Data analysis, modelling and energy flexibility assessment of an educational building in Canada

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Abstract

In this paper, the Horizon-du-Lac school (in Sainte-Marthe-sur-le-Lac, near Montréal, Canada) is used as an archetype for data analytics, modelling and energy flexibility assessment for grid interaction. This school is a fully electric building with a geothermal heat pump system, several water-to-air heat pumps and an electrically heated thermal energy storage device. It has been in operation since 2017.

A reduced order model of the classrooms is based on a grey box low-order resistance-capacitance (RC) thermal network along with its equivalent state-space formulation. The objective is to evaluate the potential of shifting the energy use from high to low price periods by adjusting setpoint profiles. Results show that the building can provide an energy flexibility of 49% during on-peak hours relative to a reference as-usual profile.

Introduction

This paper investigates energy performance in a school building in Canada and quantifying energy flexibility potential that can be provided to the grid.

School buildings are an important part of the building stock and a significant portion of the total energy use. In Canada, there are more than 15,500 schools, over 5 million students and almost 750,000 teachers work inside schools (Statistic Canada 2016). The improvement of learning and teaching performance in schools requires a higher level of indoor environmental quality (IEQ), which can have a significant impact on the health and well-being of students and teachers. However, in school buildings, systems are often far from optimal in terms of energy consumption and energy efficiency. Therefore, the operational energy cost to achieve proper thermal comfort and indoor air quality is very high in educational buildings. Thus, it is a major challenge to balance the increasing requirements of environmental performance standards and the necessity to reduce energy consumption, peak demand for electricity, and therefore operating and capital costs.

According to the Intergovernmental Panel on Climate Change (IPCC, 2013), building-related industries consume 40% of global energy and emit approximately 36% of CO_2; as a result, reducing the energy consumption of buildings has gradually become a core strategy for countries worldwide in energy saving and carbon emissions reduction (Allouhi, El Fouih et al. 2015, Navamuel, Morollón et al. 2018). Furthermore, the role of buildings as flexible loads is becoming more important for a smart electricity grid; they can act as energy generators, energy storage devices, or/and controllers of demand. In this regard, the Annex 67 of the International Energy Agency-Energy in Buildings and Communities Programme (IEA-EBC) defined energy flexible buildings as those with "the ability to manage [their] demand and generation according to local climate conditions, user needs and grid requirements."

Improving energy flexibility and reducing the peak demand will reduce the need to build new peaking fossil fuel power plants and their accompanying environmental concerns.

According to the published literature, increasing energy flexibility for the design of smart energy system and buildings is influenced by four important factors (Reynders 2015):

- physical characteristics of the building
- HVAC systems and storage equipment
- adequate control systems and strategies
- comfort requirements

In this context, the appropriate application of control strategies in HVAC systems is a key factor to improve the energy efficiency (Tabares-Velasco, Christensen et al. 2012, Afroz, Shafiullah et al. 2018) and energy flexibility of school buildings (Le Dreau and Heiselberg 2016, Jensen, Marszal-Pomianowska et al. 2017, Reynders, Lopes et al. 2018) by reducing the mismatch between supply and demand for heating or cooling (Klein, Herkel et al. 2017).

Most researchers have used modelling to investigate energy patterns in schools (Zou, Xu et al. 2018). In contrast, there are few publications on measured energy usage in schools in particular (Dasgupta, Prodromou et al. 2012, Van Dronkelaar, Dowson et al. 2016, Golshan, Thoen et al. 2018), and even fewer publications on new/low-energy schools. In studies which summarized several previous studies it was shown that newly built schools in the UK often fail to meet their calculated energy performance (Dasgupta, Prodromou et al. 2012, Van Dronkelaar, Dowson et al. 2016).

