POTENTIAL OF MODEL PREDICTIVE CONTROL (MPC) STRATEGIES FOR THE OPERATION OF SOLAR COMMUNITIES

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ABSTRACT

This paper explores the potential of control strategies based on Model Predictive Control (MPC) to increase the energy performance of a solar district heating system. The case study is the existing Drake Landing Solar Community (DLSC) in Okotoks, Alberta, Canada. Monitored operating data are used to validate the TRNSYS model of the community and to provide the weather and heating load inputs to the system model. The generic optimisation tool GenOpt is employed to find the control parameters that minimise the consumption of gas and electricity over a three-year period. Results show that current strategy performs very well but there is scope for increased energy savings.

INTRODUCTION

District heating systems represent a very small percentage of the total installed solar thermal capacity worldwide, which mostly consists of solar domestic hot water systems for individual houses or buildings (Weiss and Mauthner, 2012). In Canada, the first large district project for space heating was the Drake Landing Solar Community (DLSC). It stands out from most large-scale solar systems by the very high solar fraction target, which was designed to reach 90 % for the 5th year of operation. This solar fraction is for space heating only, as domestic hot water is provided by individual solar-assisted systems on each house. The system heavily relies on seasonal thermal storage and the solar fraction increases over the first years of operations as the large storage volume slowly reaches a steady-periodic regime. Reaching a very high solar fraction also relies on an efficient supervisory control system designed to manage, among others, the interactions between Short-Term Thermal Storage (STTS) and the long-term seasonal storage (Borehole Thermal Energy Storage, BTES).

Objectives

The objectives of the project described in this paper are to develop new control strategies based on Model Predictive Control (MPC) to increase the energy performance of solar communities and reduce their operating costs, and to assess the potential benefits of considering advanced control strategies during the design phase of new communities. This paper focuses on the supervisory control strategy that manages energy transfers between the STTS and BTES, which is often simply named the BTES controller.

Literature Review

The interest for large solar heating systems with seasonal storage emerged at the end of the 70's in Sweden, The Netherlands and Denmanrk. In 2010 there were about 130 operating installations. Numbers are to be increased in the coming years with more systems set in operation. (Dalenback, 2010)

The Drake Landing Solar Community (DLSC) project has been extensively documented, from the design phase and early results (McClenahan et al., 2006; Wong et al., 2007) to model validation (McDowell and Thornton, 2008) and annual operating reports (Sibbit et al., 2012). Many documents and real-time system status are available on the DLSC website (http://dlsc.ca). Detailed monitoring data and information on system parameters and control strategies (Enermodal, 2011) were provided by Natural Resources Canada.

Model-Predictive Control (MPC) for buildings and HVAC systems was introduced some 30 years ago, with early work focusing on controlling cooling systems and building thermal mass (e.g. Braun, 1990). Solar applications using MPC range from early works for solar collector fields (Camacho et al., 1994) to single solar thermal systems (Ferhatbegovic et al., 2011). A recent workshop organised by IBPSA affiliates demonstrated a continued interest for MPC amongst building designers, researchers and the industry (IBPSA-USA and IBPSA-Canada, 2011).

One MPC approach is described as Closed-Loop Optimisation (CLO) by Henze et al. (2004). Optimal control values are found by simulating the system performance and minimising a cost function over a defined period in the future (horizon). Only the first calculated value(s) are applied, and a new optimisation is performed taking into account the (often estimated) current state of the system and updated forecasts.

A variation of CLO is Continuous Time Block Optimisation (CTBO) (Henze et al. 2004). It is different from the CLO approach because the whole block of optimal value(s) found for the period is applied to the system. This method is used in this paper as the *ideal* case for short-term comparisons. Both CLO and CTBO methods are computationally intensive, and the logic behind control decisions is not explicit, which can be a drawback to acceptance by plant operators.

Coffey (2012) proposes to pre-compute lookup tables for a grid of scenarios. Optimal parameters are found for a given combination of system values and/or specific external conditions. The resulting tables are then employed to control the system without running optimisations. To apply the concept of Lookup tables the problem is simplified using *problem decomposition* and *conditions parametrisation*.

