Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 30 (2012) 856 – 865

Energy Procedia

SHC 2012

The performance of a high solar fraction seasonal storage district heating system – five years of operation

Bruce Sibbitt[a], Doug McClenahan[a], Reda Djebbar[a], Jeff Thornton[b], Bill Wong[c], Jarrett Carriere[c], John Kokko[d]

[a]CanmetENERGY, Natural Resources Canada, 580 Booth Street, Ottawa, K1A 0E4, Canada
[b]Thermal Energy System Specialists, 22 North Carroll Street - suite 370, Madison, 53703, USA
[c]SAIC Canada, 60 Queen Street, suite 1516, Ottawa K1P 5Y7, Canada
[d]Enermodal Engineering, 582 Lancaster Street West, Kitchener, N2K 1M3, Canada

Abstract

The Drake Landing Solar Community in Okotoks, Alberta, Canada utilizes a solar thermal system with borehole seasonal storage to supply space heating to 52 detached energy-efficient homes through a district heating network. Systems of similar size and configuration have been constructed in Europe, however, this is the first system of this type designed to supply more than 90% of the space heating with solar energy and the first operating in such a cold climate (5200 degree C-days). Solar heat captured in 2293 m^2 of flat-plate collectors, mounted on the roofs of detached garages, is stored in soil underground and later when needed for space heating, is extracted and distributed through a district system to each home in the subdivision. Independent solar domestic hot water systems installed on every house are designed to supply more than 50% of the water heating load. Annual greenhouse gas emission reductions from energy efficiency improvements and solar energy supply exceed 5 tonnes per house.

The seasonal storage utilizes approximately 34,000 m^3 of earth and a grid of 144 boreholes with single u-tube heat exchangers. The system is configured to maintain the centre of the field at the highest temperature to maximize heating capacity and the outer edges at the lowest temperature to minimize losses. A short-term thermal storage consisting of 240 m^3 of water is used to interconnect the collection, distribution and seasonal heat storage subsystems.

The system has undergone detailed monitoring since it was brought into service in July 2007 to characterize its performance and to improve the TRNSYS model employed in its design. A solar fraction of 97% in its fifth year of operation, convincingly confirms the design target, a solar fraction of more than 90% in year five, has been met. This paper describes the system and its operation, presents 5 years of measured performance and compares those results against the TRNSYS predicted performance for the same period.

doi:10.1016/j.egypro.2012.11.097

Keywords: Solar district heating; seasonal heat storage; high solar fraction; monitored performance; TRNSYS modeling

1. Introduction

In Canada, more than 80% of residential energy consumption is for space and domestic hot water heating, and most of the population lives in areas receiving more than 5.3 GJ/m^2 global solar radiation annually (on a south-facing surface with slope equal to the latitude), which is more than in many European countries with more active solar energy markets. However, a long-standing barrier to large-scale adoption of solar-heating technology is the relative lack of sunshine during the fall and winter seasons, when space heating demand is high.

Recent advances in solar seasonal storage development in Europe coupled with cost reduction in solar collectors in Canada led to the evaluation of utilizing the solar resource to displace large fractions of fossil fuel for residential space heating on a community scale in Canada. Promising feasibility study results prompted the design and implementation of the first solar heated community with seasonal storage in North America and the first in the world with a solar fraction over 90%.

The overall intent of the Drake Landing Solar Community (DLSC) project is to demonstrate the technical feasibility of achieving substantial conventional fuel energy savings by using solar energy collected during the summer to provide residential space heating during the following winter (seasonal storage). Previously, McClenahan et al. [1] and Wong et al. [2] reported on the system design and project implementation. Sibbitt et al. reported on preliminary monitored data taken before project completion [3] and later on the first 4 years of operation [4]. The objective of this paper is to summarize 5 years of system performance including meeting the design target solar fraction of greater than 90%, in year 5.

2. System description

DLSC consists of 52 homes located on two east-west streets, in Okotoks, Alberta. Each home has a detached garage behind the home, facing onto a lane. Each garage has been joined to the next garage by a roofed-in breezeway, creating 4 continuous roof structures, approximately the length of the 3 laneways, which support 2,293 m^2 of solar collectors. Figure 1 is an aerial photograph of the site.