Overview of the paper

As many new schools need to be built in the near future, and not many studies have been performed, it is essential to minimize the research gap in terms of the energy performance of recently built schools. Different stakeholders –such as the Canadian building industry, the National Research Council (NRC), responsible for building codes, and the research community– need more feedback with regard to energy performance in new/low-energy schools. In addition, codes and standards, such as the ASHRAE Handbooks, the National Energy Code of Canada for Buildings (NCEB 2015), and local standards (such as Quebec regulation) compel the construction sector to build energy efficient buildings.

After this review of potential opportunities in school buildings, this paper will first describe the Horizon-du-Lac school, the case study building. An overview of the available data and preliminary observations from the analysis of the measurements will be presented. Then, a grey-box model is developed, and used to study the effect of ramps on the load of individual classrooms. Finally, the impact on the energy flexibility of the building is discussed.

School building: Case study

This investigation is based on measurements and generic building information from the Horizon-du-Lac school located in Sainte-Marthe-sur-le-Lac, near Montréal, Canada (LAT 45.5° N). The measurements were carried out over a period of one year. Figures 1 and 2 show the school building and one of the classrooms.

Figure 1: School building – Horizon-du-Lac.

Figure 2: School building – Classroom.

A data analysis exercise was performed using measurements from this school. These data were used to calibrate a grey-box model, perform simulations and verify their validity and then quantify the energy flexibility potential of the building.

The school is a two-storey, fully electric building, in operation since 2017. The hydronic system includes a ThermElect™ high temperature thermal storage, a geothermal water-to-water heat pump, and several water-to-air heat pumps. This school is also equipped with thermal mass in floor slabs. The building is 80.7 m long by 43.8 m wide. The ceiling-floor height in the classrooms is 3.0 m. The window to wall ratio is 80% in first floor and 45% in second floor. Table 1 presents some of the characteristics of the school building which are represented by their code names in this study.

In the first year of operation, an energy use intensity (EUI) of 45.9 kBTU/ft^{2}yr (145 kWh/m^{2}yr) was achieved. This EUI value is about 27% lower than the national average (200 kWh/m^{2}yr) (Ouf and Issa 2017) for schools buildings in Canada. It can be further reduced with additional (ongoing) commissioning efforts.

Measurements

About one year's worth of BAS data was used (from 15 January 2019 to 31 Dec 2019). Thus, the study covers different seasons, with different weather conditions and activities. Numerous temperature sensors (mostly located near the classroom doors and the exhaust) were used.

Setpoint Profiles

The school considered occupied during daytime (between 7:00 to 18:00) and unoccupied during nighttime (between 18:00 to 7:00) and weekend. Figure 3 presents the thermostat set point temperature for one of the classrooms during three cold days (5 Feb 2019 to 8 Feb 2019).

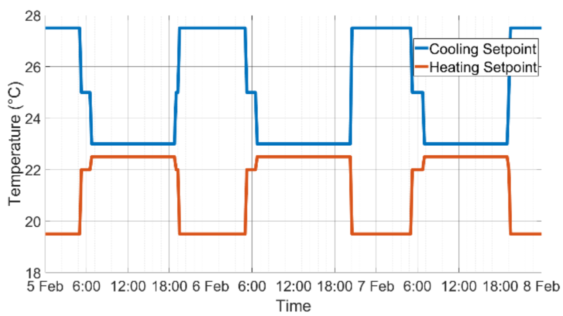


Figure 3: Setpoint temperature in classroom.

The thermostat set point temperature during occupied time is 23 °C for heating and 23.5 °C for cooling. During the unoccupied time, the set point temperature is 19.5 °C for heating and 27.5 °C for cooling.

Energy performance of the school building

Energy use intensity (EUI) is the total amount of energy consumed in a full year per square meter (kWh/m^2/year). According to the published literature, EUI of junior high schools and elementary schools range from 20 to 405 kWh/m^2/year around the world (Wang 2019).

Table 1: Key features of the school building.

