Drake Landing Solar Community: 10 Years of Operation

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Abstract

Drake Landing Solar Community is a Canadian solar district heating system with seasonal thermal storage. The demonstration project, designed to achieve over 90% solar fraction, was commissioned in the summer of 2007, reaching its 10th year of operation in 2017. The present work describes the system and its operation, presenting simulated and measured performance indicators for 10 years of operation, together with relevant operational data. Monitoring has proven the design simulations to be generally very accurate. During the last 5 years, the measured average solar fraction was 96%, including 100% achieved during the 2015-2016 heating season. The ability to easily access and view detailed system operating data combined with the ability to compare actual operation against predicted has proven to be extremely valuable for the successful commissioning and the efficient operation of energy systems at DLSC. Overall, the system has successfully demonstrated the reliable operation of a high solar fraction solar district heating system with seasonal thermal storage in a very cold climate. Although that Drake Landing system is too small to be economically competitive with the current very low price of natural gas in North America, subsequent feasibility studies show that larger systems of similar design can deliver solar energy at about half the cost compared to Drake Landing.

Keywords: Solar district heating, seasonal heat storage, borehole thermal energy storage, BTES, Drake Landing, high solar fraction, monitored performance.

1. Introduction

In Canada, space and domestic water heating account for more than 80% of greenhouse gas emissions in the residential sector. Despite that and the good levels of annual solar irradiation available in the most populated areas of the country, adoption of solar thermal technologies has been slow. This is partly due to the seasonal mismatch between the solar resource and the heating load, in particular for space heating applications. The Drake Landing Solar Community (DLSC) project was created to demonstrate the technical feasibility of achieving conventional fuel energy savings of more than 90% by using solar energy collected and stored during the summer to provide residential space heating during the following winter (seasonal storage). The system was commissioned in late June 2007, achieving 10 years of space heating operation during the 2016-2017 winter.

2. System Description

DLSC consists of 52 detached homes in Okotoks, Alberta (latitude 50.73N, longitude 113.95W). Each home has a detached garage behind the house, facing onto a lane (Figure 1). Each garage has been joined to the next garage by a roofed-in breezeway, creating 4 continuous roof structures, as seen on Figure 2. On those roof structures, 2293 m^2 (gross) of flat-plate solar collectors were installed.

The houses are located along two streets running east-west. Six different house models were available to buyers, with an average above-grade floor area of 145 m^2. The houses were built to meet Canada's R-2000 performance standard, with upgraded building envelopes, including higher insulation, low-e argon filled double panel windows and improved air tightness and construction details. The higher standard was estimated to reduce space heating load by 30% when compared to baseline houses at the time of construction. Space heating is supplied to the 52 houses through 4 parallel branches of a 2-pipe district heating system. An integrated air handler and heat recovery ventilator, incorporating fans with electronically commutated motors and a large water-to-air heat exchanger, supplies forced-

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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.

Fig. 1: View of houses with adjoined garages and houses street view

Fig. 2: Aerial view of Drake Landing Solar Community

A seasonal borehole thermal energy storage (BTES) field was installed under a corner of a neighborhood park and covered with a layer of insulation beneath the topsoil. The BTES is composed of 144 boreholes, each 35 m deep and radially plumbed in 24 parallel circuits, each with 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. Figure 3 shows the borehole field under construction and currently, as a landscaped park.

Most of the solar district energy system mechanical equipment (pumps, controls, auxiliary gas boilers, etc.) is in a dedicated building (Energy Centre, at top right corner of Figure 2), 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. A 22 kW photovoltaic array is installed on the roof of the energy centre (not visible in Figure 2, as the picture was taken before its installation)

The specially designed air-handlers and separate water heating systems allow the district system to operate at low temperatures, leading to increased effective storage capacity and higher collector performance. Typically, the supply temperature for the district heating system is below 40°C, and return below 30°C.

Fig. 3: Borehole field under construction and currently, as a landscaped park

A schematic diagram of the system is shown on Figure 4, and more details on its design and early results of operation can be found elsewhere: McClenahan et al. (2006), Wong et al. (2006) and Sibbitt et al. (2012, 2015).

