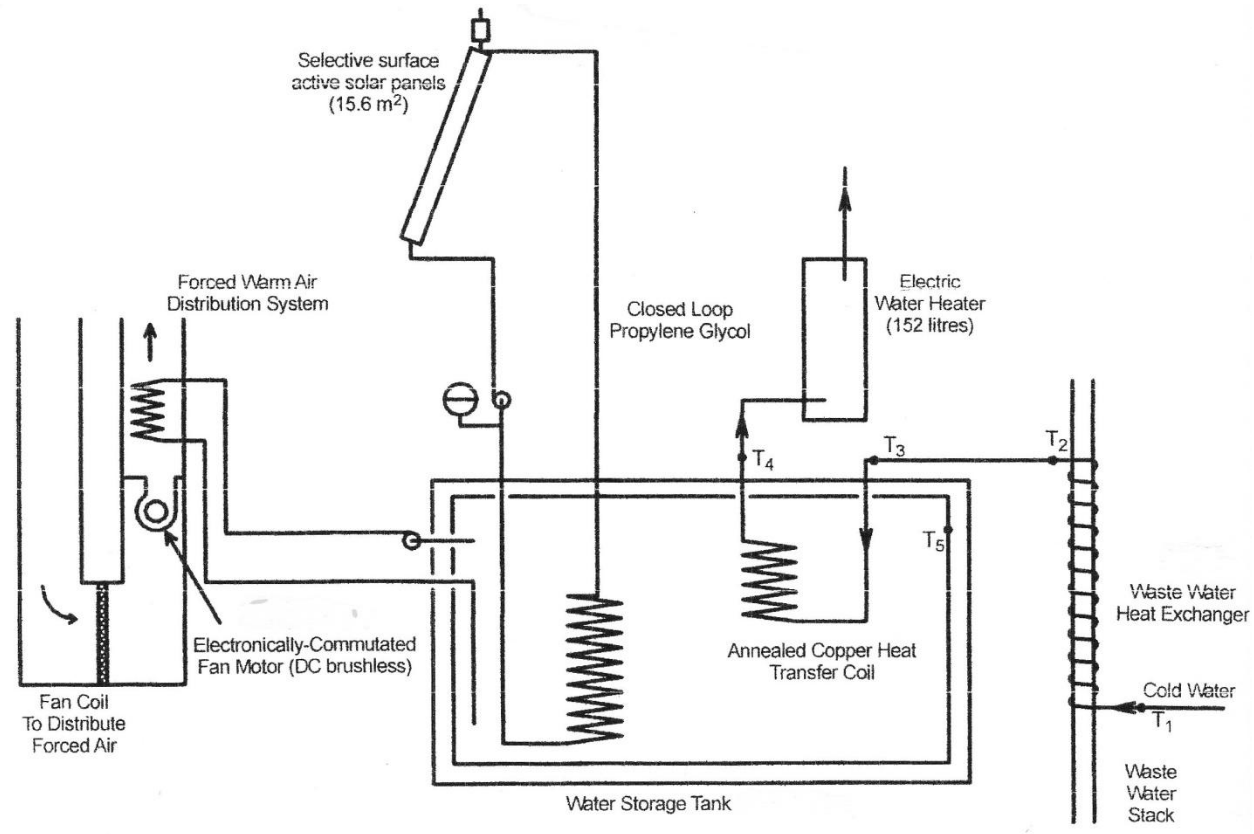

Figure 5. Schematic of the Mechanical Systems in the Dumont Residence

7. Low Embodied Energy Construction Materials
Wood is the primary construction material used in the house in part to reduce the embodied energy of construction. The roofing, roof trusses and sheathing, exterior and interior wall framing, floor joists, basement walls, window frames, the water storage tank framing, and the finish flooring are all primarily wood.

Off-Peak Charging of the Thermal Storage Tank in the Dumont Residence.

A test was performed using off-peak electricity to charge the large thermal storage tank in the Dumont Residence. The thermal energy in this large tank was then used to provide space heating for the house.

The conditions of the test were as follows:

1. The initial temperature of the top part of the large storage tank was approximately 50°C.
2. Heat was generated in the auxiliary water storage tank using a 3 kW electric resistance heater.

3. The heat was transferred to the large storage tank using a mechanical pump.
4. Heat was removed from the large storage tank using a second pump to move hot water to a fan coil, which distributed warm air to parts of the house. No other sources of direct space heating were used in the house during the testing.
5. The house was occupied during the test, and normal activities in the house took place.
6. During the 3 day test, the outdoor air temperature varied between -17°C and -9°C.

