MEASURED AND SIMULATED PERFORMANCE OF A HIGH SOLAR FRACTION DISTRICT HEATING SYSTEM WITH SEASONAL STORAGE

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1. 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. Figure 1 is a photograph showing the community on a summer day. Several 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 requirements with solar energy and the first operating in such a cold climate (5200 degree C-days). Solar heat captured in 2293 m^2 (gross area) of flat-plate collectors, mounted on the roofs of detached garages, is stored in soil underground and later is extracted and distributed through a district system to each home in the subdivision, when needed for space heating. 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 for each 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 borehole storage system is configured to maintain the centre of the field at the highest temperature and the outer edges at the lowest temperature to minimize losses and maximize delivery temperature. 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 the system design. In its fourth year of operation the solar fraction was 86%, indicating that the system should achieve the design target of more than 90% in year five. This paper describes the system and its operation, presents measured system and subsystem performance over the first four years of monitored operation and compares those results against the TRNSYS predicted performance for the same period.

2. Background

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 currently active in the solar energy market. 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.

Provident House and the Aylmer Senior Citizen’s Apartment Building were constructed in Ontario roughly 30 years ago with large water tanks for seasonal storage of solar thermal energy for space and service water heating. These systems demonstrated the technical feasibility of solar heating with seasonal heat storage but met limited success for a variety of reasons. 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 design process involved careful study of the European experience and utilized a single design team with a broad range of expertise including several expert simulators. Since the concept was untried in North America on this scale, the resulting system design was developed with the full knowledge that the system was smaller than the economic optimum.

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. (2006) and Wong et al. (2006) reported on the system design and project implementation. Sibbitt et al. (2007) reported on preliminary monitored data taken before project completion. The objective of this paper is to report on the performance of the complete solar system over its first 4 years of operation.

3. 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 and a simplified schematic of the system is shown in Figure 2.

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 series boreholes. 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.

Most of the district energy system mechanical equipment (pumps, controls, auxiliary gas boilers, etc.) is in a dedicated building (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. During periods of intense summer sunshine, the BTES field cannot accept energy as quickly as it can be collected; thus heat is temporarily stored in the STTS tanks, with transfer to the BTES continuing through the night. This situation is reversed in the winter, when heat cannot be extracted from the BTES field quickly enough to meet peak heat demands, typically in the early morning hours. 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 functional schematic, Figure 3, shows system details and the locations of monitoring sensors.

A fluid cooler mounted on the roof of the energy centre is available to reject collected energy when solar collector return temperatures become high enough that there is a risk of boiling water in the collector loop heat exchanger. This situation could arise when there are power interruptions or when there is a long series of days with high rates of solar energy collection. An automatic power fail system utilizes batteries and inverters to power critical equipment in the event of an electric power interruption in sunny weather. The batteries are charged with a PV array, which also reduces system electricity consumption, once charging requirements are met.

3.1 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. The anticipated short-term heating requirement is based on the time of day and the outdoor temperature and is expressed as “Charge Required” and it is compared against “STTS Charged” which is based on the current district loop set point temperature and several temperatures in 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 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.

4. Simulated System Performance

During the project design phase, a detailed TRNSYS (Klein 2007) 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 as a basis, the simulation model predicted that the system would provide on average, more than 90% of the heating energy to the homes with solar. 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.

One of the objectives of this project was to calibrate and improve the accuracy of the design simulation model through comparisons of predicted subsystem performance with measured performance. Initial results of this calibration activity were reported by McDowell and Thornton (2008). Further comparisons against additional monitoring data are underway and will be reported in the future. The calibrated models will facilitate more accurate design predictions and the investigation and evaluation of modifications to the system design and control strategies for enhanced performance in future projects.