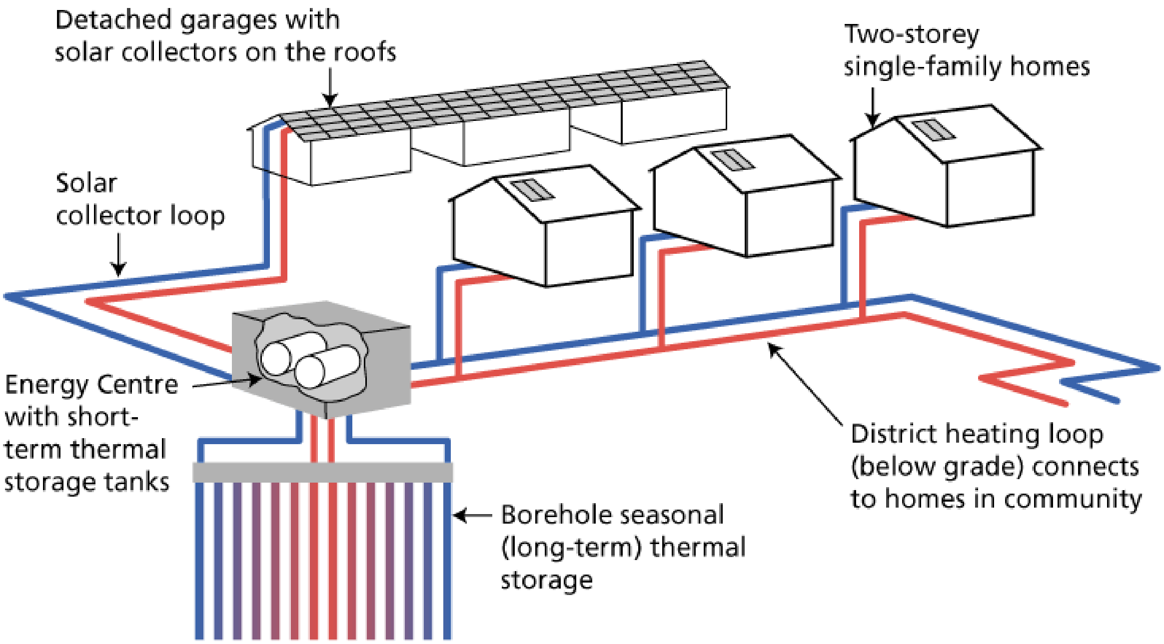

Fig. 4: Schematic diagram of the solar seasonal storage heating system at Drake Landing Solar Community

3. System Performance Results

3.1. Simulated system performance

During the design phase, a detailed TRNSYS model was developed to simulate the system operation. The model includes solar collectors, heat exchangers, short-term and bore-hole storage, piping, controls and district heating system. The house heating loads were calculated using ESP-r, and the results used as input into TRNSYS. Simulations were done both with 50 years of historical weather data and by repeating the typical meteorological year, CWEC – Canadian Weather for Energy Calculation, for the site. Both analysis predicted average solar fractions above 90% over 50 years of operation. The TRNSYS simulations were used to optimize some of the main design parameters, such as solar collector area, short-term storage size and number and depth of boreholes. Table 1 presents the results of the simulated 10 years of operation with repeated CWEC data.

The results of 50 years simulations using the same load and weather data show very little change beyond the 10^{th} year of operation. Therefore one can see the results for the 10^{th} year on Table 1 as the final steady state condition for the simulations. The system reaches a maximum solar fraction of 91%, with an all pumps electrical COP of 46. COP calculations are based on home heating load as a way to compare its values to distributed heat pump systems. Two different COPs are defined: COP_{ss}, based on the solar and storage pumps electricity consumption and the solar contribution to the houses heat load, and COP_{ap}, based on all pumped electricity consumption and the houses heat load.

$$COP_{ss} = {(Q_h f)}/{E_{ss}} \quad \text{(eq. 1)}$$

$$COP_{ap} = {Q_h}/{E_{ap}} \quad \text{(eq. 2)}$$

Tab. 1: Summary of simulated system performance

Year of Operation (Jan-Dec)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Heating Degree-Days (18°C ref.)	5200	5200	5200	5200	5200	5200	5200	5200	5200	5200
Homes Heating Load (GJ)	2328	2328	2328	2328	2328	2328	2328	2328	2328	2328
Horizontal. Global Irradiation (GJm^{-2})	4.97	4.97	4.97	4.97	4.97	4.97	4.97	4.97	4.97	4.97
Incident Global Irradiation (GJm^{-2})	6.08	6.08	6.08	6.08	6.08	6.08	6.08	6.08	6.08	6.08
Collected Solar Energy (GJ)	4480	3830	3630	3550	3520	3510	3490	3490	3480	3470
Collector Efficiency[1]	0.32	0.27	0.26	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Energy into BTES (GJ)	3030	2390	2200	2110	2080	2060	2050	2040	2030	2020
BTES Efficiency[2]	0.09	0.23	0.35	0.40	0.41	0.43	0.43	0.45	0.45	0.45
Solar Energy to District Loop (GJ)	1670	1930	2140	2230	2230	2270	2280	2300	2300	2300
Total Energy to District Loop (GJ)	2530	2530	2530	2530	2530	2530	2530	2530	2530	2530
Solar Fraction	0.66	0.76	0.85	0.88	0.88	0.90	0.90	0.91	0.91	0.91
Solar and Storage Pumps Electricity Consumption (GJ)	46	47	47	46	45	45	45	45	45	45
All Pumps Electricity Consumption (GJ)	53	54	53	52	52	52	51	51	51	51
COP_{ss}	33	37	43	45	45	46	47	47	47	47
COP_{ap}	44	43	44	45	45	45	45	45	45	46

Although the results on Table 1 were obtained with the TRNSYS model developed at the time of system design, many efforts have been made to improve and calibrate the model. McDowell and Thornton (2008) performed an initial model calibration during the first year of operation, and additional efforts are currently under way to review and calibrate the model by comparing the results between measured and modeled energy performance results using measured weather and load data as inputs to the model.