Exterior Conditions

The test run was done over a three day period (259 200 seconds) from December 20 to 23, 2010.
The solar radiation values on a south facing vertical surface were as shown in Figure 6.

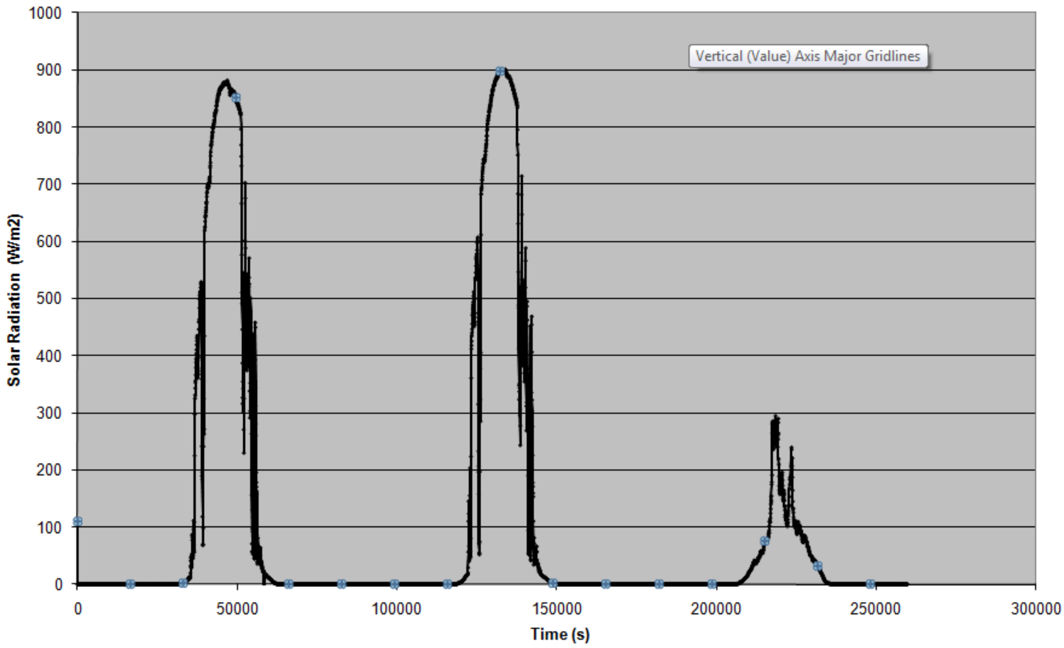

Figure 6. South Vertical Incident Solar Radiation from December 20 to 23, 2010

As can be seen, there were two sunny days followed by a mostly cloudy day.
The exterior temperature during the three days is shown in the lower part of Figure 7.