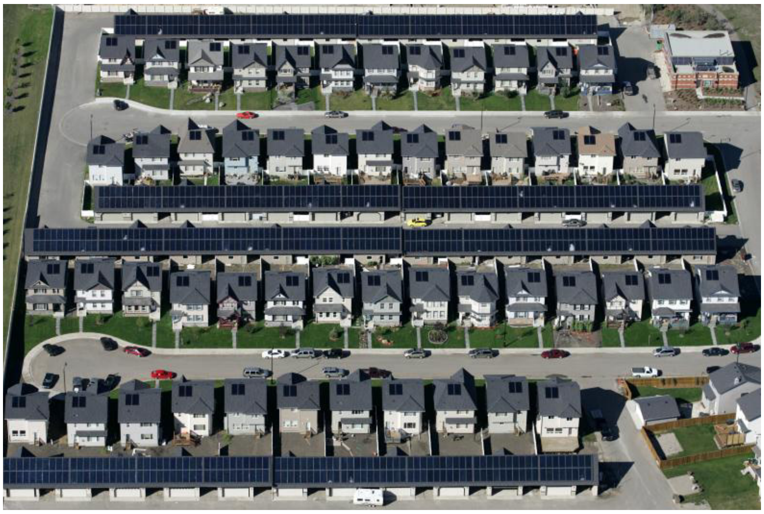

Fig. 1. Drake Landing solar community

A borehole thermal energy storage (BTES) field is used to save heat collected in the spring, summer and fall for use the following winter. Installed under a corner of a neighborhood park, and covered with a layer of insulation beneath the topsoil, 144 boreholes, each 35 m deep, are plumbed in 24 parallel circuits, each a string of 6 boreholes in series. Each series string is connected in such a way that the water flows from the centre to the outer edge of the BTES when storing heat, and from the edge towards the centre when recovering heat, so that the highest temperatures will always be at the centre.

Space heating is supplied to the 52 energy-efficient detached houses through 4 parallel branches of a 2-pipe district heating system. Certified to Natural Resources Canada's R-2000 standard and Alberta's Built Green - Gold level, each house benefits from upgraded insulation, air barrier, windows, low water consumption fixtures and heat recovery ventilation. An integrated air handler and heat recovery ventilator, incorporating fans with electronically commutated motors and a large water-to-air heat exchanger, supplies forced-air heating and fresh air. An independent, 2-collector, solar domestic hot water system, backed-up with a high-efficiency gas-fired water heater, supplies service hot water.

District energy system pumps, controls, auxiliary gas boilers, etc. are located in the Energy Centre which also houses two short-term thermal storage (STTS) tanks with a combined water volume of 240 m^3. The STTS acts as a buffer between the collector loop, the district loop, and the BTES field, accepting and dispensing thermal energy as required. The STTS tanks are critical to the proper operation of the system, because they can accept and dispense heat at a much higher rate than the BTES storage which, in contrast, has a much higher capacity. Variable speed drives are employed to power the collector loop and district heating loop pumps to minimize electrical energy consumption while handling a wide range of thermal power levels. A system schematic, Fig. 2, shows system details and the locations of monitoring sensors.