[1] Based on gross area
[2] Apparent efficiency; does not account for year-to-year change in stored energy

3.2. Measured system performance

DLSC operation has been closely monitored since its commissioning in 2007 and a summary of the performance measurements between July 1, 2007 and June 30, 2017 is presented on Table 2. The annual collector efficiency has remained relatively constant over the period at approximately 34%, 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. Such low BTES contribution happened again in 2015-2016, when the system reached 100% solar fraction and the house heating loads were the lowest for the 10 years of operation. During the last 5 years, the average solar fraction was 96%, including 100% achieved during the 2015-2016 heating season.

Tab. 2: Key measured performance indicators for the first 10 seasons of operation

Year of Operation (Jul-Jun)	**2007 2008**	**2008 2009**	**2009 2010**	**2010 2011**	**2011 2012**	**2012 2013**	**2013 2014**	**2014 2015**	**2015 2016**	**2016 2017**
Heating Degree-Days (18°C ref.)	5060	5230	4890	4910	5480	4580	5300	4860	4130	4760
Homes Heating Load (GJ)	2790	2470	2400	2700	2100	2380	2520	2160	1840	2340
Horizontal. Global Irradiation (GJm^{-2})	4.63	4.96	4.65	4.58	4.75	4.70	4.63	4.57	4.50	4.26
Incident Global Irradiation (GJm^{-2})	5.82	6.07	5.49	5.45	5.67	5.55	5.55	5.41	5.48	5.06
Collected Solar Energy (GJ)	4470	4390	4270	4060	4430	4330	4290	4340	4360	3920
Collector Efficiency[1]	0.34	0.32	0.34	0.33	0.34	0.34	0.34	0.35	0.35	0.34
Energy into BTES (GJ)	2610	2710	2500	2260	2520	2570	2460	2680	2670	2270
BTES Efficiency[2]	0.06	0.21	0.35	0.54	0.36	0.51	0.56	0.42	0.32	0.54
Solar Energy to District Loop (GJ)	1670	1790	2030	2460	2050	2430	2780	2390	2270	2550
Total Energy to District Loop (GJ)	3040	2960	2550	2860	2120	2490	3030	2500	2270	2750
Solar Fraction	0.55	0.60	0.80	0.86	0.97	0.98	0.92	0.96	1	0.93
Solar and Storage Pumps Electricity Consumption (GJ)	133	135	126	120	81	72	84	64	65	72
All Pumps Electricity Consumption (GJ)	153	156	145	138	93	83	97	74	79	78
COP_{ss}	12	11	15	19	25	32	28	33	28	31
COP_{ap}	18	16	17	20	23	29	26	29	23	30

[1] Based on gross area
[2] Apparent efficiency; does not account for year-to-year change in stored energy

Measured irradiation has been consistently lower than CWEC typical meteorological year numbers. Solar collectors have performed better than estimated through the simulations. Those discrepancies are currently under closer investigation. COP values have improved considerably since the beginning, mostly due to control strategies that reduced pump electricity consumption. Lower initial COP values were due to higher pump consumption and the fact that the BTES was being charged for the first time. The system has consistently produced COP results above 28. Moreover, the electricity consumption for pumps is almost entirely off-set by onsite PV generation. Unlike PV, however, the solar thermal system with seasonal storage delivers energy when it is mostly needed, without seasonal imbalances. Overall, the system has surpassed performance expectations and has operated with a high level of reliability.

