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Electrical thermal storage optimization for demand side management

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1. Introduction

IEA Demand-Side Management (DSM) program aims at achieving large scale energy efficiency by responding to changes from the demand side of the market. One of the strategies available is load shifting, and can be done by using sensible thermal energy storage. It offers the possibility to shift load to lower peak demand periods (IEA-DSM, 2011).

As the Québec (Canada) climate is considered cold and humid (Gouvernement du Québec, 2012), thermal storage may have an impact on the power demand peaks that occur at this time of the year, especially for a building heated by electricity. Thermal storage equipments are commercially available for institutional and commercial buildings. One of them is the ThermElect® (Steffes Corporation, 2011), a central electric thermal storage device. Even though the operating curves are available in the manufacturer's datasheets, its impact on the electricity bill had yet to be evaluated.

A MATLAB® function is developed to simulate the impact of ThermElect® devices on building electric demand from the digitized manufacturer operating curves. This function uses periodic demand data and an annual fixed set point for the control of electric thermal storage. It optimizes the annual savings based on the set point and different models of ThermElect®. The function has been used to assess the best arrangement of ThermElect® for a simple payback of 5 years from demand data recorded from a building of the École de technologie supérieure (ÉTS), the Centech.

2. Québec's power demand and pricing

Based on data from 1982 to 2006 at the Montréal's Pierre-Elliott Trudeau airport, the average annual temperature is 6.9 °C, with extreme annual dry bulb temperature mean between -26.5 °C and 32.3 °C. There is an average of 4428 heating degree-days at 18.3 °C and 1748 cooling degree-hours at 23.3 °C (ASHRAE, 2009). These weather conditions, and the wide spread use of electric heating, are responsible for large electric power demand in winter.

A financial incentive for peak demand reduction is offered by Hydro-Québec (the Québec government owned utility company). As such, a minimum billing demand of "Rate M" customers is never less than 65% of the maximum peak demand recorded during winter (from December 1 to March 31). Energy consumption price is 4.46 ¢/kWh for the first 210,000 kWh and 3.19 ¢/kWh for the following kWh, combine to a monthly peak demand charge of 13.44 $/kW. If the monthly peak demand is less than 65% of the winter peak the penalty is applied because the demand cost is determined for 65%.

When recorded data are unavailable, computer simulation can help evaluate a building hourly electric demand. Simeb® is a free software available to perform buildings energy simulations. It has been developed by Hydro-Québec and is based on DOE2 engine (Simeb, 2011). Figure 1 shows building electric demand and heating demand for a typical 9,300 m^2 commercial building, having electricity as its primary heating source.

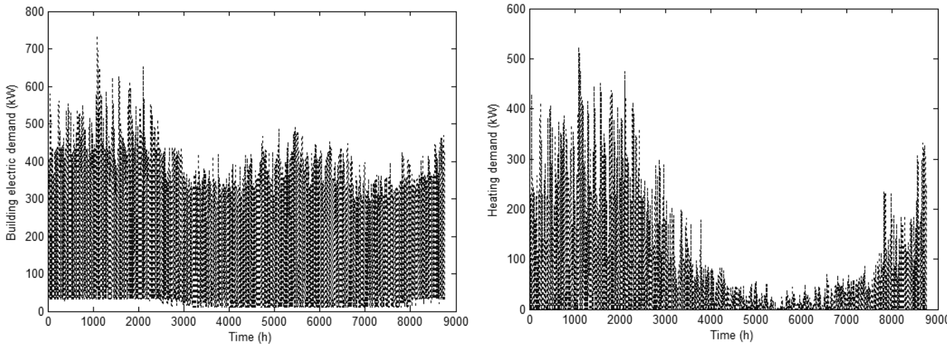

Figure 1. Hourly building electric demand (left) and heating demand (right) profiles

In this simulation, peak demand of the building is around 750 kW, while heating peak demand for the same period is around 525 kW. The highest peaks only occur a few times in the winter and are responsible for paying penalties due to the "Rate M" billing structure. This is where the thermal storage could make a difference.