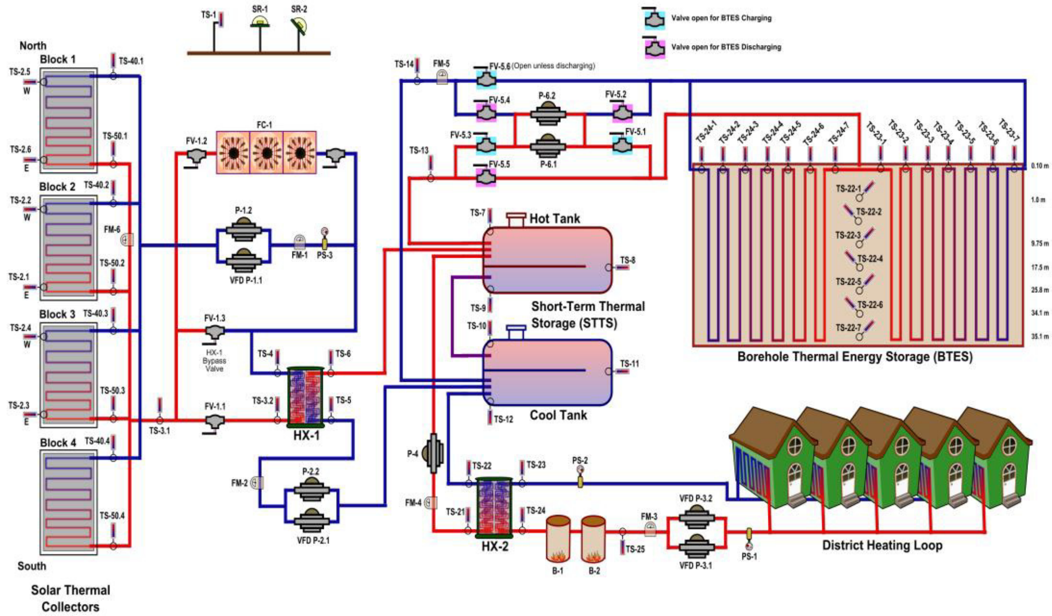

Fig. 2. Functional system schematic with monitoring points

System control

The control system is designed to initiate and maintain collector loop operation whenever there is sufficient incident solar energy available. Initial operation each day warms up the collector loop and when the collector loop fluid is hot enough, heat is transferred from the glycol to the STTS through a plate-frame heat exchanger and water loop. When space heating is required, energy from the STTS heats the district loop fluid through a second plate-frame heat exchanger. If there is insufficient energy in the STTS to meet the anticipated heating requirement, heat is transferred from the BTES into the STTS to meet the requirement. If the stored water temperature is insufficient to meet the current heating load, natural gas fired boilers raise the temperature of the district loop as required. When there is more heat in the STTS than is required for space heating in the short-term, water is circulated from the STTS through the BTES to store heat for later use.

In summer when space heating requirements are small, virtually all of the solar energy collected is transferred to the BTES. In winter when heating loads tend to exceed collected solar energy, heat is retrieved from the BTES. In the shoulder seasons, heat must be available to the homes and there must also be sufficient capacity available in the STTS to accept large quantities of solar heat. Control of charging and discharging must balance the anticipated heating requirement against the need for capacity to accept solar energy that may be collected.

Thermal stratification is important in both the BTES and the STTS to allow the high temperature water to be available for space heating needs while making relatively low temperature glycol available to supply the collectors. Both glycol and water collector loops utilize variable speed pumping. The control system was designed to vary the flow rate to achieve a 15 C temperature rise in the glycol loop and the water side pump would mimic the glycol side flow rate. This strategy enhances stratification in the STTS while reducing pump electricity consumption.

The district loop supply water temperature is varied linearly from 37 C for ambient air temperatures of -2.5 C or above to 55 C for ambient air at -40 C. Variable water flow rates are also used in the district loop to allow a wide range of space heating loads to be met while facilitating efficient use of solar heat over a range of source and load temperatures and limiting pump electricity consumption.

3. Simulated system performance

During the project design phase, a detailed TRNSYS model was developed to simulate the Drake Landing system including the collectors, short term storage, seasonal storage, district heating system, all interconnecting piping and controls. The house heating loads were predicted using detailed ESP-r simulations and the resulting load data were used in the TRNSYS system simulation. With Canadian Weather for Energy Calculation (CWEC) weather data driving it, the simulation model was capable of predicting temperatures and energy flows in each component of the system. Using an optimization routine, the distribution and number of solar collectors, the size of the short-term storage tanks, and the number and depth of the boreholes for the ground storage were varied within the limits defined by the project constraints and objectives, to find the combination that maximized the economic performance of the system.

Using 50 years of historical weather data, the simulation model predicted that the system would provide on average, more than 90% of the heating to the homes with solar energy. The simulated 5-year design system performance, shown in Table 1, was generated by repeating the CWEC weather data five times. It predicts that collector efficiency will drop from 32% to 25% over that period, as the average operating temperatures increase. It also predicts that the BTES efficiency will increase from 9% to 41% over 5-years of operation, as the soil temperature increases. The solar fraction was expected to increase from 66% to 89% over the period. These design simulations were performed with a January 1st start date.