Architectural	
In operation since	2017
Site	Sainte-Marthe-sur-le-Lac, Quebec, Canada
ASHRAE climate zone	6
Net floor area, ft^2 (m^2)	2596 m^2/storey
Number of storey	2
Window type	Double-glazed argon low-e wood-frame
Mechanical	
Space heating/cooling	GSHP & local water to air HP
Ventilation system	Balanced mechanical ventilation with DCV, with centralized AHUs with rotary heat recovery. Centralized dedicated outdoor air system (DOAS) modulated based on CO2
Main system, features	Ground source heat pump (GSHP), energy recovery ventilator (ERV)
DHW source	GSHP/ electricity boiler
Electrical	
Lighting, typical type, controls	LED - 1–2 tube luminaires

The EUI of 129 junior high and elementary schools in Manitoba, Canada is investigated by Ouf and Issa (2017). Their results show EUI in an elementary school is 270 kWh/m^2/year; in a junior high school is 264 kWh/m^2/year; and in the K-12 schools is 127 kWh/m^2/year. The average of EUI was 253 kWh/m^2/year, and the average of electricity EUI was 118 kWh/m^2/year. A study in Canada examined both electricity and natural gas use in school energy consumption (Ouf and Issa 2017). They divided the schools into three groups based on the year they were built: before 2004, between 2004 and 2013, and after 2013, and found that the electricity EUIs before 2004 was 58, between 2004 and 2013 was 116, and after 2013 was 125 kWh/m^2/year. It should take into account, newly built buildings tend to be energy efficient in heating/cooling, but because of the teaching equipment, school electricity consumption has increased.

Figure 4 presents the total power electricity of local heat pumps in the school. This figure shows peak power load is around 120 kW. Measurements show that the average of total power load during heating season (November – April) is 109 kW and average of energy consumption is 27234 kWh. Moreover, average of power load and energy consumption during cooling season (May – October) is 89 kW and 19612 kWh, respectively.

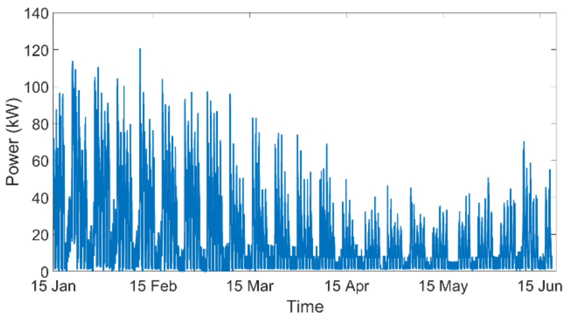


Figure 4: Electricity load of the school – From January 15 to June 15.

Highest electricity consumption was noted to be between January and February; with peak power demand of 166.3 kW and energy consumption of 46440 kWh. Measurements show EUI in the school is 145 kWh/m^2/year, which is about 27% lower than the national average which is 200 kWh/m^2/year (Ouf and Issa 2017) for schools in Canada. This could be explained by using brand new equipment, efficient windows, proper control systems and insulation in the school.

Energy consumption and end-use breakdown

The building automation system (BAS) has been logging data since 15 January 2019. It should be considered that there are gaps and corrupted data due to misread or controller restarts. Figure 5 presents power consumption of major subsystems on a typical winter day at the school.

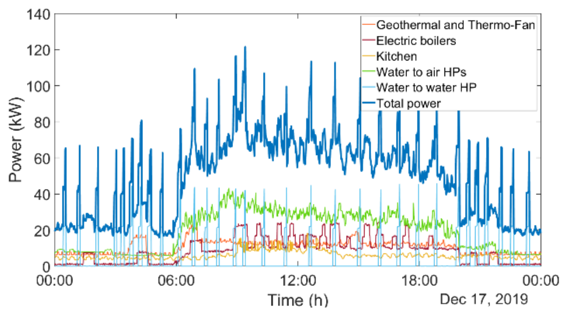


Figure 5: Power consumption distribution on a typical winter day for different subsystems.