3. Heating system operation

In a building heated by an electric boiler, the heating demand (*L*) is covered by the boiler (*Lc*). Building electric demand (*Pb*) depends directly on this heating demand. By adding an electric thermal storage, a part of the demand (*L*) may be covered by this storage device thermal output (*Ld*). The fraction covered by the thermal storage device is controlled according to a set point (*T*). When heating demand of the building (*L*) is lower than the set point (*T*), the storage system uses the difference between these values for recharging (*Pr*) until the energy accumulated (*S*) reaches its maximum capacity (*Smax*). Two scenarios may occur with the heating demand of the building higher ($\mathbf{L_1}$) or lower ($\mathbf{L_2}$) than at the set point (*T*), then, three scenarios of level of energy accumulated are possible: empty ($\mathbf{S_1}$), enough to cover demand ($\mathbf{S_2}$) and full capacity ($\mathbf{S_3}$). Figure 2 shows the first scenario ($\mathbf{L_1{:}S_2}$) representing the discharge of the storage device. The building heating demand is superior to set point ($L > T$), with energy accumulated enough to cover demand ($0 < S \leq Smax$):

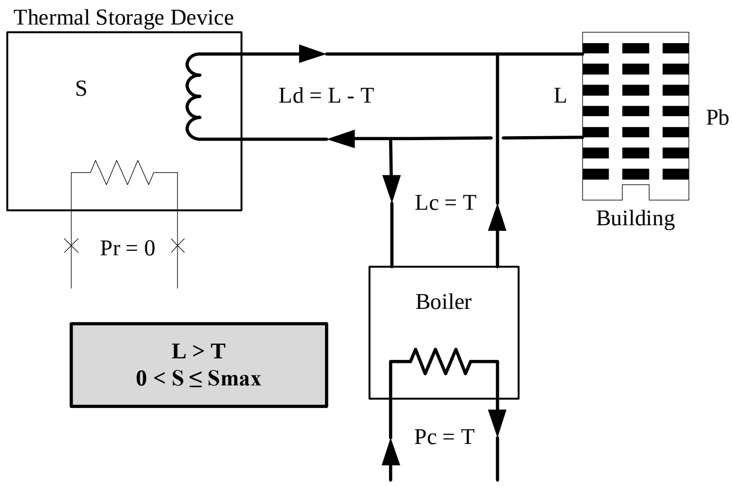

Figure 2. Thermal storage device supplies heat

In this case, storage device discharge heat equal to the difference between the building's heating demand and the set point (*Ld* = *L* - *T*). When the building heating demand falls under the set point (**L_2:S_2**), it is possible to recharge the heat accumulator, as shown in figure 3:

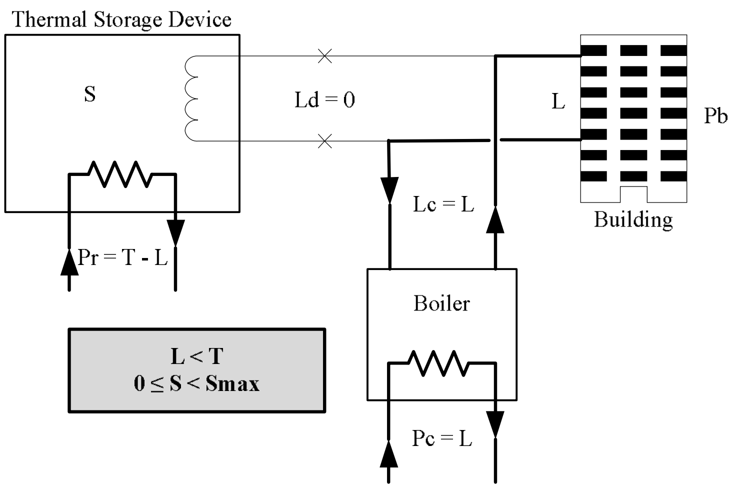

Figure 3. Thermal storage device recharges

The building heating demand covered by the thermal storage device, or thermal output (*Ld*), is disabled because the set point is not exceeded. The recharge of the storage device (*Pr*) is equal to the difference *T* – *L* until the energy accumulated reaches its maximum capacity (*Smax*). Two other scenarios could occur: either the building heating load is less than set point while the storage is at maximum capacity (**L_2:S_3**), or the heating demand exceeds the set point while the storage device is empty (**L_1:S_1**). Figure 4 shows the operation of the system for these two scenarios.