Table 1. Summary of design simulation system performance

Year of Operation (January 1 – December 30)	1	2	3	4	5
Heating Degree-Days (K d)	5200	5200	5200	5200	5200
Horizontal Global Irradiation (GJ m^{-2})	4.97	4.97	4.97	4.97	4.97
Incident Global Irradiation (GJ m^{-2})	6.08	6.08	6.08	6.08	6.08
Collected Solar Energy (GJ)	4480	3830	3630	3550	3520
Collector Efficiency [a]	0.32	0.28	0.26	0.25	0.25
STTS Efficiency [b]	0.99	0.99	0.98	0.98	0.98
Energy into BTES (GJ)	3030	2390	2200	2110	2080
BTES Efficiency [b]	0.09	0.23	0.35	0.40	0.41
Solar Energy to District Loop (GJ)	1670	1930	2140	2230	2240
Total Energy to District Loop (GJ)	2530	2530	2530	2530	2530
Solar Fraction	0.66	0.76	0.85	0.88	0.89
Pump Electricity Consumed (GJ)	54	54	53	52	52
District Loop Losses (GJ)	247	249	250	251	250

One of the project's objectives was to calibrate and improve the accuracy of the design simulation model through comparisons of predicted and measured subsystem performance. Initial results of this calibration activity were reported by McDowell and Thornton [5] and further comparisons against additional monitoring data will be reported in the future. The calibrated models will continue to facilitate more accurate design predictions and the investigation and evaluation of modifications to this system and to future project designs and control strategies for enhanced performance.

4. Measured system performance

The complete solar system began operation in late June 2007 and its performance has been monitored since then. A summary of the performance measured between July 1, 2007 and June 30, 2012 is presented in Table 2. The annual collector efficiency has remained relatively constant over the period at approximately 33%, based on the gross area of the collectors and the collected energy measured at the heat exchanger in the energy centre. In the first year of operation, most of the collected energy (2610 of 4470 GJ) was sent to the BTES. Although the BTES only returned 152 GJ (6%) of the input energy for heating later in the first year, 1520 GJ of solar energy was also supplied directly from the STTS. Together, 1670 GJ of solar energy, out of a total of 3040 GJ was delivered to the district loop, giving a solar fraction of 55%. In the next 3 years, the BTES returned a greater fraction of the heat supplied to it, reaching 54% in the fourth year, allowing the solar energy contribution to the load to increase to 60% in year two, 80% in year three and 86% in year four. In year 5 the solar fraction increased to 97% but the heat returned from BTES dropped to 36% of the heat supplied to it.

a Based on gross collector area

b Apparent efficiency; does not account for year-to-year change in stored energy

Part of the improvement in overall performance over the period was due to the gradual charging of the BTES and part was the result of modifications to the system and controls that were implemented to allow the system to operate in accordance with the design. In the first year of operation, it was observed that the highest temperature water in the STTS was not accessible to the district heating loop or to charge the BTES since the water pick-ups and diffusers were not near the top of the hot tank. The tanks were modeled in detail and replacement pick-ups and diffusers were designed and then installed in late March and early April 2009. Also, during early system operation, before all 52 homes were completed, the district loop temperature control settings were raised to ensure occupant comfort in homes near the end of one street. The design settings were not restored until early January 2010. Both of these corrections contributed to the noticeable improvement in system performance in the second half of the third year of operation. Other changes that have made smaller contributions to improved system performance include closer control of the district loop supply temperature to reduce heat loss, upgrades to the HRV defrost system to prevent core blockage from freezing, increased collector delta-T to improve stratification in the STTS and reduce pump power and revised BTES charge and discharge set points to enhance BTES stratification and reduce pumping.

Table 2: Summary of monitored system performance

Year of operation	1	2	3	4	5
Period (July 1-June 30)	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012
Heating degree-days (K d)	5060	5230	4890	5480	4500
Horizontal global irradiation (GJ m^{-2})	4.63	4.96	4.65	4.58	4.75
Incident global irradiation (GJ m^{-2}) [c]	5.82	6.07	5.49	5.45	5.67
Collected solar energy (GJ)	4470	4580	4270	4060	4430
Collector efficiency [d]	0.34	0.33	0.34	0.33	0.34
STTS efficiency [e]	0.96	0.91	0.95	0.93	0.88
Energy into BTES (GJ)	2610	2810	2500	2260	2520
BTES efficiency [e]	0.06	0.20	0.35	0.54	0.36
Average BTES core temperature (C)	38.7	50.0	54.1	52.2	56.9
Solar energy to district loop (GJ)	1670	1790	2030	2460	2050
Total energy to district loop (GJ)	3040	2960	2550	2860	2120
Solar fraction	0.55	0.60	0.80	0.86	0.97
Total electricity consumed (GJ) [f]	209	211	200	193	173
District loop losses (GJ)	235	385	142	141	1.4