5. Measured System Performance

The complete solar system began operation in late June 2007 and its performance has been monitored since then using its automated control and data acquisition system. A summary of the performance measured between July 1, 2007 and June 30, 2011 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. Based on aperture area, the four year average collector efficiency is 35%. 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 that input energy for heating later in the first year, a significant solar contribution (1520 GJ) was provided by heat from the STTS, which did not go to BTES. 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 each of the subsequent years, the BTES has 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.

Part of the improvement in performance is due to 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. The tanks were modeled in more detail and replacement diffusers were designed and constructed. The tanks were drained, the new diffusers installed and the storage systems returned to operation 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.

6. Subsystem Performance

The performance of the three main Drake Landing system energy transfer loops, the solar collector loop, the borehole thermal storage and the heat distribution loop are examined in more detail in the following subsections.

6.1 Collector Loop

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

$$\eta_{collector} = 0.693 - 3.835\left(\frac{T_i - T_a}{G}\right) \qquad \text{(eq. 1)}$$

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 Figure 4. Collector flow rate is variable. Assuming uniform flow distribution in the array, the flow per collector has been limited to flow rates greater than 0.013 l/s. The data has also been filtered to limit transient data and incident flux values below 700 W/m2 and to minimize incident angle effects by using only data recorded within one hour of solar noon. Given that the field data includes pipe losses, agreement with the laboratory measured module efficiency is excellent.

6.2 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 C warmer than the coldest temperature and heat losses average approximately 6% of the input energy over the four years of operation.

Large seasonal storages require 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 from them. Figure 5 shows the amount of energy delivered to the BTES and the amount extracted from it , in each year of system operation clearly illustrating the steady improvement in storage efficiency (defined here as energy extracted divided by energy input). Figure 6 shows how the BTES core temperature has cycled over the same period. Since the measured soil temperatures are strongly influenced by the temperature of water flowing through adjacent boreholes (during charging and discharging), the core temperature is based on soil temperatures measured at least 4 hours after water flow has stopped. It is defined as:

$$T_{core} = (T_t + 2 \times T_m + T_b) / 4 \qquad \text{(eq. 2)}$$

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. Subsequently, operation of the whole system allowed that temperature to peak above 45 C in late October 2007 and fall to a minimum of approximately 37 C in February 2008. Operation over the next two years brought higher maximum and minimum core temperatures which permitted increased heat output. The peak temperature in the third and fourth years were similar, however, the warm core temperatures extended to a larger radius in year four than they had previously. The fourth year was also colder than usual with 12% more heating degree-days than in the year before. As a result, the core temperature was drawn to a lower minimum than in the 2 previous years. The core temperature has recovered rapidly since then.

6.3 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 heat delivered to the loop and the sum of heat quantities reaching the homes. Much of the variability in that quantity is attributed to the significant uncertainty when taking the difference of 2 large numbers. A trend towards lower heat loss in recent years is consistent with the lower delivery temperatures in those years. Figure 7 shows a breakdown of heat delivered to the distribution loop over the operating period. It shows that the solar component of the heating, particularly that part coming from the seasonal storage, has increased in importance in each successive year.

7. Comparison of Measured and Predicted Performance

In the first two years of system operation, the system appeared to be falling short of the predicted solar fraction, although some uncertainty resulted from the design simulations using a January 1st start date while the effective system start date was actually July 1st. Collector array efficiency, STTS efficiency and BTES efficiency were all reasonably close to predicted values, however, the total heat supplied to the distribution loop was 20% higher than expected in the first year and 17% higher in the second. Calculated district loop losses weren't very different from predicted values so the house heat loads were examined more closely. It was determined that on average, internal heat gains were as expected, however, testing showed that the heat recovery ventilator efficiency was considerably lower than specified and modeled. The simulations used to determine the house heat loads employed a heat recovery efficiency of 65% at both 0 C and -25 C, whereas test efficiencies at those temperatures were approximately 48% and 40%, respectively. The added ventilation air heating requirement was identified as the primary cause for the higher than anticipated system heating load. 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 the third year, it appears that better than expected collector efficiency partially compensated for the increased heating load and helped raise the solar fraction reasonably close to the predicted 85%. It is likely the monitored annual solar collector array efficiency was greater than predicted for several reasons, however, the relative importance of each has not yet been quantified. The side and back heat losses will tend to be lower for flashed-in, array-mounted collectors than those measured in single-collector testing. The pyranometer used in the monitored collector efficiency calculation, which is 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). Stratification in the STTS may be better than predicted on average, resulting in lower than predicted collector inlet temperatures. Finally, piping losses to and from the four collector blocks may be lower than those simulated, due to shared trenches.