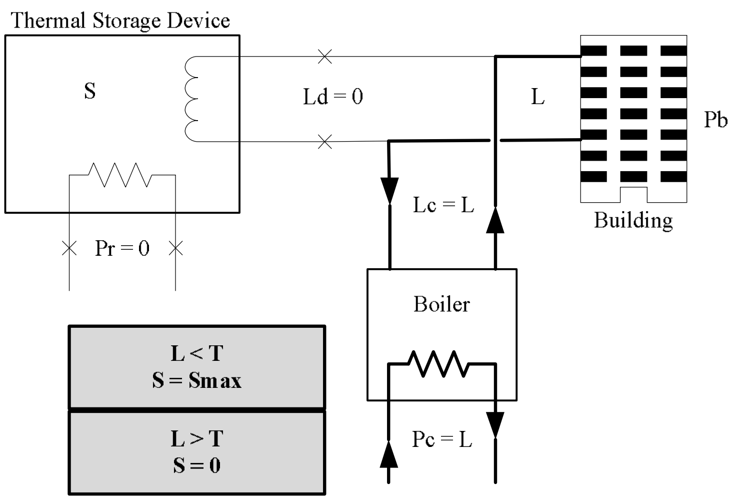

Figure 4. Thermal storage device off

In both scenarios, the boiler covers the whole building heating demand (*Lc* = *L*), but if the storage device is empty and *L* > *T* an excess of demand beyond the set point will be noted.

4. Set point

In this study, the control strategy considers the set point of thermal storage device (*T*) fixed all year long. This set point is the limit to which the storage device starts or stops. The annual fixed set point is selected to reach the electric bill savings on an annual basis. The figure 5 shows the profile of electric heating demand of the same previous commercial building example (chapter 2) with and without the storage device. The set point in this example is fixed annually to 95 kW:

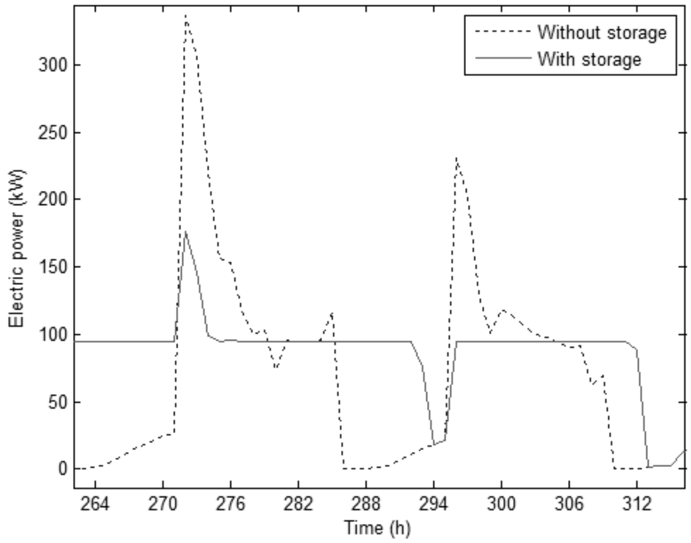

Figure 5. Commercial building electric demand for heating (December 10h to 12th)

In this case, excess of demand beyond the set point occurs in winter. Nevertheless, after exhaustive exploration of the possible values, it is yet at this level that the annual electric bill savings are the best in the simulated conditions.

5. The ThermElect® storage device

The ThermElect® is a central electric thermal storage that stores sensible heat in refractory materials with high thermal capacity. Hydro-Québec participated in its development (Hydro-Québec, 2010). Electrical elements are inserted in a mass of brick. A flow of air is heated passing through these bricks. In a hydronic system, an air-to-water heat exchanger is installed to provide heat to the building heating water loop. Figure 6 shows a diagram of a ThermElect® hydronic operation:

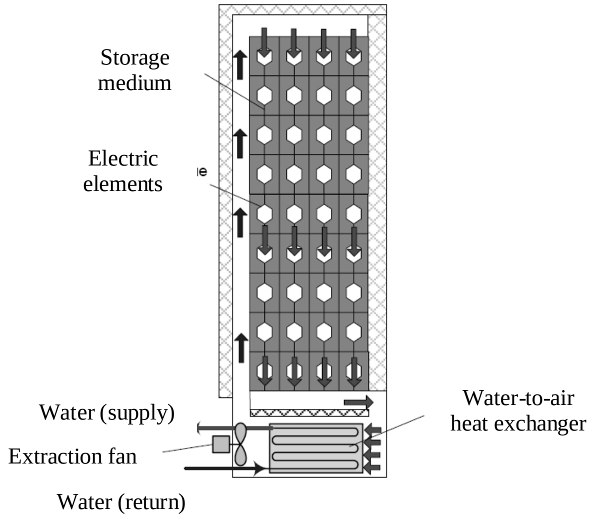

Figure 6. Adapted from ThermElect® diagram (Moreau, 2010)

The storage device consists of brick heated to a maximum temperature of 900 °C by electrical elements (Moreau, 2010). Figure 7 shows the thermal output of storage device (model of 80 kW) during its discharge under different heating demand represented by the curves 80, 65, 50, 40 and 27 kW.