c Pyranometer shading at very low sun angles; 4.9% estimated annual impact

d Based on gross collector area

e Apparent efficiency; does not account for year-to-year change in stored energy

f Energy centre electricity consumption including pumps, controls & monitoring, interior & exterior lighting and ventilation fans; pump consumption is estimated to be approximately 130 GJ in year 5

5. Subsystem performance

5.1. Collector loop

Several sample collectors supplied to the DLSC project were tested at the National Solar Test Facility (NSTF) at the time of system construction. The performance characteristic, measured at a flow rate of 0.02 l/s, after a 30 day stagnation test period is:

$$\eta_{collector} = 0.693 - 3.835\left(\frac{T_i - T_a}{G}\right)$$

Performance of the array of 798 collectors, together with the piping to and from the energy centre, for the third year of operation, was compared to the efficiency of a single collector module in Fig. 3. Given that the field data includes collector loop pipe losses, agreement with the laboratory measured module efficiency is excellent.

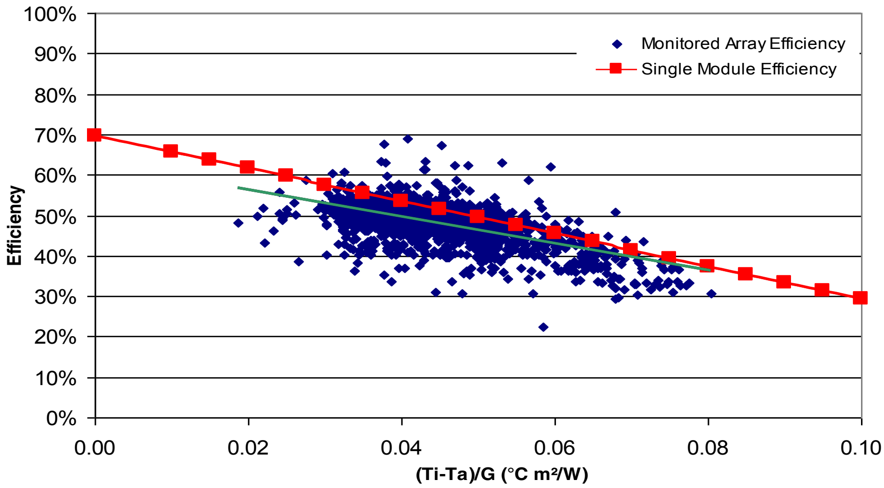

Fig. 3. Monitored array efficiency and single collector module efficiency

5.2. Thermal energy storage

The STTS is intended to operate with a high degree of thermal stratification so that high temperature water is available for space heating and for charging the BTES, while relatively low temperature glycol is available to supply the collectors. The highest temperature zone in the STTS is frequently 15 to 20 C warmer than the coldest region and heat losses average approximately 7% of the input energy over the five years of operation.

A large seasonal storage requires a significant length of time to charge and achieve final efficiency since the storage medium must be heated-up to the minimum useful temperature before heat can be extracted. Figure 4(a) shows the amount of energy delivered to the BTES and the amount extracted from it, over 5 years of system operation and Fig. 4(b) shows how the BTES core temperature has cycled over the same period. It is a weighted average, defined as the sum of the BTES centre top temperature, twice the BTES centre mid-height temperature and the BTES centre bottom temperature, divided by 4.