SYSTEM DESCRIPTION

The Drake Landing Solar Community (DLSC) is a district of 52 homes which uses seasonal storage to store the excess of solar thermal energy during the summer and the shoulder seasons so it is available through the colder months. Operation and monthly reporting started in July 2007.

Figure 1 depicts the different components: the solar collectors, facing south, cover an area of 2293 m^2 and deliver collected solar energy to the Short-Term Thermal Storage (STTS) (two identical tanks, totalising 240 m^3). The STTS provides the district loop with hot water for space heating needs. The seasonal storage (Borehole Thermal Energy Storage, BTES) is composed of 144 boreholes (35-m deep) connected in series of 6 and contained in a volume of 35,000 m^3 of earth (McClenahan et al., 2006). The district heating loop is equipped with a back-up gas boiler that keeps the supply temperature at the desired District Loop Set Point (DLSP) if the STTS is not warm enough.

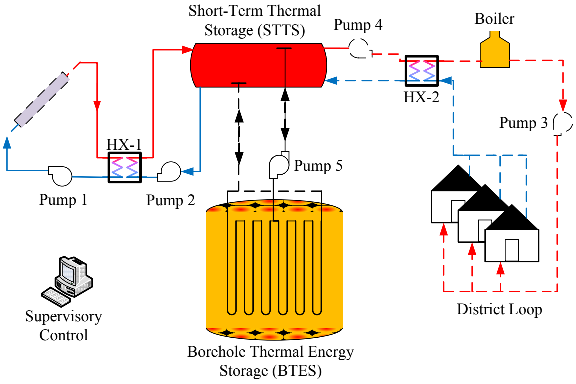

Figure 1 DLSC components

The supervisory control system is designed to maximise collected solar energy and dispatch it to the BTES or to the district heating through the STTS, as well as to maintain the STTS at a suitable temperature level by discharging the BTES into the STTS if required. The STTS is the central element for all heat transfer operations and is also the key focus of control strategies (Wong et al., 2007). The BTES controller is the supervisory control module that determines when the BTES has to be charged or discharged depending on the STTS having an excess or a deficit of thermal energy. Its rules of operation are different for each of two modes: summer and winter. These modes are not only dictated by predefined periods but also by recorded degree-hours above or below 17 °C. In summer mode the District Loop is turned off because there is no space heating needs, instead, the collected solar energy is directed to charge the BTES (Enermodal, 2011). Our study focuses on the winter-mode behaviour since this operation is the most challenging for the BTES controller regarding energy performance.

METHODOLOGY

The first objective is to obtain a validated model of the historical and current DLSC operation in TRNSYS (Klein, 2012). This model will be the reference case to compare new control strategies. In addition to accuracy, the model is also refined to improve computational speed. In a second stage, the validated model is employed to test new control strategies. For the most promising ones, control parameters are tuned by coupling the optimisation program GenOpt (Wetter, 2001) to TRNSYS.

Model tune-up

The initial task was the understanding of the actual Drake Landing physical system and the existing TRNSYS model provided by the design team. The design model uses a typical weather file for Calgary (Alberta, Canada) and a simple regression on dry bulb ambient temperature to calculate the space heating load. A new BTES controller model was developed to mimic the current control strategy described by Enermodal (2011), because the original controller has evolved over time. Other control rules were also adjusted, especially the range of values for the District Set-point (DLSP).

Given that the 5-year measured data was available, the CWEC file and the heating load formula were replaced by the actual measured weather and heating load. This allowed finding a first tuned model that matches closely the reported item *Solar energy sent to District Loop* for years 4 and 5. The model was not tuned for the whole five years due to the changing operating conditions through the years. The resulting model out of this process is called the *reference long-run* model because it runs from year 1 until year 5. It is worth mentioning that DLSC years start on July and end on next year's June, e.g. the first year of operation is between July 2007 and June 2008.

To achieve shorter computation time a *reference short-run* model was created. The start time is at year 2.5 (January 2010) but it keeps the same *long-run* model behaviour for years 4 and 5. Figure 2 describes the concept: the *short-run* simulation starts on January 2010, skipping the period indicated by the dashed line.