The energy end-use breakdown is shown in Table 2 for the period between January 15, 2019, and December 31, 2019. Fan and pump power take up a significant portion due to the radiant slab systems requiring circulation pumps and the fan coil units having each their own fans. The Other category includes plug loads such as computers.

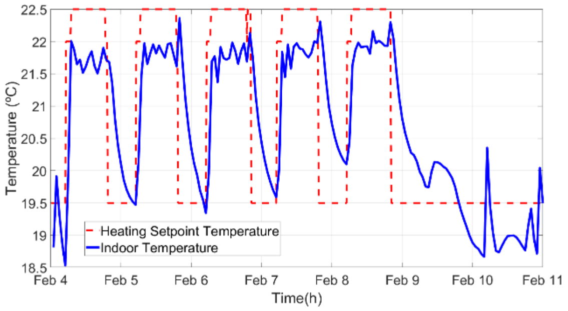
Table 2: End-use breakdown.

End use breaker	Percentage
Electric boiler for hot water	14
Kitchen & lighting the Gym	12
Geothermal, pumps and thermo-fan	18
Water to air heat pumps and lighting	38
Water to water heat pump	15

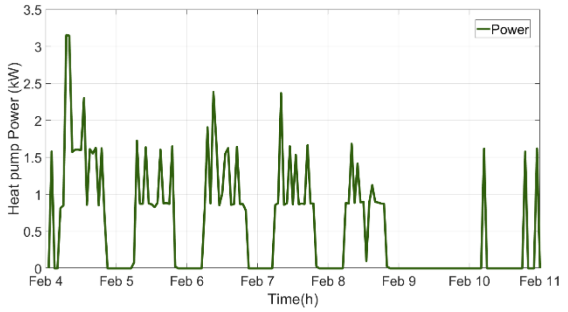
Results show around local heat pumps use 20% of total energy, and around 15 % of total energy is used by water-to-water heat pump (in heating mode of operation).

Temperature and power in a classroom

Figure 6(a) presents heating setpoint temperature and indoor air temperature in one of the classrooms, and Figure 6(b) shows electric heat pump power in the class.



(a)



(b)

Figure 6: (a) Temperature and (b) electricity consumption profile in a classroom.

As can be seen in Figure 6(a), indoor air temperature follows the setpoint temperature during occupied time (weekdays in daytime). During unoccupied time (nighttime and weekend) heat pump turned off and the indoor temperature is left free to fluctuate without any mechanical heating (free-floating).

Control strategies

The appropriate application of control strategies in HVAC systems is a key factor to improve the energy efficiency and energy flexibility of buildings. In this regard, suitable control strategies have a significant impact on the performance of the system. Thus, both system operating and capital costs can be reduced in an effective manner.

The following sections outline the results obtained from application of a linear ramp of room temperature setpoint into a classroom toward achieving peak load reduction and increasing energy flexibility on peak hours.

Weather conditions

Weather data in cold days (5 Feb to 8 Feb 2019) in Montreal is selected, since the demand load tends to peak under these conditions. Figure 7 presents the outdoor temperature and solar flux during these days. These weather data were obtained from Montreal weather file.

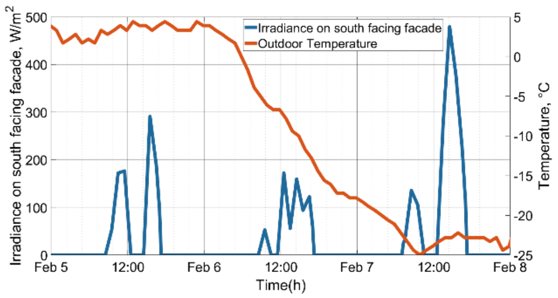


Figure 7: Outdoor temperature and solar flux.

Methodology

Modelling methods

In order to study the effect of alternative setpoint profiles, a model of the classrooms is needed. In general, two approaches are used to create building energy models.