With the year-over-year improvement in BTES efficiency, the installation of new tank diffusers and the restoration of design district loop set points, solar fraction in year four reached 86%, within 2 percentage points of the design prediction, despite a colder than usual winter.

The measured BTES efficiency closely tracked the simulated efficiency for the first three years of operation, however, it appears to significantly exceed the prediction in year four. It is likely that the departure from the earlier agreement is due mainly to the cold weather and the corresponding high load imposed on the system that year. As a result, the greater peak to trough temperature change in the BTES allowed access to energy stored before year four. This effect was not observed in simulations that use the same weather year for several years in a row but it does appear when a series of real weather years is used.

The Drake Landing Solar Community system was the first of its kind to be constructed in North America and some unusual costs (such as those related to flooding of the site) were encountered. Table 3 summarizes best estimates of what it would have cost to build it again, with those unusual first costs excluded. If annual operating and maintenance costs and an allowance for future replacement of most of the collectors is added, the unit cost of solar energy delivered over 40 years may be estimated to be approximately 0.17 CAD $/kWh.

8. Summary and Conclusions

The system is performing very close to expectations. In its fourth year of operation the solar fraction was 86%, indicating that the system should achieve the design target of more than 90% in year five.

The TRNSYS and ESP-r design simulations have proven to be generally very accurate. Of course, discrepancies occur when design inputs are incorrect.

Monitored performance over four 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 combination of ongoing monitoring and detailed simulation results have been extremely important in identifying aspects of performance that differed from design expectations, understanding the importance of various parameters and the reasons and permitting corrective actions. This is viewed as particularly valuable for system designs where there is limited field experience.

The success of the Drake Landing Solar Community project has led to the possibility of implementing a similar but much larger system, serving twenty times the number of living units. The feasibility study for this second project is underway.

9. Acknowledgements

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10. Nomenclature

G	incident solar flux (W m^{-2})
$\eta_{collector}$	collector efficiency
T_a	ambient air temperature (C)
T_b	BTES centre bottom temperature (C)
T_{core}	BTES core temperature (C)
T_i	collector inlet temperature (C)
T_m	BTES centre mid-height temperature (C)
T_t	BTES centre top temperature (C)

11. References

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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[*]	0.32	0.28	0.26	0.25	0.25
STTS Efficiency	0.99	0.99	0.98	0.98	0.98
Energy into BTES (GJ)	3030	2390	2200	2110	2080
BTES Efficiency	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

Table 2: Summary of Monitored System Performance

Year of Operation	**1**	**2**	**3**	**4**
Period (July 1-June 30)	2007-2008	2008-2009	2009-2010	2010-2011
Heating Degree-Days (K d)	5060	5230	4890	5480
Horizontal Global Irradiation (GJ m^{-2})	4.63	4.96	4.65	4.58
Incident Global Irradiation (GJ m^{-2})[†]	5.82	6.07	5.49	5.45
Collected Solar Energy (GJ)	4470	4580	4270	4060
Collector Efficiency[‡]	0.34	0.33	0.34	0.33
STTS Efficiency	0.96	0.91	0.95	0.93
Energy into BTES (GJ)	2610	2810	2500	2260
BTES Efficiency	0.06	0.20	0.35	0.54
Avg. BTES Core Temperature (C)	38.7	50.0	54.1	52.2
Solar Energy to District Loop (GJ)	1670	1790	2030	2460
Total Energy to District Loop (GJ)	3040	2960	2550	2860
Solar Fraction	0.55	0.60	0.80	0.86
Purchased Electricity[§] (GJ)	198	197	186	163
District Loop Losses (GJ)	235	385	142	141