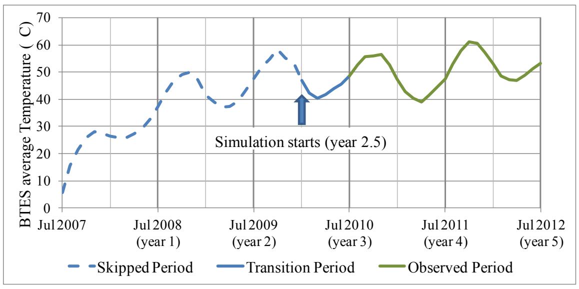

Figure 2 BTES preheating

To accomplish this, the TRNSYS Type 557, which models the BTES, was configured to use optimised preheating parameters. The BTES status, at the beginning of the short simulation, becomes very close to the long simulation case at year 2.5. To be more accurate, optimal parameters were found by means of applying root-mean-square-error (RMSE) to compare models' temperatures for each of the BTES concentric zones.

The 6-months *transition period* shown in Figure 2 is included to let the whole system and not only the BTES reach *long-run* model conditions. Therefore, results are only analysed for year 4 and beyond (*observed period*).

The *reference short-run* model had some adjustments to the control parameters to get the desired accuracy for gas consumption. Parameters of the pumps in the solar and district loop and the BTES pump, which together represent 80% of electricity usage, were also adapted according to measured data. The performance indicators used for validation are shown in the following table.

Table 1
Performance indicators used for validation

Energy type (GJ)	**Year 4**		**Year 5**	
	Report	**Model**	**Report**	**Model**
Solar	2 456	2 489	2 048	2 028
Gas	436	429	76	76
Electricity	145	142	130	123

Testing and optimisation of Control strategies

To evaluate the impact of new strategies, each strategy is applied during a period including years 4 and 5. Year 6 (July 2012 to July 2013) is also simulated, but with the standard control strategy, to assess the long-term impact of modified BTES control strategies. As the actual year six' data were not available, two cases were considered for analysis purposes: year 6 is warm as year 5, or it is cold as year 4.

Figure 3 represents how TRNSYS is executed by GenOpt. At each iteration different parameters are tried with the objective of finding the optimal values that minimise the simulation's output defined as Cost Function.

Cost Function

It is defined as the addition of gas and *weighted* electricity consumption. Two *weight (W)* factors were applied:

- 3, to take into account the usual/average performance of fossil-fuel plants. This is also close to the average electricity to gas cost ratio for 2008-2010
- 8, to account for a possible but extreme cost ratio between electricity and gas in Alberta

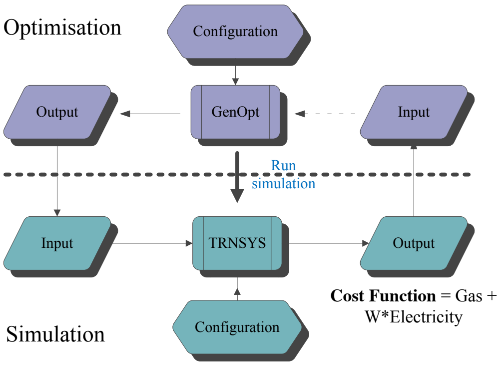

Figure 3 Optimisation process

BTES CONTROL STRATEGIES

The Standard Control Strategy (STD) as described by Enermodal (2011) is the one implemented in the *reference short-run* model. Its main objective is to reduce boiler gas consumption by trying to maintain 'enough thermal energy' in the STTS so the District Set-Point (DLSP) is more easily reached.

The main source of energy for the STTS comes from the sun. When solar energy is absent or is not sufficient to keep the required STTS charge levels, the BTES is discharged into the STTS. Due to the nature of Geothermal Heat Exchangers (GHX) the BTES flow rate is relatively low and its heat transfer rate cannot track rapid changes in the heating load.

When designing new control strategies, STTS charge is still important but it is complemented with the possibility of driving ahead the BTES discharge whenever difficult weather conditions are expected for the near future. As weather data exists for all the simulated period, no actual weather forecasts were used, i.e. the tested strategies are evaluated under *perfect* forecasts conditions taken from the actual measured DLSC data. They can indicate the relevance of the strategy before going further with *actual* forecasts.

In the next sections, the standard strategy (STD) and four other strategies will be explained: Standard improved (STD+), Force BTES discharge coupled with STD, Force BTES discharge with STD+ and Continuous Time Block Optimisation (CTBO).