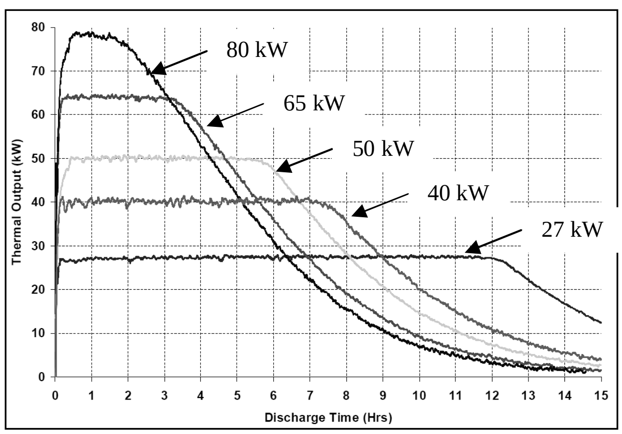

Figure 7. Supplied heating load, ThermElect® 80 kW (Steffes Corporation, 2011)

The storage device can only cover the heating demand requested by the HVAC controls for a few hours. Its internal temperature decreases with time, which causes a lack of thermal output. After 6 hours of discharge period at 80 kW of constant heating demand requested by the control system (80 kW curve), only 30 kW of this heating demand can be covered by it. This limit in thermal output implies that the storage device should be used as an auxiliary heating system and not as the primary heating system in a large building.

Two models are available for the 9100 series: 53 kW and 80 kW. These specified power values are close to the recharge power of each model, the thermal output, however, is variable. Without a deep knowledge of the device components, it is difficult to develop a numerical model that would simulate precisely the devices behavior, and thus, the impact it could have on the building electric demand. For this reason, a method to digitize the performances curves of the storage device is proposed based on empirical curves provided by the manufacturer of the device.

5.1 Digitizing the ThermElect® performances

As shown in figure 7, thermal output of storage device depends on the level of energy accumulated in it. The empirical performance curves supplied by the manufacturer were superimposed to tabulated values in Excel®, for every hour of discharge period of the device. These tabulated values are used to evaluate the fraction of the heating demand that the unit can cover. Two data are required at each step of the simulation to evaluate this fraction of the heating demand: the heating demand requested from the control system (*Ld*) and the amount of energy accumulated in the device (*S*).

This fraction of heating demand can be evaluated in three steps, represented in figure 8:

Step 1: A vector of accumulated thermal energy is generated from the interpolation of the rows of accumulated thermal energy corresponding to the initial thermal output curve (at hour zero, or *Smax*).

Step 2: The position of the value of accumulated thermal energy is found between two values on this vector from step 1.

Step 3: The position of the value of accumulated thermal energy is then returned on the actual maximum thermal output vector by interpolation which is used to find the faction of heating demand that can be covered by the device.

6. Real case application

The developed MATLAB® function and control strategy presented in the previous chapters are used in a real case of Centech building. The Centech is a building owned by the École de technologie supérieure (ÉTS) located in Montréal, Québec (Canada). It is heated with an electric boiler and electric coils installed in air supply boxes. The building is well instrumented and the building electric demand (*Pb*) is recorded every 5 minutes.

The objective of the simulation is to help choose an arrangement of devices and to find the set point of thermal storage device (*T*). In this analysis, simulation assesses the impact of storage devices of 53 kW and 80 kW on heating and building electric demand profile. The arrangements of devices to be compared are: (1) one of 53 kW, (2) one of 80 kW, (3) two of 53 kW, (4) two of 80 kW and (5) three of 80 kW. For each of these arrangements, an optimal fixed set point (*T*) providing the best annual electric bill savings is determined.

The best set point (*T*) is found by iterating set points values from a low limit to a high limit. The increment of set points can be of any value, the smallest increment giving more precise results, but also lengthen simulation duration.

Simple return on investment (simple ROI) is used to find the most advantageous arrangement for the analyzed demand profile. The cost of the devices are estimated to $ 11,000 for a 53 kW device, $ 15,000 for a 80 kW device and $ 15,000 for the installation of each device.