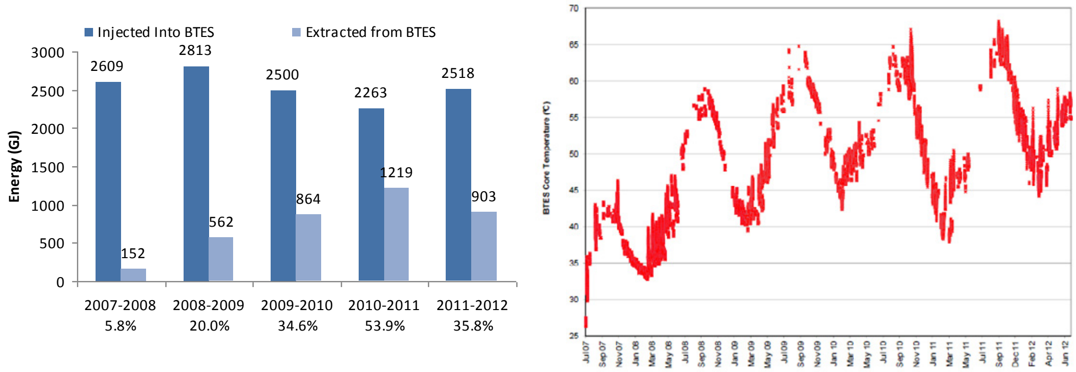

Fig. 4. (a) Energy injected into and extracted from BTES; (b) BTES core temperature

Before July 2007, one quarter of the collector array had operated for a few months and warmed the soil at the centre of the BTES to about 25 C. Over the next five years, with the whole system operating, that temperature cycled through annual peaks in September or October and minimums typically in late February superimposed on an increasing annual average core temperature trend. Higher temperatures typically permitted increased heat output and apparent efficiency (energy extracted divided by energy input). The fourth year minimum was lower than in the first 3 years but in year 5 the minimum, maximum and average core temperatures were all higher than in previous 4 years.

5.3. Heat distribution loop

The quantity of heat delivered to the distribution loop is measured in the energy centre and heat meters in each of the homes record the amount that is delivered to the homes. The distribution loss quantity in Table 2 is calculated as the difference between the heat delivered to the loop and the sum of heat quantities reaching the homes. A trend towards lower heat loss in recent years is consistent with the lower delivery temperatures in those years. Figure 5 shows a breakdown of heat delivered to the distribu-

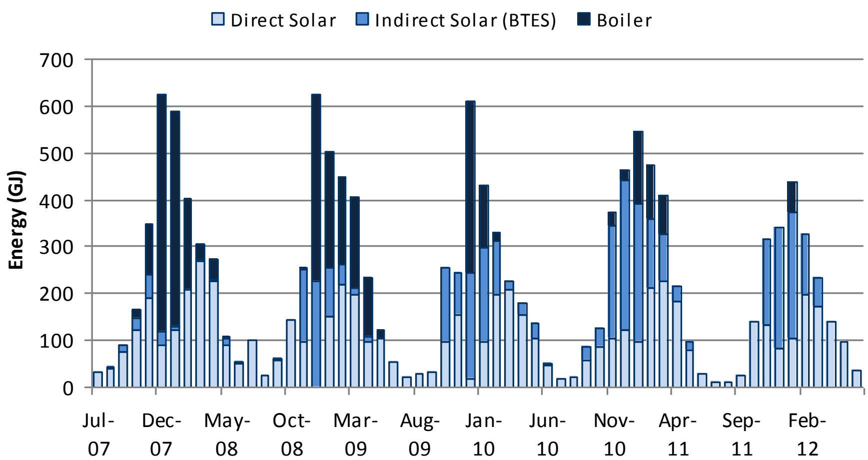

Fig. 5. Monthly energy supplied to the distribution loop

tion loop over the operating period. It shows the solar component of heating has increased in importance in each successive year and the importance of solar energy from BTES increased through year 4 but decreased with the smaller load encountered in year 5.

6. Comparison of measured and predicted performance

In its first two years of operation, the system appeared to be falling short of the predicted solar fraction. Collector array efficiency, STTS efficiency and BTES efficiency were reasonably close to those expected, however, the total heat supplied to the distribution loop was close to 20% higher than predicted for the first two years. An investigation found that below-specification recovery efficiency of the HRVs was the main cause for the higher than anticipated system heating load (additional detail in [4]). As noted previously, STTS diffuser design and control system set points also limited overall performance in the first two-and-a-half years of operation.

In year 1, the measured annual collector efficiency was very close to that predicted, however, in subsequent years the measured efficiency remained near constant while the predicted value dropped from 0.32 to 0.25 over 4 years. It is possible that several factors have contributed to the difference, as noted in [4]. For example, the sloped pyranometer, mounted at the centre of one of the four collector blocks, experiences shading at the very beginning and end of days, when the sun path is low in the sky (estimated to reduce the measured annual incident radiation and radiation incident on the collectors by 4.9% in a typical year) likely accounts for a steady overestimate of measured efficiency by about 1.6%. Further investigation will be undertaken to understand the growing component of collector over-performance.