Standard Control Strategy (STD)

The control process is similar for both summer- and winter-modes, but only the latter is described below.

The main rules for this strategy define when the BTES discharge must start and stop. A similar set of rules apply for the BTES charge.

As seen in Figure 4, the decision for starting each process depends on an evaluation of the STTS charge (*STTS % Charge*) vs. the estimated STTS required charge (*% Charge required*).

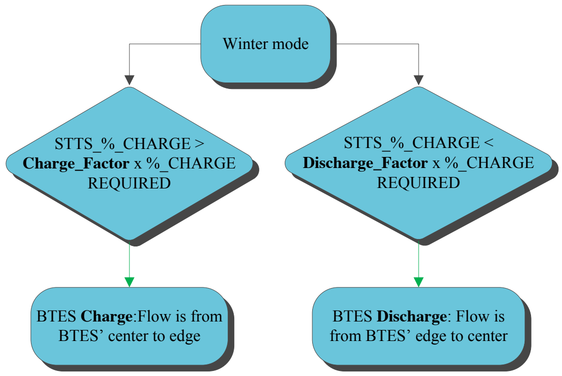

Figure 4 STD's Flow Diagram

Two Factors, *Winter Charge Factor* and *Winter Discharge Factor*, define the relation between them:

1. If *STTS % Charge* is less than *Winter Discharge Factor* times *STTS % Charge Required* the BTES pump is enabled for discharge.
2. Otherwise, if *STTS % Charge* is *Winter Charge Factor* times greater than *STTS % Charge Required* the BTES is charged from the STTS.

In both cases, the process stops whenever the rule condition is not longer true or when the BTES input and output temperatures imply there is a change in the direction of the net heat transfer rate, e.g. BTES discharge is actually removing energy from the STTS.

Parameters details follow:

1. The District Loop Set Point (DLSP) is between 37°C and 55°C depending on three air temperature ranges limited by -40°C and -2.5°C (Figure 5).

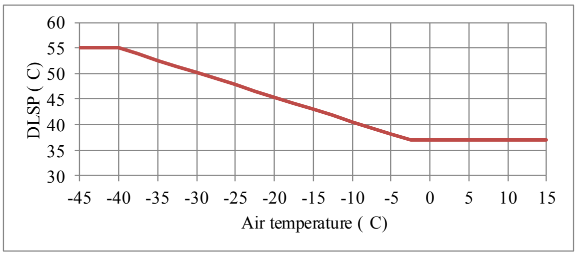

Figure 5 DLSP vs. Air Temperature

2. *STTS % charge* is calculated from the temperatures of four STTS tank nodes and air temperature. Each temperature is only taken into account for the total % value if it is higher than a certain limit depending on DLSP. This makes this measure relative to the air temperature.
3. *STTS % Charge required* is defined by a schedule in terms of the time of day and the three ranges of DLSP values presented before.
4. Charge and discharge factors always imply the BTES being affected by the operation.

Standard Control Strategy Improved (STD+)

The hypothesis for this modification is that the STD's parameters *Winter Charge Factor* and *Winter Discharge Factor* could be optimised to obtain increased energy performance.

Optimisation results show that the BTES should be charged only in cases where the STTS has a very high *% Charge* even if this reduces the collectors' efficiency. On the other hand, *Discharge Factor* is almost doubled, it basically means that the discharge process should be started before the relationship *STTS % Charge* and *% Charge required* goes too low. In both situations, the net effect is to maintain higher STTS charge compared to the STD case, imposing a charge reserve for difficult weather conditions. A positive collateral effect is the reduction of BTES pump electricity consumption.

The parameter *STTS Absolute Charge Level (ACL)* was defined to better evaluate the STTS *level of charge* when comparing strategies. It is based on the same formula as the *STTS % Charge* (function of STTS temperatures and DLSP) but the calculations always refer to the same minimum DLSP (37 °C). As it is independent of air temperature variations, *STTS Absolute Charge Level* is more helpful to compare different control strategies. The following table shows the values of this parameter for three possible sets of STTS temperatures.