6.1 Best arrangement

Each devices arrangement presents different annual economy according to their respective annual fixed set point. These best set points are reported in table 1 for five studied arrangements.

Table 1. Evaluation of arrangements

Arrangement	1 × 53 kW	1 × 80 kW	2 × 53 kW	2 × 80 kW	3 × 80 kW
Set point (kW)	60	55	55	50	55
Annual savings	5,685 $	6,050 $	6,330 $	6,730 $	7,250 $
Simple ROI (years)	4.6	5.0	8.2	8.9	12.4

Even though the simple ROI is shorter for the 1 × 53 kW arrangements, the difference with the 1 × 80 kW device is marginal. For this reason, the 1 × 80 kW arrangements is kept for further simulation. With the set point fixed at 55 kW, the simulated annual savings is $ 6,050.

6.2 Impact on electric demand

Taking this 80 kW device, figure 8 shows the initial heating demand without storage device and power demand for heating with storage device, at a set point to 55 kW.

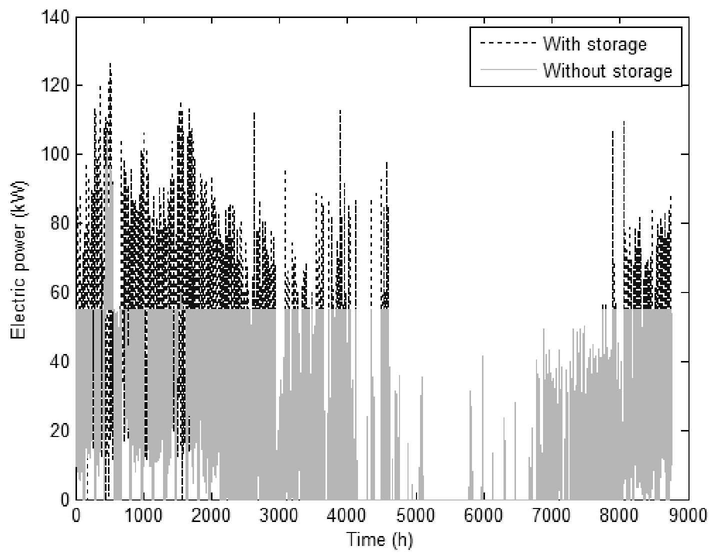

Figure 8. Building electric demand for heating with and without thermal storage

The power demand for heating remains at the set point for most part of the year, but there is a period at the beginning of the simulation where the power demand exceeds the set point. Since the simulation period starts on December 1st 2009, this period corresponds to December 17th to 20th. For a short time, power demand for heating exceeds 55 kW and reaches 100 kW. The algorithm of optimization allows this excess and even if penalties are paid during the lowest building electric demand months, it is at this point that the maximum economies are found.

Thermal output of the storage device depends on requested heating demand and of the level of accumulated thermal energy. Figure 9 shows a zoomed portion of the previous figure, between December 17th and 20th. The initial heating demand without thermal storage device, the electric demand for heating with thermal storage device, and the level of accumulated thermal energy.

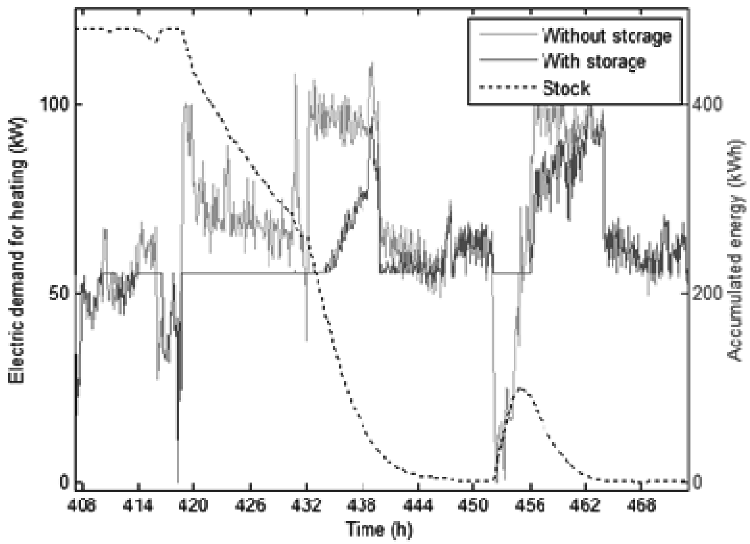

Figure 9. Heating demand and accumulated thermal energy

There are several operation scenarios visible on this chart. Before 433 hours, initial heating demand is below or above the set point (*T*) and the power demand for heating with storage device tops at the set point and the accumulated energy of the device decreases. At 433 hours, initial heating demand and the power demand for heating with storage device passes above the set point because the storage device output cannot cover the required heating demand. At 452 hours, the heating demand passes under the set point, which allows the device to partially recharge its accumulated energy.