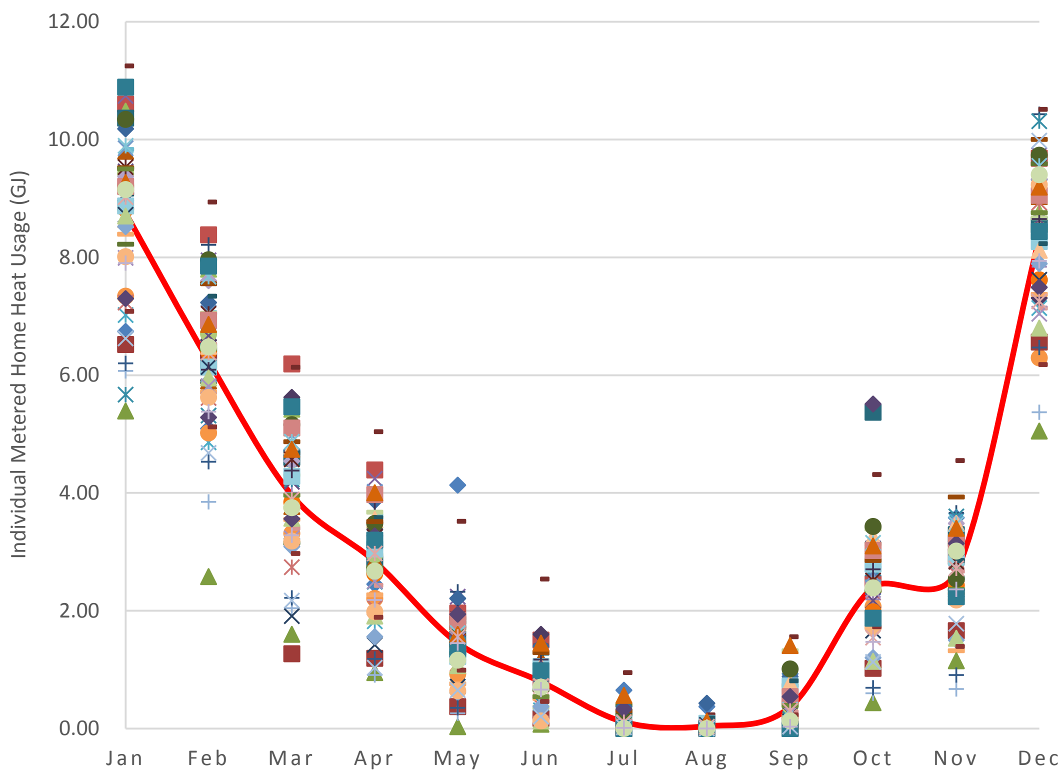

Fig. 5: Monthly metered heat usage for each one of the 52 houses for the calendar year of 2016

The individual heat metering results shown in Figure 5 show a large variation in heat usage among the 52 houses, even though there is not a significant difference in house sizes or construction. However, many other variables can lead to such variations, such as thermostat settings, and internal and solar passive heat gains. The original design heat load estimates showed that internal gain and passive solar represent about half of the contribution to the total heat load. It should be noted, however, that despite large individual variations, the average annual heat usage for the 52 houses is very close to the design value. For the initial 10 years, the average heating load for the 52 houses has been metered at 2370 GJ/year, compared to 2328 GJ/year simulated.

4. System Operation and Control

DLSC is controlled and monitored through METASYS, a building automation system (BAS) developed by Johnson Controls. Data is recorded every 10 min and the system operation is followed remotely by the project utility partner, ATCO and by researchers at CanmetENERGY Ottawa. There are no operators on site, and a number of alarms are set in the BAS, providing immediate awareness of operational issues. Figure 6 shows a functional diagram for DLSC with the system monitoring points.

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, bypassing the glycol-water plate-frame heat exchanger. When the collector loop fluid is hot enough, the flow is directed to the heat exchanger, transferring the heat to the water loop connected to the STTS. 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 supplying relatively low temperature glycol to the collectors. Both glycol and water collector loops utilize variable speed pumps. The control system was initially 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.

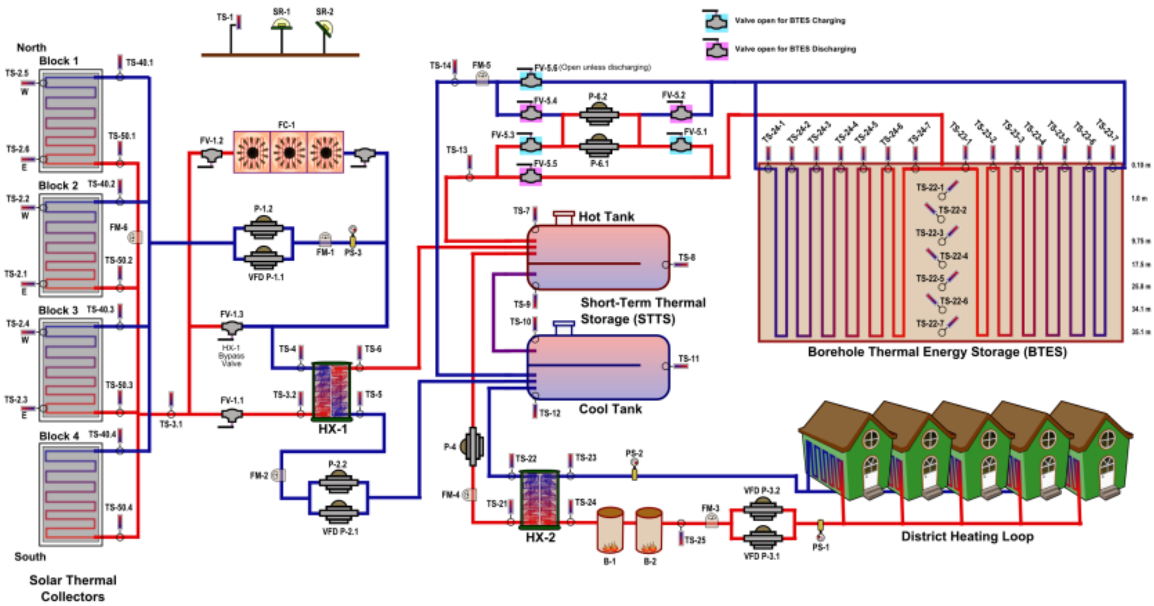

Fig. 6: Functional system schematic with monitoring points

One of the goals of the project is to evaluate control strategies that can optimize net energy production, maximizing the amount of collected energy and reducing power consumption for pumps. The solar collection pumps (primary glycol and primary water) account for more than 45% of all the electricity used for pumps (Table 3), despite the fact that the glycol loop was designed with a relatively low maximum flow rate of 25 l/hm^2. Therefore, during the years of system operation, a number of experiments were conducted to evaluate, through different control strategies, the impact of primary circuit flow reduction on electricity usage and thermal performance.