- The first approach consists of white-box models that simulate the heating demand by simplified physical equations. Typical building simulation programs, use this white-box (building physics based) approach. Although white-box models make it possible to analyze the physical behavior of buildings and are therefore interesting for research purposes, the accuracy of control strategies relying on these physical models has not been satisfactory, since the real building parameters are often unknown in existing buildings and tend to deviate from the values used during the design of the control system.
- Conversely, black-box (purely data-driven) models with self-learning capabilities have become a popular option. However, a substantial amount of data might be required to achieve the accuracy needed for a control-oriented model, and the resulting parameters may lack a clear physical interpretation.

To overcome these problems, grey-box models which are partly data driven are a compromise that keeps both physical insight and the trustworthiness of real data. Grey-box models rely on physical knowledge about the system dynamics to define the model structure. Statistical methods are then used to estimate the unknown parameters. These parameters may be directly linked to the physical properties of the building, given that the model structure correctly represents the physical behavior of the system.

A second order RC thermal network structure (Figure 4) was proposed to model the thermal dynamics of the classrooms.

Governing equations

Equation 1 shows an explicit finite-difference formulation of the heat balance in a node.

$$\sum_j U_{ij}^t(T_j^t - T_i^t) + \sum_k U_{ik}^t(T_k^t - T_i^t) - \frac{C_i}{\Delta t}(T_i^{t+1} - T_i^t) + \dot{Q}_i^t = 0 \quad (1)$$

To assure numerical stability in the solution, the time step must be chosen according to the stability criterion defined in equation 2:

$$\Delta t = min(\frac{C_i}{\sum U_i}) \quad (2)$$

State – space representations describe systems of linear differential equation in a compact manner, as shown in equation 3:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$$
$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du} \quad (3)$$

In which the state (x), input (u), and output vectors (y) are:

$$\mathbf{x} = \begin{bmatrix} T_1 \\ T_3 \end{bmatrix} \qquad \mathrm{u} = \begin{bmatrix} T_{\mathrm{ext}} \\ q_{\mathrm{SG}} \\ q_{\mathrm{IG}} \\ q_{\mathrm{aux}} \end{bmatrix} \qquad \mathrm{y} = \begin{bmatrix} T_1 \\ T_3 \end{bmatrix}$$

Model identification is the process to determine physical properties of unknown systems according to some experimental data or training data. The model is based on low-order resistance-capacitance (RC) thermal network along with equivalent state-space formulation. Figure 8 presents the thermal network model structure for a 4R2C model, to calculate building thermal performance.

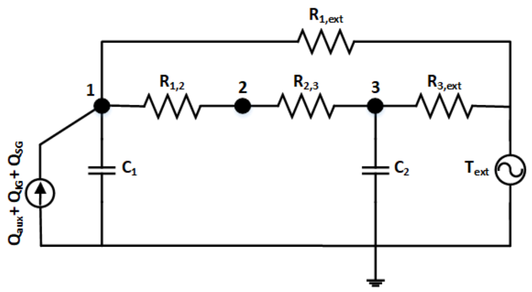


Figure 8: RC thermal network.

Table 3 describes the parameters of the RC model.

Table 3: Low-Order 2 Capacitance RC Circuit Parameters.

Parameter	Description
1	air temperature node
2	envelope node - inside
3	envelope node - middle
T_{ext}	outdoor temperature
Q_{SG}	solar gain
Q_{IG}	internal gain
Q_{aux}	heating power
$R_{3, ext}$	half of wall resistance
$R_{2,3}$	half of wall resistance
$R_{1,2}$	interior film coefficient
$R_{1, ext}$	infiltration
C_1	effective interior capacitance
C_2	envelope capacitance

Numerical experiment for ramp profiles

The initial conditions were the following:

- The initial temperature of the room, at t = 0, was set at 19.5 °C (equal to nighttime setpoint temperature) everywhere.
- Measurement interval – 15 minutes

The simulation runs for a period of 7 days using the weather conditions presented in Figure 7. The simulation time step was set to 5 minutes. The COP of the local heat pump in the classroom is COP = 3.2 as the heating system. Capacity of the heating system is 7000W. The controller is simple PI (Proportional-Integral) controller.