Table 2
STTS Relative and Absolute Charge Level

STTS % Charge Level (relative)	**STTS Absolute Charge Level (ACL)**
100% if DLSP=37°C (or other value if DLSP≠ 37 C)	1.0 (100%)
200% if DLSP=37°C (or 100% if DLSP=48°C)	2.0 (200%)
310% if DLSP=37°C (or 100% if DLSP=55°C)	3.1 (310%)

Forced BTES Discharge (FRC) introduction

It is an *add-on* to the STD strategy; it means that STD is working all the time except for some intervals when the FRC strategy takes over it.

The mechanism is derived from manual trials that showed that starting the BTES discharge some time ahead of the moment determined by STD provide the STTS with higher level of charge for difficult weather situations. FRC will overwrite STD's output when forecasted weather for the near future indicates:

- Very low air temperatures, leading to an increase of the district heating load, or,

- Low solar irradiation, meaning a reduction of the thermal energy sent to the STTS

To determine how low these values can go before forcing the discharge, representative threshold levels are established for them.

The strategy FRC can be summarised like this:

> IF (District Load > *Maximum District Load* Threshold)
>
> OR (Usable Solar Energy < *Minimum Usable Solar Energy* Threshold)
>
> THEN Force BTES discharge

Usable Solar Energy is a fraction of the total incident solar energy on the collectors over a 24-hour period; that fraction represents the reduction due to the average collector performance (30%) and heat losses (10%) between the collectors and the STTS. *District Load* is also calculated over the same period.

This rule is evaluated every hour with a forecast horizon of 24 hours. The controller has a built-in verification to avoid that *forcing* the BTES discharge during a whole hour would lead to reversing the flow of heat transfer and mistakenly remove thermal energy from the STTS.

Forced BTES Discharge (FRC) implementation

Before applying Model Predictive Control (MPC) to FRC, it is very important to highlight how optimising control parameters for a short period could affect the simulated system performance for the next days or months. E.g. If the BTES is completely discharged to avoid using the boiler for a few weeks, it will surely cause an increase in gas consumption for the coming months because no energy would be left in the BTES. This constraint implies that the parameter optimisation has to cover the whole heating season (and possibly the next one(s)) when evaluating the *cost function*.

To implement the concept of lookup tables, the problem is *decomposed* to consider only the conditions for *winter* BTES discharge. The external conditions are *parametrised* so they are expressed in terms of parameters that convey more information: District Load and Usable Solar Energy.

An additional *parametrisation* is done to define the grid of scenarios in terms of the internal conditions: STTS status and BTES status. Using *STTS Absolute Charge Level (STTS ACL)*, three STTS charge-related scenarios were defined:

- STTS_L (low), STTS ACL < 1
- STTS_M (medium), 1 <= STTS ACL < 2
- STTS_H (high), STTS ACL >= 2

Regarding BTES status, two scenarios were derived in an approximate way: January-June (BTES_L) and July-December (BTES_H). For the scenario BTES_L, BTES temperatures are usually low and for BTES_H they are normally higher than BTES_L's. This pattern is represented in Figure 6 by two different parameters: BTES average earth volume's temperature (simulation) and BTES core temperature (reports).

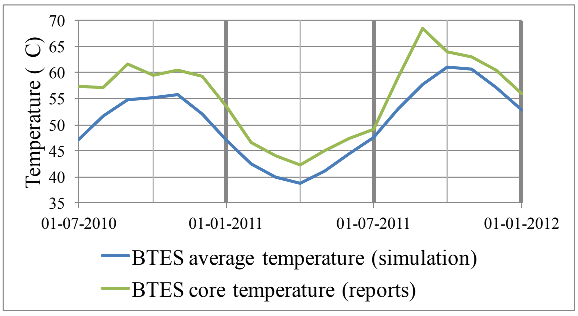

Figure 6 BTES temperatures

For each one of these six (3 x 2) possible scenarios the thresholds *Minimum Usable Solar Energy* and *Maximum District Load* are defined.

Force BTES Strategy with STD+ (FRC+)

It is the same FRC strategy with the only difference being that the BTES *Charge* and *Discharge* Factors are also included in the optimisation process as it is done for the improved Standard strategy (STD+). Most of the test cases were driven by this strategy because it combines the best characteristics of both FRC and STD+.