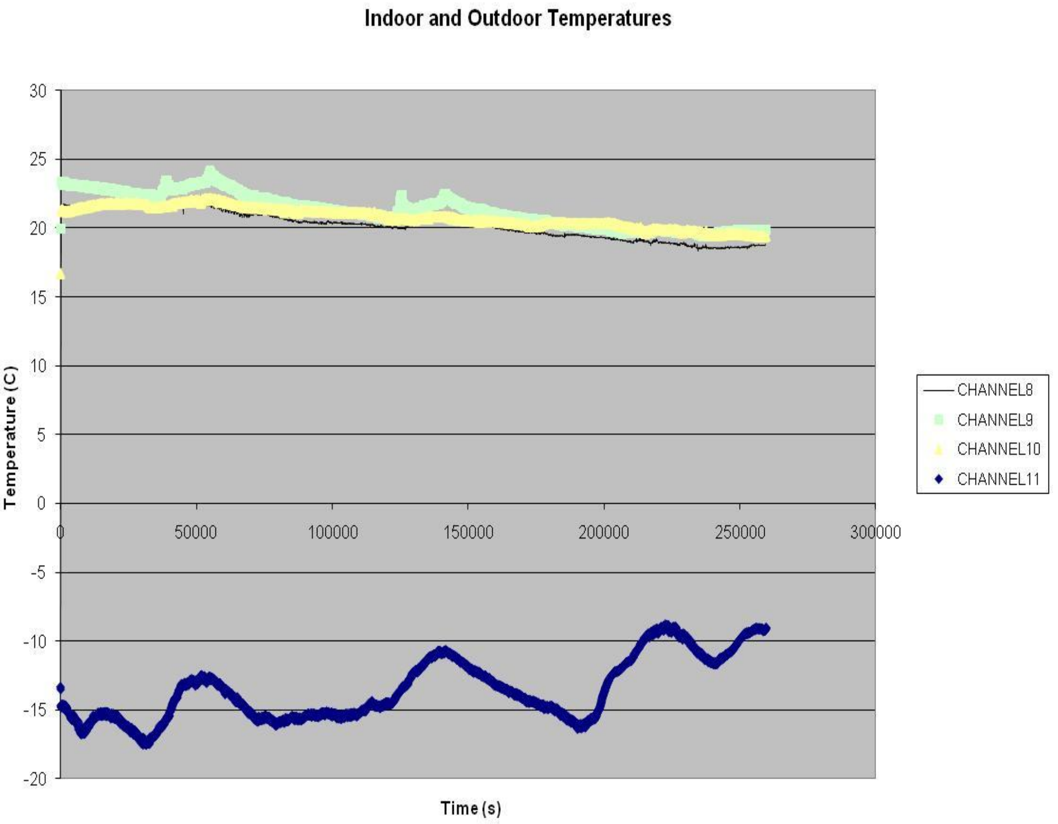

Figure 7. Indoor and Outdoor Temperatures over the three day period

The indoor temperatures for the three floors of the house are shown in the upper part of Figure 7.
Channel 9 represents the temperature of the main floor of the house. This floor has the greatest amount of south window area, and the room temperature of this floor will rise on sunny days relative to the temperatures on the other floors because of passive solar heating. Channel 8 is the upper floor temperature and Channel 10 is the basement temperature.

In Figure 8, the temperatures of the thermocouples in the large storage tank are shown.

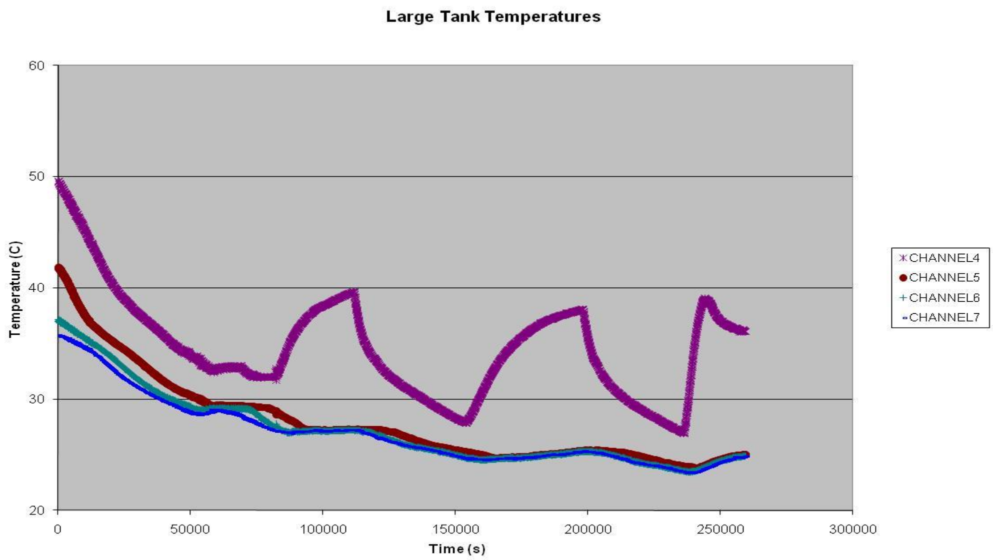

Figure 8: Temperatures in the large storage tank over the three day period with intermittent addition of heat to the tank and heat extraction for space heating.

The uppermost temperature (Channel 4) is that of the top part of the tank. The thermocouple is located 138 mm below the water level surface in the tank. The 2nd temperature down (Channel 5) is located 395 mm from the tank surface. The 3rd temperature down (Channel 6) is located 653 mm from the tank surface. The 4th temperature down (Channel 7) is located 886 mm from the tank surface.

As can be seen from the graph, heat was extracted from the tank from 0 seconds until about 80 000 seconds with no heat addition. Heat was then added to the tank until 109 000 seconds. Then heat was removed until 150 000 seconds. Heat was then added until 195 000 seconds, then removed until 234 000 seconds, and then heat was added until 243 000 seconds. During the three day period, heat was extracted periodically to satisfy the room thermostat located on the main floor of the house. As can be seen from the tank temperatures, there is stratification of the temperatures in the large tank, with the uppermost thermocouple demonstrating the most change in response to heat additions and removal. A single tank temperature would not adequately represent the heat storage characteristics of the tank.

