Energy flexibility quantification with integrated heat pump, floor heating system, and thermal storage in a school building

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Abstract

This paper investigates promising predictive control strategies aimed to reducing peak demand and quantifying the energy flexibility potential of office zones in a school building. The office zones are equipped with integrated geothermal heat pump, floor heating system, forced air system, and concrete slab as a thermal energy storage. This paper consists of three parts: (1) development of models for the offices based on data-driven grey-box formulation and calibration with measured data; (2) employing the model to predict the concrete slab surface temperature, the indoor air temperature, and the heat delivered to the offices; (3) quantifying the energy flexibility through the estimation of the state of charge (SOC) of the concrete slab, and a Building Energy Flexibility Index (BEFI).

Results show that with appropriate predictive control strategy the offices can use maximum SOC of the concrete slab and provide an energy flexibility of 25% during on-peak hours relative to a reference as-usual profile.

Introduction

According to the Intergovernmental Panel on Climate Change (IPCC, 2013), buildings account for 40% of global energy and 36% of CO2 emissions. 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 et al. 2015, Navamuel et al. 2018). In Quebec (second largest province of Canada), the electricity demand has two peak demand periods in the heating season in the morning and evening which put a lot of strain on the electrical grid to provide the peak power demand during extreme cold weather (Hydro-Québec 2019).

The role of buildings as flexible loads is becoming more important in the context of a smart electricity grid: they can act as energy generators, energy storage devices, or/and controllers of demand. Annex 67 of the International Energy Agency-Energy in Buildings and Communities Programme (IEA-EB) 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” (Jensen et al. 2017).

Buildings can provide different flexibility services to reduce peak loads and shift demand in accordance with local Renewable Energy Sources (RES) production, e.g., utilization of thermal mass (Foteinaki et al. 2018, Weiß et al. 2019), storage in batteries, charging of electric vehicles (Zhou and Cao 2019) and adjustability of the HVAC system use (Jensen et al. 2017). In this context, thermal energy storage (TES) in building components along with appropriate control strategies can be a key contributor to energy flexibility. Aelenei et al. (2019) improve the energy flexibility of a non-residential building, by integrating a battery energy storage. Their results show, the self-consumption factor and the self-generation factor can increase by 15.4% and 6.1%, respectively.

Thermal energy storage

Thermal Energy Storage is one of the most essential elements for energy management in buildings due to mismatch between energy generation and demand (Strith et al. 2018, Morovat et al. 2019). TES can provide flexibility to shift electricity use in time and contribute to Demand Side Management (DSM) and grid balancing.

There are different perspectives to take into account when considering the use of TES for managing heating energy flexibility: the amount of heat shifted in time, the duration of this flexibility, the direction of the change (increase or decrease compared to reference case), and the costs of activating this energy flexibility (Bozkaya et al. 2017).

Thus, radiant floor (RF) systems typically combined with a heat pump (HP) can be used as an effective and active way to storing thermal energy within the floor. This also allows for heat power demand reductions in peak power periods, especially in the morning.

The heat that can be stored not only depends on the thermal properties of the building, but also on the properties and actual use of the heating and ventilation systems. Therefore, a quantitative assessment of the energy flexibility provided by the slab is essential to large scale deployment of thermal mass as dispatchable TES in an Automated Demand Response (ADR) context.

This paper investigates energy flexibility of office zones in a school building, which zones are equipped with integrated geothermal water-water heat pump (HP), forced air HP, and radiant floor system. The possibility of TES is provided by the large thermal inertia of the slab.
Overview of the paper
The first part of this paper presents the case study building and overview of the heating systems. The second part provides modelling and calibration of the grey-box model with measured data. The third part explores testing of different control scenarios to assess impact on electricity demand and energy performance. The results obtained by using flexible scenarios are compared to current operation of the building as a reference case. The last part investigates energy flexibility assessment, including the application of state of charge (SOC) of the concrete slab and a Building Energy Flexibility Index (BEFI) to quantify energy flexibility and enable interaction between building, aggregators and utilities.

The following section describes the case study school building and the offices characteristics.