The apparent BTES efficiency closely tracked the simulated efficiency for the first three years of operation, however, it significantly exceeded the prediction in year 4 and then fell below prediction in year 5, since it does not account for changes in stored energy. In year 4, the high load imposed on the system from the cold winter and the lower district loop temperature profile, caused a large temperature drop in the BTES, allowing energy stored before year four to be used, leaving less energy stored in the BTES. In year 5, typical input to BTES and a lower than average energy draw resulted in a notable increase in stored energy. Both of these effects were not observed in simulations that use the same weather year for several years in a row but they do appear when a series of real weather years is used. The difference between year 4 and year 5 minimum core temperatures shows there was a significant quantity of stored heat available in year 5 that was not needed in that year.

With the BTES warming-up over the period, the installation of improved tank pick-ups and diffusers and the restoration of design district loop set points, the system solar fraction increased from 55% in year one to 97% in year 5.

Excellent results from of the Drake Landing Solar Community project have led to considerable interest in implementing similar but larger systems, that will take advantage of opportunities for performance improvements and lower unit costs. A series of research projects to investigate promising avenues to further reduce costs and improve performance in future designs and to glean more useful knowledge from the DLSC, are being initiated. Several community system implementation projects are also undergoing feasibility investigations.

7. Summary and conclusions

The system is performing very close to expectations and achieving a 97% solar fraction in its fifth year of operation confirms that the system has met the design target of more than 90% in year five.

The collector and BTES storage are performing at least as well as predicted and the TRNSYS and ESP-r design simulations have proven to be accurate.

Monitored performance over five years of operation has proven that high solar fraction systems of this type are technically feasible in a cold Canadian location with 5200 heating degree-days and a design temperature of -31 C.

The ongoing monitoring and detailed simulation results are particularly valuable for operating and learning from system designs such as this, where there is limited field experience.

The success of the Drake Landing Solar Community project has led to the possibility of implementing similar but much larger systems, which offer opportunities for performance improvements and lower unit costs.

Nomenclature

G	incident solar flux (W m^{-2})
$\eta_{collector}$	collector efficiency
T_a	ambient air temperature (C)
T_i	collector inlet temperature (C)

Acknowledgements

Funding of the monitoring and technical support for DLSC following construction has been provided by the Government of Canada (CanmetENERGY, the Program of Energy Research and Development and the ecoENERGY Technology Initiative). We also acknowledge the efforts of the entire project team including ATCO Gas, Sterling Homes, the Town of Okotoks, Hurst Construction, J. E. Taylor Plumbing, Quigley Electric, and Johnson Controls in the operation, maintenance and monitoring of the system. We would also like to acknowledge all of the organizations who made the design and construction of this project possible through their funding support, cash, in-kind contributions and dedicated efforts.

References

[1] McClenahan, D., Gusdorf, J., Kokko, J., Thornton, J., Wong, B. Okotoks: Seasonal Storage of Solar Energy for Space Heat in a New Community. Proceedings of ACEEE 2006 Summer Study on Energy Efficiency in Buildings, Pacific Grove; 2006.

[2] Wong, W.P., McClung, J.L., Snijders, A.L., Kokko, J.P., McClenahan, D., Thornton, J. First Large-Scale Solar Seasonal Borehole Thermal Energy Storage in Canada, Proceedings of Ecostock Conference, Stockton, 2006.

[3] Sibbitt, B., Onno, T., McClenahan, D., Thornton, J., Brunger, A., Kokko, J., Wong, B. The Drake Landing Solar Community Project – Early Results. Proceedings of 32ndAnnual Conference of the Solar Energy Society of Canada, Calgary, 2007.

[4] Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J., Kokko, J. Measured and Simulated Performance of a High Solar Fraction District Heating System with Seasonal Storage. Proceedings of the ISES Solar World Congress, Kassel, 2011.

[5] McDowell, T.P., Thornton, J.W. Simulation and Model Calibration of a Large-Scale Solar Seasonal Storage System, Proceedings of 3rd National Conference of the International Buildings Performance Simulation Association -USA, Berkeley, 2008.