Effect of linear ramp of room temperature set point

It is well known that a sudden setpoint transition –e.g. between a night setback and daytime setpoint– creates a spike in the peak demand. The effect of using ramps to transition between setpoints has been investigated by (Braun and Lee 2006, Lee and Braun 2008, Candanedo, Dehkordi et al. 2015), among others.

Figure 9 shows electric power load with sudden setpoint transition (from 19.5 to 22.5 °C). Results show, in this case, the peak load is 2300 W.

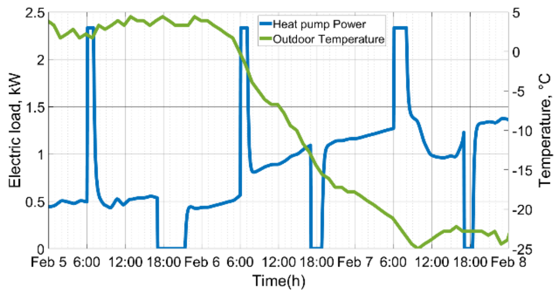


Figure 9: Electric power demand without ramp.

This section examines the effect of using two-hour linear ramp of room temperature set point on reducing peak load in a classroom. Figure 10 presents thermostat set point with ramp and room air temperature. Figure 18 presents results regarding heating load required considering ramp in set point temperature.

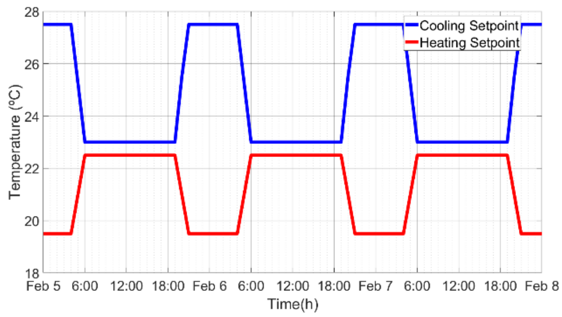


Figure 10: Set point temperature with 2 hours ramp.

Figure 11 presents results regarding heating load required considering ramp in set point temperature.

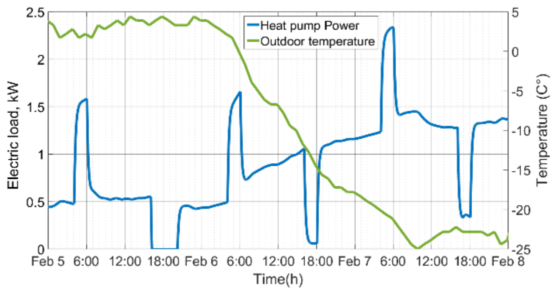


Figure 11: Power load with 2 hours ramp.

Figure 12 presents a comparison of the results for the electricity demand.

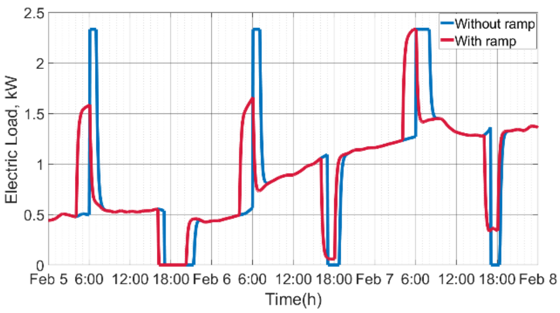


Figure 12: Comparison of Power load with and without ramp.

As can be seen in Figure 12, using 2-hour ramp in temperature setpoint can reduce peak load by 30%, form 2300 W to 1600 W. Results show, by using 2-hour linear ramp peak load can be shifted from on-peak hours to off-peak hours, making building more flexible.