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[*] Based on gross collector area

[†] Pyranometer shading at very low sun angles; 4.9% estimated annual impact

[‡] Based on gross collector area

[§] Energy Centre electricity consumption including pumps, controls & monitoring, interior & exterior lighting and ventilation fans less rooftop PV generated

Table 3: System Cost Summary

Item	Cost (CAD$ 2005-07)
Solar Collectors	710,000
Installation of Solar Collectors	430,000
Seasonal Storage Borehole Field	620,000
District Heating & Solar Collection Loops	1,025,000
Energy Centre including STTS Tanks	600,000
Total	3,385,000

Fig. 1 Drake Landing Solar Community

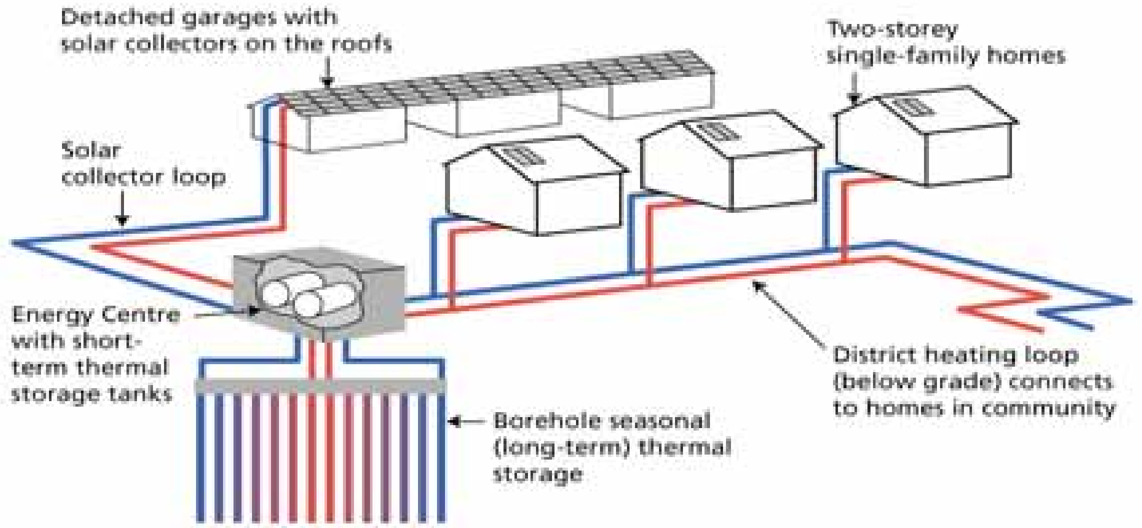

Fig. 2 Simplified System Schematic

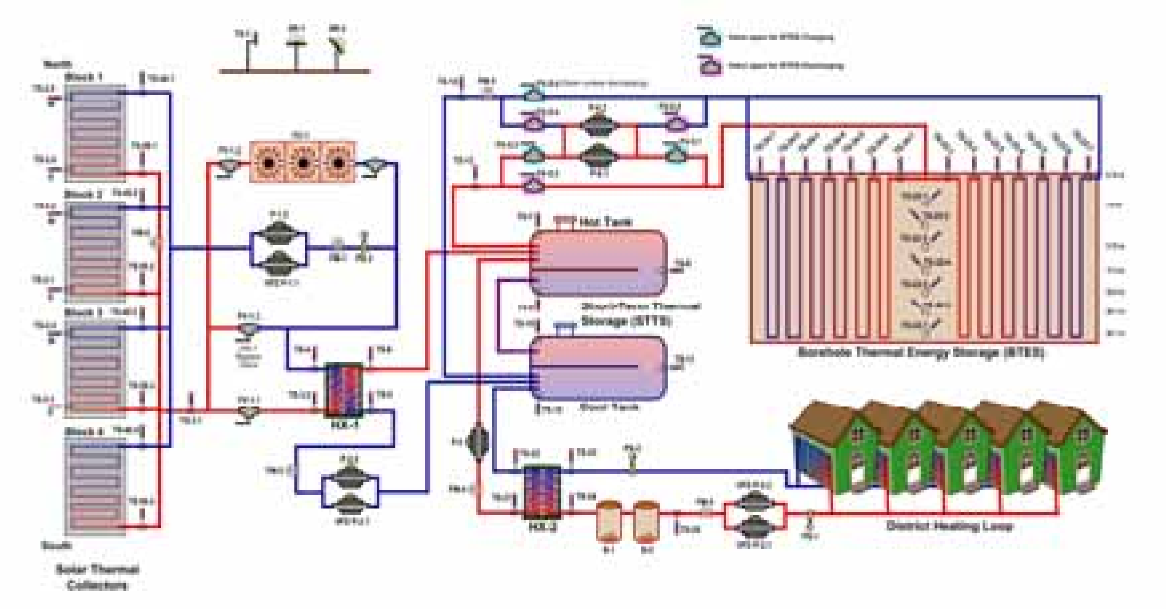

Fig. 3: Functional System Schematic including Monitoring Sensors

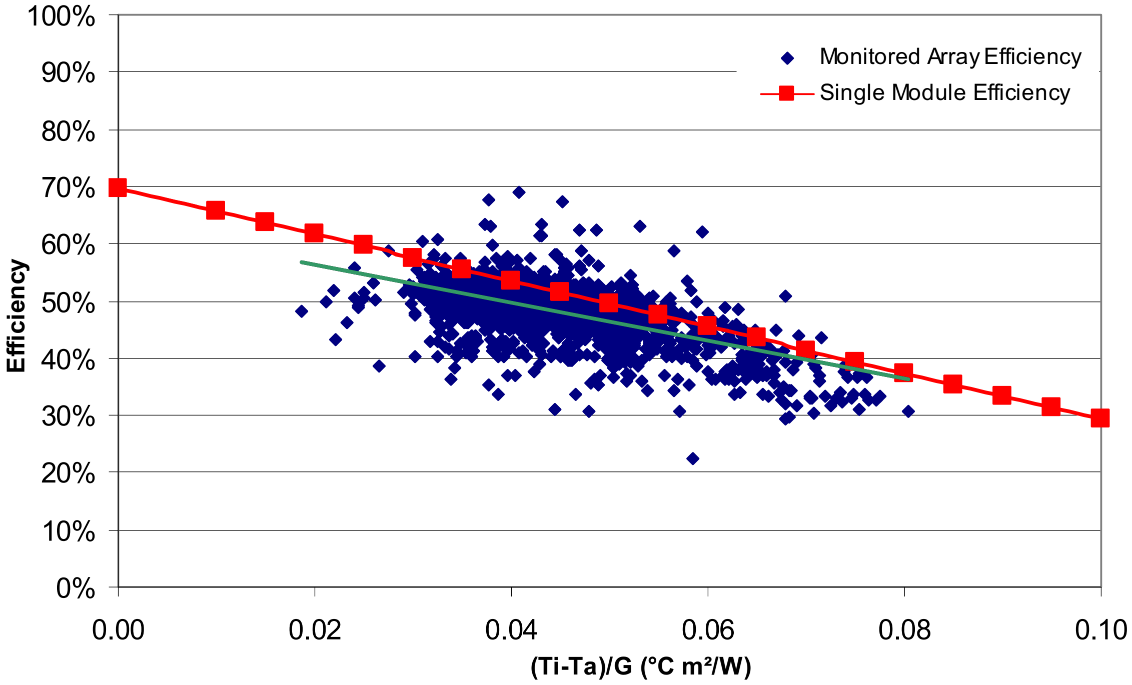

Fig. 4: Monitored Collector Array Efficiency and Single Collector Module Efficiency