Tab. 3: Pump electricity consumption (GJ) for 2016-2017

Description	Pump					
	Primary Glycol	Primary Water	District Loop	STTS to HX	BTES	Total
Annual Consumption (GJ)	26.16	10.81	6.38	7.99	26.85	78.19
Percentage of Total	33.5%	13.8%	8.2%	10.2%	34.3%	-

Power consumption vs pump speed was measured for each one of the pumps equipped with variable frequency drives (VFD). Figure 7 shows, as expected, the marked increased in electrical power that follows an increase in pump speed.

The main strategy to reduce power consumption has been to increase the set temperature differential through the glycol loop, which leads to lower flow rates and pump speed. This effect can be observed on Figure 8. Compared to 2010-2011, both 2015-2016 and 2016-2017 show less hours of operation at high flow rates, which translates into a reduction of electricity usage. With negligible impact on collector annual efficiency, the electricity savings are calculate to be approximately 50% of the amount used with the original control strategy.

For the BTES pump the approach has been to use a predictive manual control, preventing energy from being moved from the STTS to the BTES if a cold front is forecasted, and only charging the BTES in the winter if the top temperature in the hot tank surpasses 60°C.

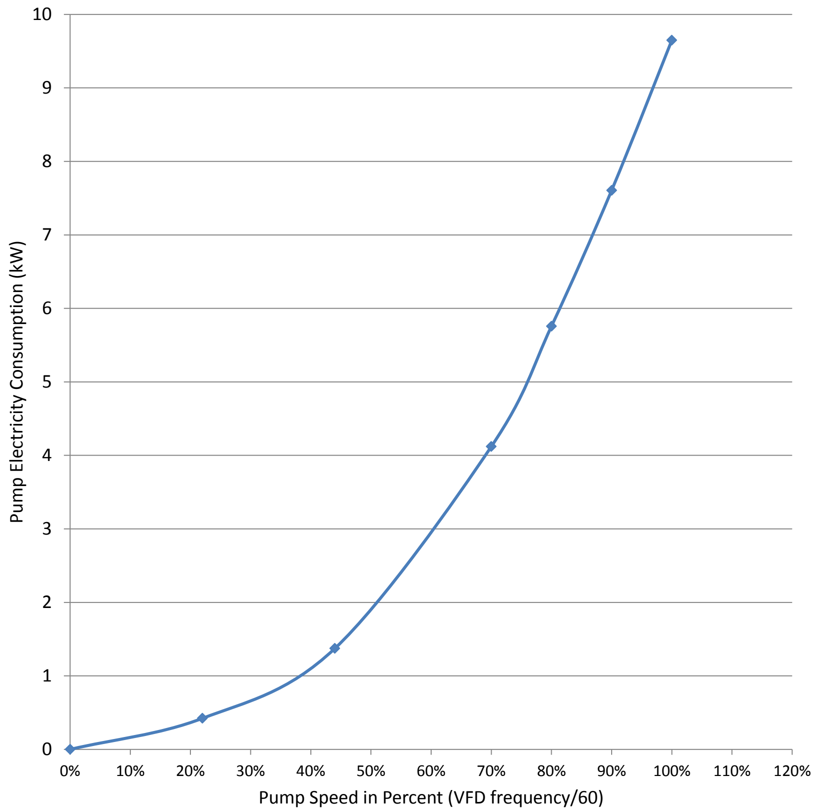

Fig. 7: Measured glycol pump (P1.1) electricity consumption as function of VFD setting