Energy Flexibility

The objective of this section is to show the potential of shaving/shifting peak load from high to low price periods.

Time-of-Use Pricing (Hydro Quebec Rates) is used as an indicator of the price of electricity (Figure 13). In Quebec, the grid's peak demand occurs during the winter since most small to medium commercial, institutional and residential buildings using electricity as a primary source of energy for heating.

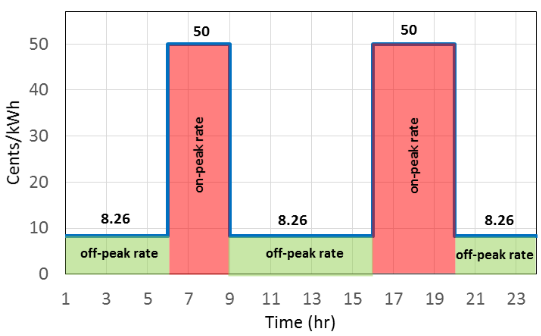


Figure 13: Time-of-Use Pricing in winter.

Energy flexibility in buildings has been defined as "the possibility to deviate the electricity consumption of a building from the reference scenario at a specific point in time and during a certain time span" (Torres Ruilova 2017). In this section, a flexibility factor has been calculated based on Equation (4). A building Energy Flexibility Index would help to define the amount a power variation that is available from a building (Finck, Li et al. 2020). This index shows the ability to reduce the peak load during on-peak hours(Le Dreau and Heiselberg 2016). The calculation of the ratio ($\bar{P}_{Flex}/\bar{P}_{Ref}$) compared the peak power under flexible case and the reference as-usual profile (Equation 5).

$$\overline{BEFI} = \frac{\int P_{Ref}dt - \int P_{Flex}dt}{Duration\ time\ of\ flexibility} \tag{4}$$

$$Relative\ BEFI = \frac{\bar{P}_{Flex}}{\bar{P}_{Ref}} \tag{5}$$

Where:

$\overline{BEFI}$ means average of Building Energy Flexibility Index during event, *+ or -* indicate flexibility up or down, and *Duration* is the duration time of the flexibility.

Table 4 provides a comparison between reference case study (without ramp) and the flexible case (with two-hour linear ramp).

Table 4: Flexibility scenarios of the building.

Case study	**Ref. case**	**With ramp**	**Changes Relative to Ref. case**
Mean power load during on-peak hours (W)	1845	915	930 W down (49 %)
Energy consumption (kWh)	131.91	132.42	0.3 % increase

The results presented in Table 3 shows that appropriate control strategies could provide flexibility to the grid, reduce mean power load during daytime and peak power demand, simultaneously.

Conclusion

In this paper, the Horizon-du-Lac school is used as a case study to measure real data, develop a control-oriented model, verify/validate the model, and use this model to assess the energy flexibility potential of the building based on the adjustment of setpoints in the classrooms. This 100% electric school has been in operation since 2017. Results of this study show:

- In the first year after inauguration, an operational energy use intensity (EUI) of 45.9 kBTU/ft^2/year (145 kWh/m^2/year) was achieved. This is 27% EUI lower than the national school average.
- Results show that around 20% of total energy is used by local heat pumps in the classrooms, and around 15% of total energy is used by a water-to-water heat pump (in heating mode of operation) used for the radiant floor heating of the offices and gym.
- Appropriate control strategies such as the two-hour linear ramp of temperature setpoint can achieve 30% peak load reduction and increase 49% energy flexibility of the building. A Time-of-Use pricing scheme (proposed Hydro Quebec rates) is used as an indicator of the price of electricity.

Results show that appropriate control strategies could be effective to improve the energy flexibility in buildings, reduce the sizing of the HVAC unit at the design stage, thus reducing both operation and initial capital costs.

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