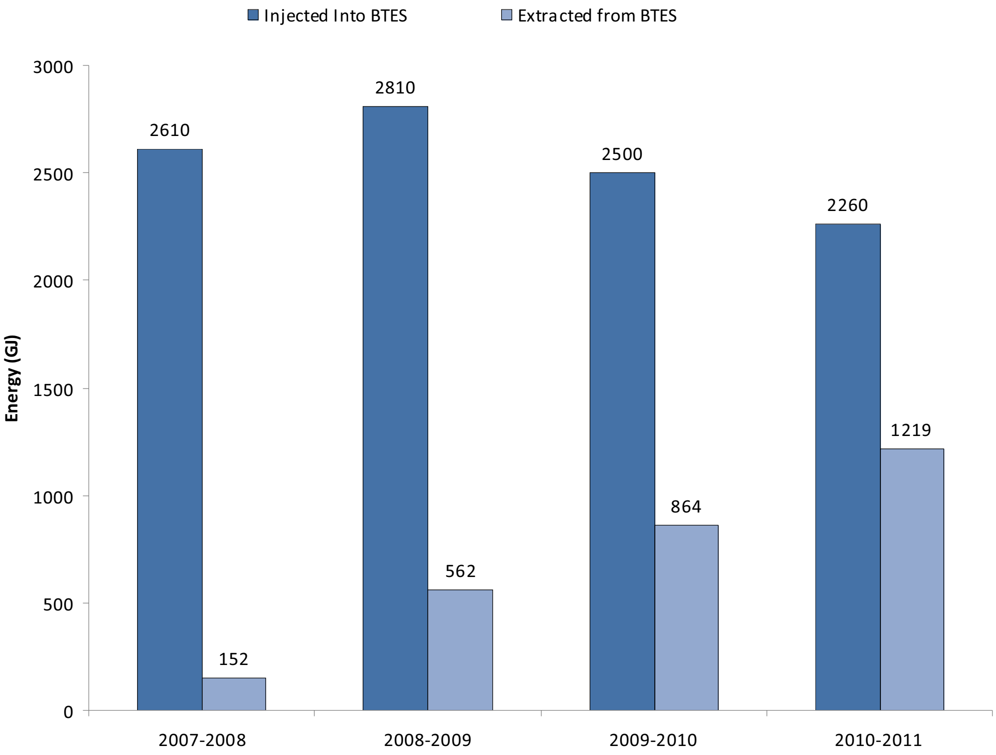

Fig. 5: Energy Injected Into and Extracted from BTES

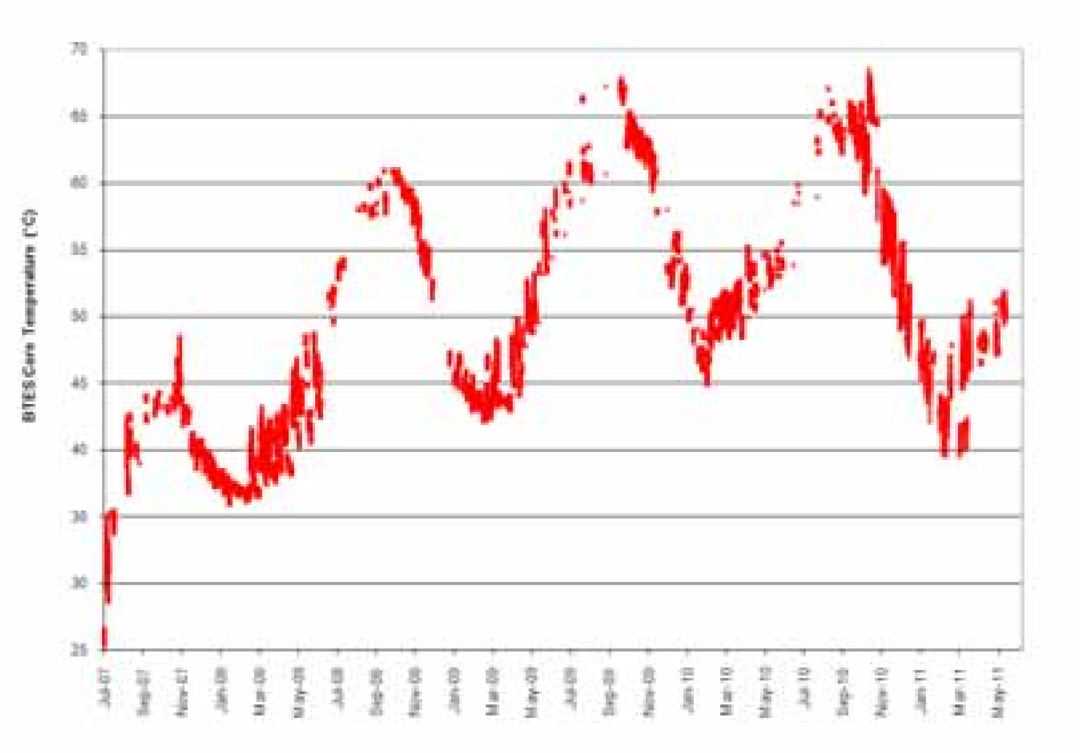