Continuous Time Block Optimisation (CTBO)

This control strategy is presented as the best-case when comparing system dynamic behaviour for a particular 4-day period – where BTES discharge timing is only critical the first day. Optimal control settings with 1-hour intervals are chosen from one of three options: BTES charge, BTES discharge, Off.

Figure 7 depicts the period. CTBO is employed only for the first 24-hours, then STD is applied for the remaining 3 days that are less relevant for the results.

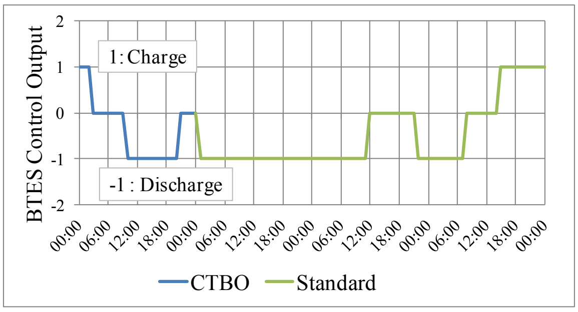

Figure 7 CTBO example

CTBO is close to the ideal optimal control settings but it would require the highest computational power if it were implemented for the whole period.

RESULTS ANALYSIS

The FRC+ strategy was applied to four cases. They differ on the *Electricity Weight* factor used in the *cost function* and the year six' weather conditions: warm or cold (Table 3).

Table 3
FRC+ Test cases

	Electricity Weight = 3	Electricity Weight = 8
Year 6 is *Warm*	3E_W	8E_W
Year 6 is *Cold*	3E_C	8E_C

The results are analysed from multiple perspectives. The first one looks at optimal values for parameters and thresholds. The second aspect is the dynamic behaviour; it examines the system's response over a short period. Finally, three-year results are compared in terms of overall *energy savings* and BTES average temperature.

Parameters of STD Strategy

Table 4 shows the *BTES Factors* values compared to the STD's. *Charge Factors* always reach a very high value which means that BTES Charge is avoided.

Table 4
BTES Charge and Discharge Factors

Case	Charge	Discharge
STD (reference)	3.5	1.00
STD+	9.0	2.13
FRC+ (3E cases)	9.0	0.50
FRC+ (8E cases)	9.0	0.75

Besides STD+ where *BTES Discharge* is the double of STD value, the FRC+ cases values are actually lower. The feature of *forcing* the discharge is more important than this factor for reducing energy usage.

Optimal thresholds of FRC+ strategy

Figure 8 represents the *Maximum District Load* threshold for all the scenarios but STTS_H thresholds. It was found that there is no reason to *force* the discharge when the STTS charge is high.

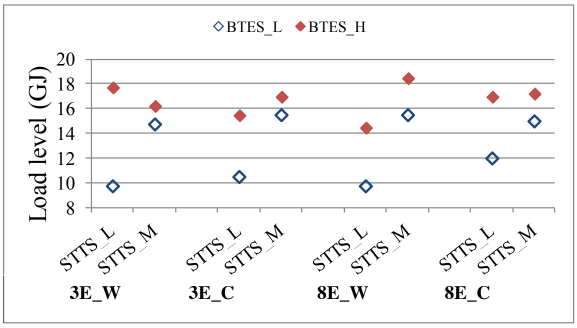

Figure 8 Maximum Load before BTES discharge

For each case, low STTS charge and low BTES conditions ([STTS_L, BTES_L]) bring the lowest threshold value. The other thresholds do not follow an exact pattern but the BTES_H's values are always higher than BTES_L scenarios. As the next year weather conditions are not actually known and as the costs relationship between gas and electricity changes every year, these thresholds values give only an approximation of the superior or inferior limits for them.

The threshold values for *Minimum Usable Energy* are always the lowest for the worst scenario [STTS_L, BTES_L], but the values are very close to those of [STTS_L, BTES_H]. These thresholds are small and they seem very sensible to simulation and optimisation conditions. For the scenarios *STTS_M* the threshold values are zero or very close to it, and always zero for *STTS_H*. In the last two set of scenarios the STTS has enough charge to deal with most of the heating demand situations. It could also be said that low solar irradiation is less important than excessive heating load to trigger the BTES discharge.