A graph of the whole house electrical power consumption over the 3 day period is shown in Figure 9.

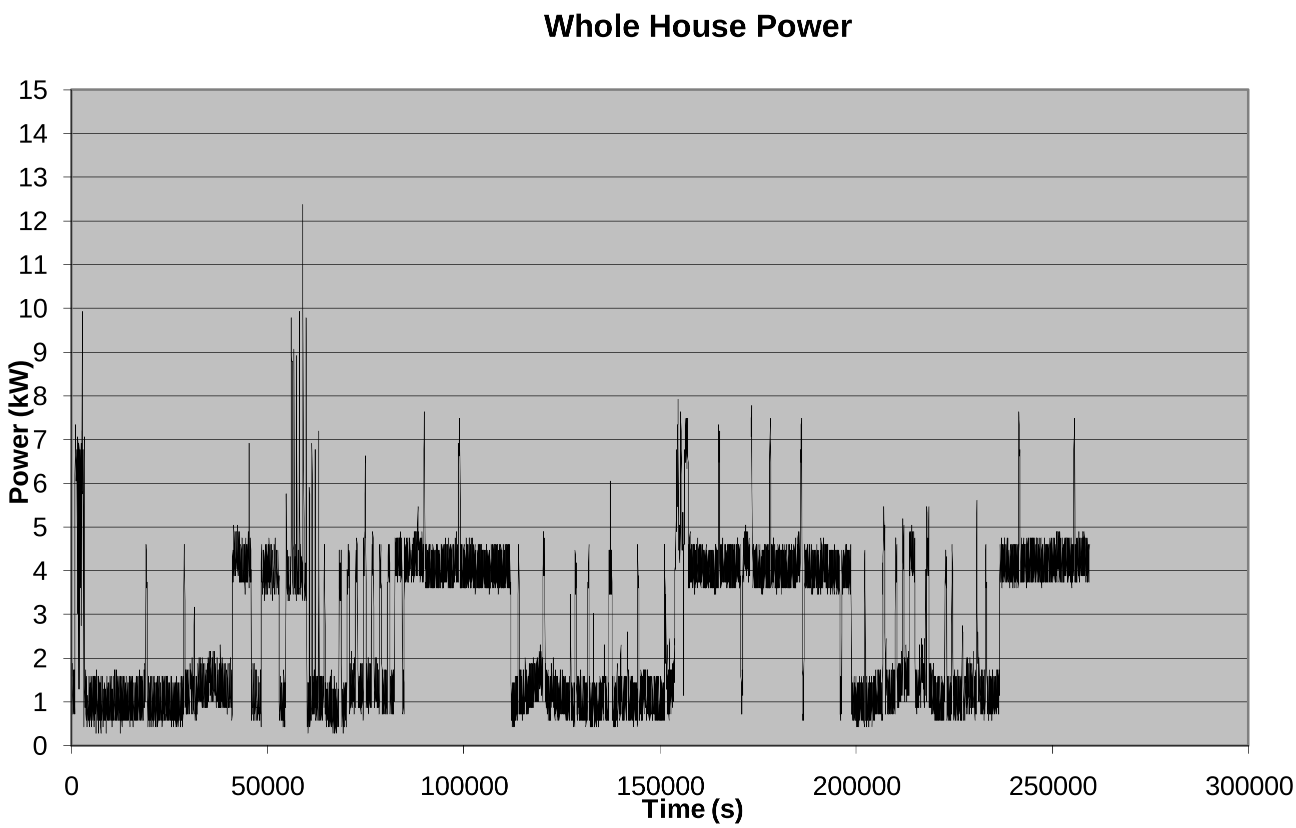

Figure 9. Whole house electrical power consumption.

As can be seen from the graph, there is a base electrical consumption for lights, appliances, domestic water heating and miscellaneous electricity of approximately 1 kW. When the auxiliary heater is on, the average power increases to about 4 kW. The peak power consumption was 12.3 kW, which occurred when the electrical dryer and other appliances were used by the occupants.

Summary

The house was able to maintain temperature with only a slight drop in temperature during the three day time period even though heat was being added to the large tank on an intermittent basis. The thermal storage capacity of the large tank provided an adequate buffer of energy to maintain temperature even though a modest source of auxiliary heat (3 kW) was used intermittently.




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Photographs: Iqaluit, Nunavut: installing piping for the new northern system that feeds the hospital, Canada - Hamilton Community Energy plant under construction, Canada - Bundang Plant, South Korea - Avedøre CHP plant, Denmark, photo: DONG Energy