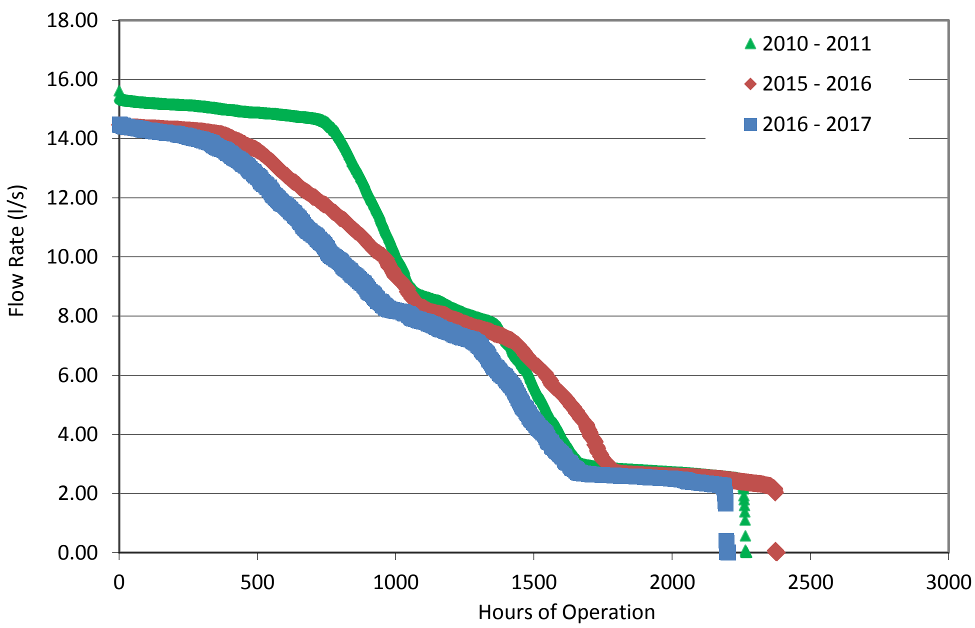

Fig. 8: Numbers of hours of operation at different flow rates for the glycol pump (P1.1) (selected years)

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. Figure 9 shows the heat supply to the system based on type of source for the

2016-2017 operational year. In this particular year, which was somewhat typical, direct solar was responsible for 48% of the energy supplied, while indirect solar, i.e., energy extracted from the BTES, accounted for 45% and the boilers for 7% of the supply.

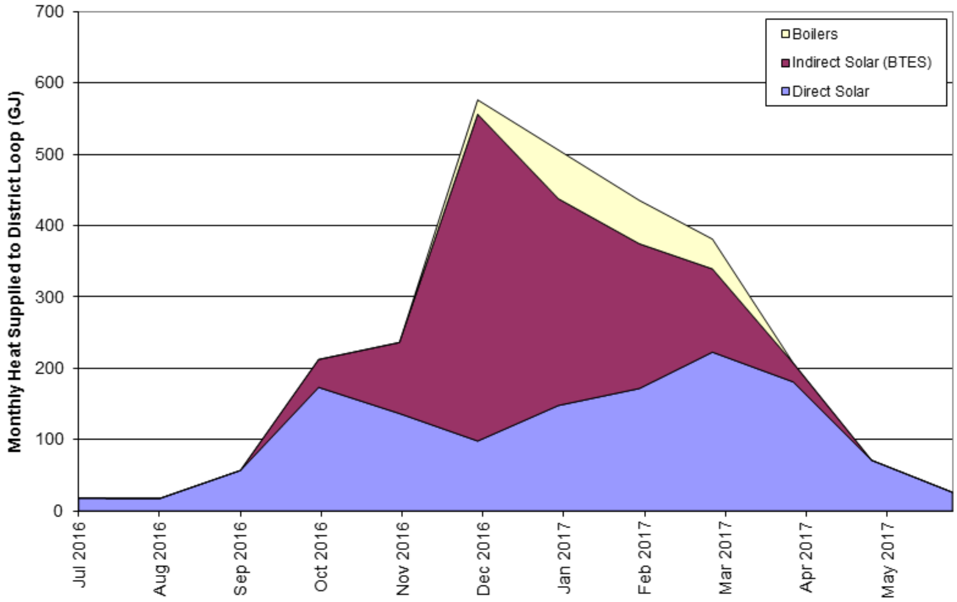

Fig. 9: Heat supply to the district loop in 2016-2017, according to the source

As mentioned previously, the home air handlers were designed to deliver the necessary amount of heat at a relatively low temperature. This, and the fact that the district heating system does not supply domestic hot water, allows the system to operate at low temperatures. 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. Figure 10 shows the weekly average supply and return temperatures for 2016-2017. The slightly higher temperatures in the summer months are not indicative of operation set points. When the district loop is not operational in the summer, the surrounding air heats up the temperature sensors, which are located in the mechanical room close to the heat exchanger. Ambient temperatures in the mechanical room are usually close to 40°C in the summer.