Fig. 6: BTES Core Temperature

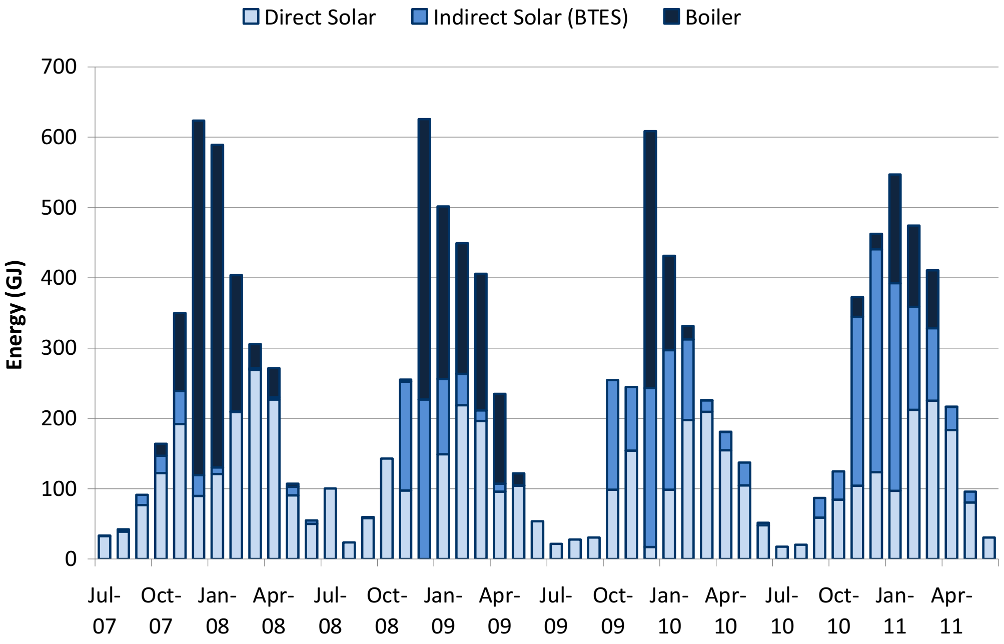

Fig. 7: Energy Supplied to the Distribution Loop