Dynamic Behaviour

The 4-day period from February 4th - 7th / 2011 is selected to analyse in detail the control strategies mechanisms and short-term results. These four days are characterised by low temperatures (high *District Load*) and low *Usable Solar Energy* (*Figure 9*).

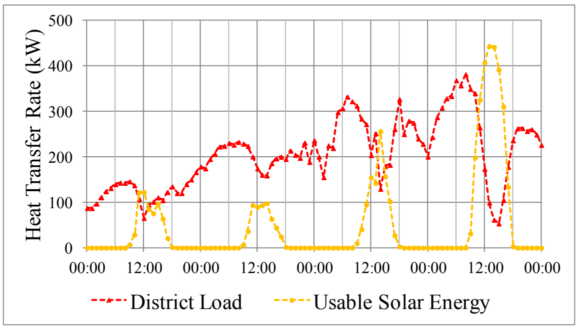

Figure 9 External conditions

Figure 10 represents boiler gas consumption (Q_Boiler) and BTES thermal energy transfer rate (Q_BTES); negative values are for energy being extracted (BTES discharge). It can be seen in this figure how FRC anticipates the increase in the heating load to start the BTES discharge before STD does. This causes a higher *STTS ACL* for FRC but it is not sufficient to avoid using the boiler.

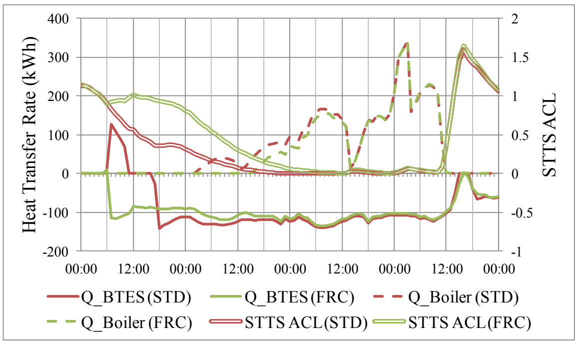

Figure 10 Simulation's outputs

For the next three figures, only the case 3E_W is compared. Other FRC+ cases exhibit a similar behaviour.

Heat Transfer rates are portrayed in Figure 11. CTBO's Q_Boiler line is not drawn because it is practically equal to FRC+'s. CTBO and FRC+ differ in the time the BTES discharge begins, but the net effect on Q_Boiler indicates that FRC+ is not far from the ideal control strategy for the period.

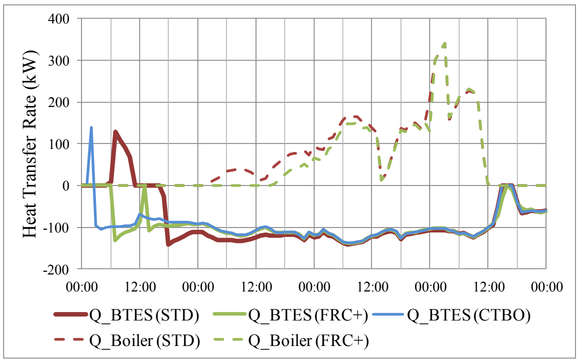

Figure 11 Heat Transfer

Related to the same period and cases, STTS ACL levels are depicted in Figure 12. The values for the 3 Strategies are the same at the beginning of the period. STTS ACL starts changing depending on the timing of BTES discharge: CTBO is the first to force the discharge, followed by FRC+. STD is the last but the heat transfer rate is not high enough to better charge the STTS for the coming intense heating period.

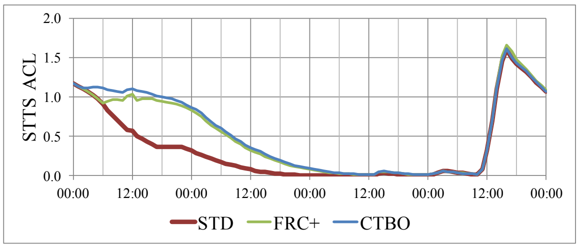

Figure 12 STTS ACL for the period

From Figure 13, the difference between CTBO and FRC+ is very small in both Q_BTES and Q_Boiler. The improvement respect to STD is not only due to the amount of Q_BTES but also the discharge timing. Again, FRC+ behaves almost as efficiently as CTBO.