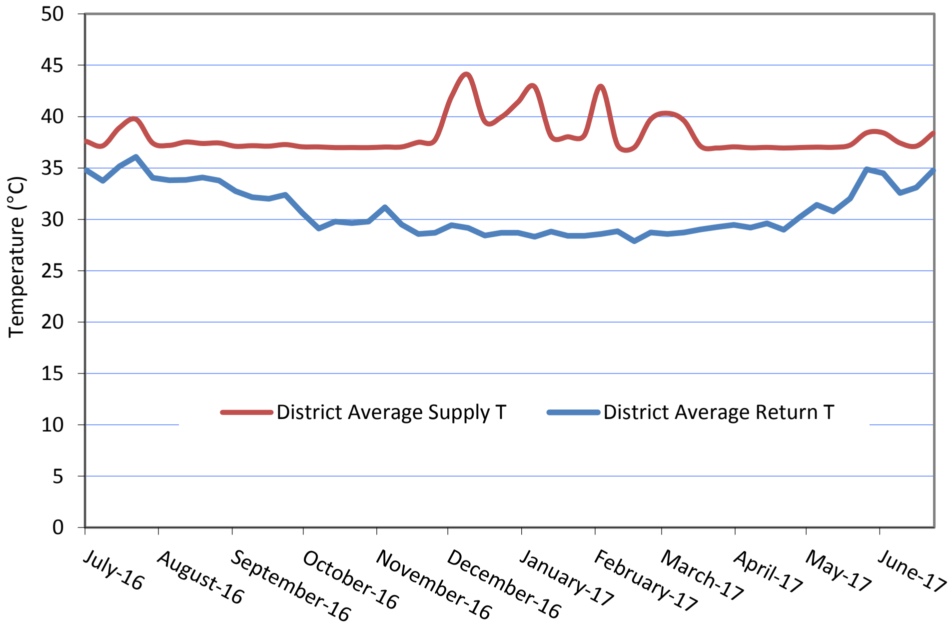

Fig. 10: Weekly average supply and return district loop temperatures for 2016-2017

Low supply and return district loop temperatures improve the effective thermal capacity of the BTES. In most cases, the BTES is able to meet the demand, with the exception of stretches of extreme cold days, which require higher supply temperature and thermal power. Figure 11 shows the maximum and minimum yearly temperatures for sensors located in the water piping at the top of the boreholes, with 24-1 and 23-1 being closest to the centre, and 24.7 and 23.7 being closest to the edge of the BTES (see Figure 6). Charging and discharging of the BTES is done in a way to promote thermal stratification within the BTES, with higher temperatures at the centre.

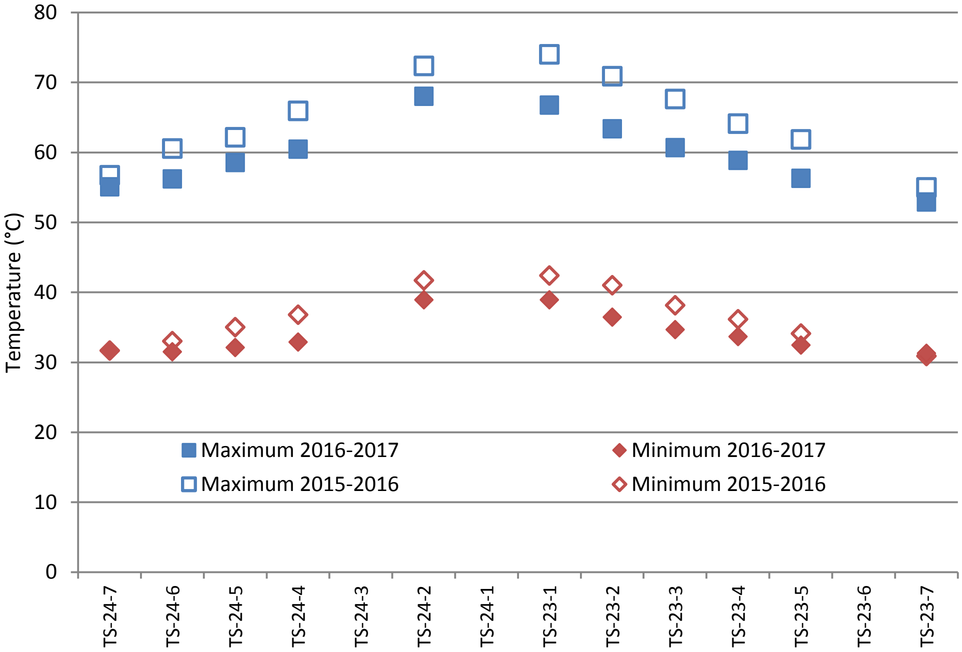

Fig. 11: Maximum and minimum yearly temperatures for sensors located at the top of the boreholes

During those 10 years of operation, DLSC has not experienced a stagnation episode in its glycol loop. This is mostly because there is enough capacity in the BTES to absorb all the energy produced. Nonetheless, the system is equipped with dry coolers that can reject enough heat to prevent the system from reaching a boiling state. The favourable conditions have resulted in longer glycol life and the fluid has not been replaced since the initial charge in 2007. Figure 12 shows the results of glycol pH and reserve alkalinity analysis throughout the last 10 years.