6.3 Monthly billing

The savings on the power demand for heating induced by the 80 kW thermal storage device are subtracted from the total building electric demand. The figure 10 compares these monthly maximum building demands with and without storage device:

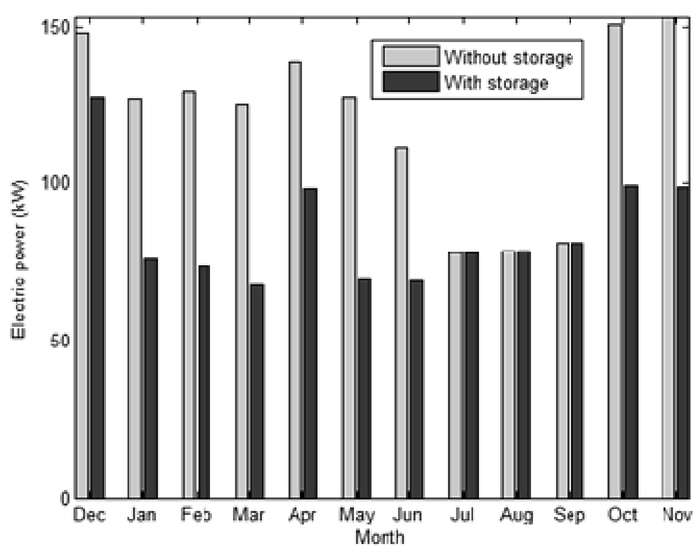

Figure 10. Monthly building peak electric demand

The “Rate M” limits monthly minimum billable building demand from the values recorded between December and March. A decrease in building demand during this period affects also the bills for the rest of the year. The annual profile of building electric demand is therefore essential. It is also interesting to note that the device with 80 kW of nominal electric power reduces the maximum monthly building power demand to 58 kW at most under the simulated conditions.

The table 2 compares each month bills with and without storage device.

Table 2. Monthly building electric bills

Simulated monthly bills			
	Without storage device	With storage device	Savings
December’09	4,509 $	4,237 $	272 $
January’10	4,305 $	3,617 $	688 $
February’10	4,081 $	3,334 $	747 $
March’10	3,785 $	3,012 $	773 $
April’10	3,309 $	2,760 $	548 $
May’10	3,013 $	2,416 $	597 $
June’10	2,653 $	2,263 $	390 $
July’10	2,411 $	2,235 $	177 $
August’10	2,436 $	2,259 $	177 $
September’10	2,548 $	2,371 $	177 $
October’10	3,420 $	2,722 $	698 $
November’10	3,957 $	3,223 $	734 $
Total	40,427 $	34,449 $	5,978 $

Monthly savings are solely due to peak demand reductions as there is no energy savings with the ThermElect®.

7. Conclusions

Despite the fact that a heating storage device coupled to an electric boiler does not allow energy savings, it allows to reduce buildings peak power demand by moving the heating demand to off-peak periods. The ThermElect® is a device that provides an economic advantage in Québec’s winter conditions for institutional and commercial buildings for customers heating with electricity. The price structure of the “Rate M” offered by Hydro-Québec is responsible of this advantage.

The heating demand of the CENTECH , an ÉTS building, with an electric boiler combined with a thermal storage device was simulated using recorded data and a function developed on MATLAB® software. The simulation results show that the maximum monthly building power demand could be reduced by moving the heating demand to off-peak periods with a ThermElect® device. This decrease of monthly peak power demand is greatly affected by the thermal storage device set point (T). A simple payback period of 5 years is possible for a

ThermElect® hydronic device of 80 kW, with a set point at 55 kW to annual savings of approximately $ 6,000.

The thermal storage device should be used as an auxiliary heating device. As the device could be used to reduced peak demand in another control strategy than with the fixed set point, the annual savings could be different than those presented in this study. Therefore, it would be interesting to evaluate the impact of a more complex control strategy, like a strategy with a variable set point depending on anticipated heating demand which is based on weather forecasts.

8. References

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