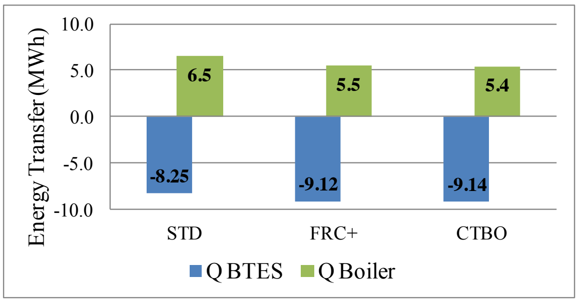

Figure 13 Energy Transfer for the 4-day period

Long-term analysis

The long-term effects are assessed in terms of average *Energy Savings per year* over a three-year period: years 4 and 5 with the tested strategy and the fictitious year 6 with the STD strategy. The energy savings in Figure 14 are referenced to the case where STD is applied for the three years. In percentage terms, the best FRC+ strategies are close to 4% energy savings; this includes electricity consumption with a normalised weight factor of three for comparison purposes.

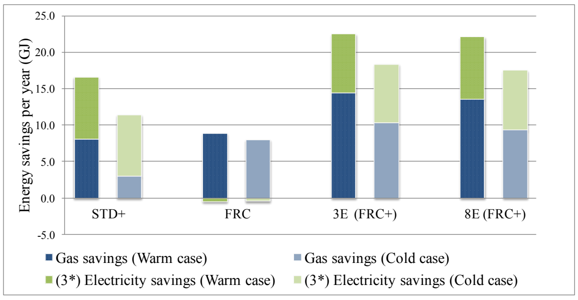

Figure 14 Energy Savings per year

It can be noticed that FRC suits better the objective of reducing gas consumption but STD+ is superior for lowering electricity usage. Combining the two of them in FRC+ leads to the best energy performance.

BTES temperatures

The following figure shows the impact in the BTES average temperature of the strategies STD and 3E.

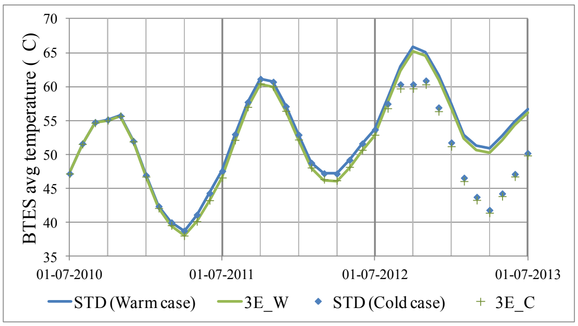

Figure 15 BTES average temperature

The temperature levels are slightly lower for 3E cases because they require a more intensive usage of the energy stored in the BTES. Starting the year 6 (July 2012) there is an important difference between the *warm* and *cold* cases but not between STD and 3E strategies. It can be said that year's weather has much more influence in the BTES temperature than the tested control strategies employed in past years.

CONCLUSIONS AND DISCUSSION

The process of finding different control strategies based on MPC started with the adoption of a validated TRNSYS model which features shorter computation time because of BTES preheating.

Our results have shown that achieving significant energy savings is only possible during short periods of extreme weather. Other factors affecting the control strategies performance are the trade-offs between electricity vs. gas consumption and collected solar energy vs. STTS charge level.

The predictive strategy FRC+ delivered between 2.7 % (case 8E_C) and 3.9 % (case 3E_W) energy savings when using a weighted sum of electricity and gas use to reflect costs. In all the cases, strategy FRC+ contributes towards the objective of operating costs reduction.

Long-term improvements of the solar fraction and energy performance (or operating costs) are possible but relatively small. In this respect, one of the conclusions of our work is that the current control strategy, which has been developed and refined by the DLSC team over these years of operation, delivers excellent results.

Refining the strategy FRC+ to include more scenarios for the lookup tables could help to get more precise thresholds values and eventually increase the energy performance.

Further work

Our work did not consider the possibility of varying the BTES pump speed, and the solar pump controller was left as is (fixed inlet/outlet temperature difference). Further work will assess the potential benefits of modifying their control strategies to reduce operating costs. A long-term objective of our work is to assess whether more cost-effective system designs could be achieved to deliver the same solar fraction, if optimised predictive control strategies are taken into account during the design phase.

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