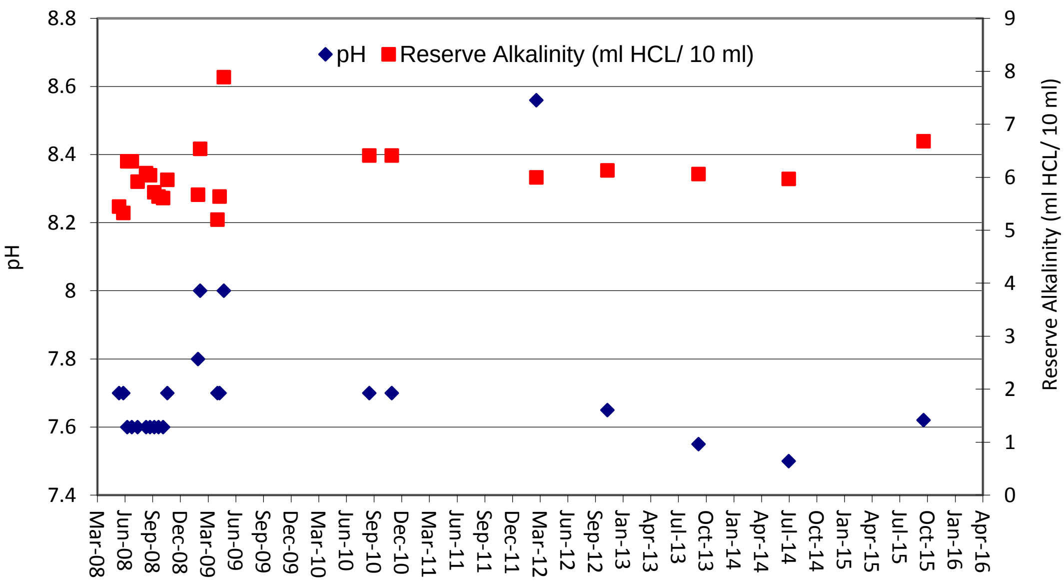

Fig. 12: Glycol pH and reserve alkalinity

5. Lessons Learned and Future Outlook

Overall, the system has successfully demonstrated the reliable operation of a high solar fraction solar district heating system with seasonal thermal storage in a very cold climate. In ten years of operation, only 2 of 798 solar collectors have been replaced and regular testing of the propylene glycol-water heat transfer fluid shows negligible deterioration, indicating many more years of service can be expected.

Adjustments and improvements have been implemented, such as better controls. Issues that could have led to significant performance and reliability problems were corrected early on. For example, a design oversight of the outlet ports in the upper half of one of the short term storage tanks led initially to lower thermal performance. It was promptly identified and corrected. This underlines the importance of technical and financial resources for monitoring and correction of eventual issues, common in pilot systems with this level of complexity. Careful design is seldom enough.

The DLSC builder, land developer and municipality were included in the project planning process from the beginning. This proved to be the right approach since their experience with and understanding of the home buyer's perspective had a significant positive influence on important design decisions throughout the process. It was also valuable in building confidence in the project regarding the market acceptance of the unfamiliar technologies being applied.

The homes were sold very quickly, with a long waiting list of potential buyers wanting to move into the community. People who live in the community are very pleased with it and they have adapted very well to the constant attention from outside, including opening their homes to people from over 20 countries around the world as far away as South Korea, China, and Chile. DLSC house values have increased in step with conventional homes in the area. The builder, the utility, the land developer and the municipality have all expressed interest in participating in the implementation of similar projects in the future.

As with the other utilities, district heating loop piping needs be installed before the houses are built. Shut-off valves in the utility easement near the street should be considered for subsequent projects to simplify the line installation and connection process for the builder.

It is essential to have committed partners. In significant projects, unexpected issues will almost certainly arise, however, with high levels of dedication and commitment, teams can identify acceptable paths forward which can be successfully executed. Some of the unexpected issues the DLSC team faced included severe construction site flooding, lower than expected reliability for some conventional equipment and some components that didn't actually perform to specification.

The ability to easily access and view detailed system operating data combined with the ability to compare actual operation against predicted is extremely valuable for the successful commissioning and the efficient operation of energy systems such as that used at DLSC. Going well beyond the obvious benefits of fine tuning control set points and identifying failed sensors and mechanical components, the availability of these data has identified inoperative control logic, inadvertent use of "temporary" set points, instances where plumbing modifications were warranted and opportunities to reduce electricity consumption with improved control logic. The performance and financial implications can be very significant if issues like these are not corrected.

Using the system data in conjunction with the TRNSYS design simulation has raised confidence in the ability to predict the energy performance of similar systems. Monitoring has proven the design simulations to be generally very accurate. Refined simulations have been subsequently used to perform feasibility studies for follow-on projects using similar designs. The simulation model has also been used to look for evidence of soil drying within the borehole field and conclude that no significant change has taken place in the bulk properties of the soil or in the performance of the seasonal storage.

Drake Landing system is too small to be economically competitive with the current very low price of natural gas in North America. However, subsequent feasibility studies show that larger systems of similar design can deliver solar energy at about half of the cost compared to Drake Landing, and additional work is underway to improve cost performance further. Current work includes model refining, O&M cost evaluation, and predictive control analysis and test implementation.

6. Nomenclature

Heat load (GJ)	Q
Coefficient of Performance	COP
Electricity consumption (GJ)	E
Solar Fraction	*f*
Subscripts	
Solar and Thermal Storage	ss
All Pumps	ap
Houses	h

7. Acknowledgements

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