Case study: Newly built school
School buildings are an important part of the building stock; they also represent a sizeable portion of the total energy use in the building sector. In Canada, there are more than 15,500 schools, having more than 5 million students and almost 700,000 teachers and other workers (Statistic Canada 2017). Higher levels of indoor environmental quality (IEQ) are instrumental to achieve optimal teaching/learning performance, given the impact of IEQ’s on the health and well-being of teachers and students. However, HVAC systems in schools are often non-optimized in terms of energy consumption and efficiency; thus, the energy cost of educational buildings is considerable. Therefore, satisfying the increasing requirements of environmental performance—along with the need to enhance energy flexibility as a Smart Grid necessity – is a challenging task.

The case study school (located in Montreal, Canada) has been in operation since 2017, and is an all-electric building (Figure 1). This two-storey school building has floor area of 2596 m²/storey (Total 5192 m²). Features of the school include a high temperature thermal storage device with capacity of 80 kW, 36 terminal fan coil units by local water-to-air heat pumps with local water-to-air heat pumps with maximum capacity of 40kW, and a geothermal water-to-water heat pump with maximum capacity of 33 kW (Figure 2) used for radiant floor system in gym and offices (Figure 3).

There are several sources of high-resolution data, including the building automation system (BAS) and dedicated electrical sub-meters. The sampling timestamp for collecting data is every fifteen minutes for all HVAC systems, classrooms, and offices. The building also has large thermal mass in the form of floor slabs of the gym and offices. These components can offer much energy flexibility and, in turn, can increase the energy flexibility and reduce energy consumption and peak energy demand through predictive control.

System description
Figure 4 presents the schematic of the building heating systems. The system consists of integrated geothermal system, water-to-water heat pump, floor heating system, and thermal storage in offices of a school building. All heating systems are electrical devices and hence provide a link with the electrical grid. This link can be exploited by a predictive controller to help, for instance, balance electricity production and demand.

The water-to-water HP for space heating had a nominal heating output of 33 kW in two stages, and a maximum supply temperature of 48.8 °C. Low-temperature heat on the evaporator side of the HP is generated by a borehole thermal energy storage (BTES) with 28 loops. Electrically heated thermal energy storage device (ThermElect) can be used for preheating the water inlet to local water to air HPs and the water-to-water HP. In this paper, the sensor data from the ground heat exchanger, the thermal storage device, and the water-to-water HP are collected (fifteen minutes time stamp) and then used as the inputs for the modelling of the offices.

A thermostatic three-way valve regulates the temperature of the supply water of the HP to the zones, with a maximum setting of 48.8 °C. Space heating is supplied by an integrated floor heating system and ceiling forced air system throughout the offices and the gym. Thermostats regulate the indoor temperature on each zones separately.

Office zones
This paper focuses on the office zones on the first floor, shown in Figure 5. These offices are heated with radiant floor system and local forced air systems, with individual office thermostats. The heating systems are controlled by line-voltage thermostats, operating in proportional-integral mode.

The thermocouples instrumented in the offices are special T type, which have been calibrated. Air temperatures are
measured throughout the HVAC system and floor temperatures are measured in eight locations shown in Figure 5.

The floor area of the offices with radiant floor system and the piping length in each office are presented in Table 1. Figure 6 shows the front view of the slab with radiant floor piping. The floor is made of a 15 cm thick concrete slab with a layer of insulation (5.64 m²K/W) at the bottom. The bottom of pipes is in depth of 6 cm of the concrete. The pipes are made of conventional cross-linked polyethylene (PEX) and have an external diameter of 1.25 cm.

The pipes are installed and fixed on a wired mesh that also facilitates keeping them in place before the concrete is cast. The pipes have an approximate separation of 30.4 cm between them.

Table 1: Floor area and piping length of the radiant floor system.

<table>
<thead>
<tr>
<th>Thermal zone</th>
<th>Area (m²)</th>
<th>Piping length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office 1</td>
<td>64.4</td>
<td>244.5</td>
</tr>
<tr>
<td>Office 2</td>
<td>12.5</td>
<td>69.2</td>
</tr>
<tr>
<td>Office 3</td>
<td>20.8</td>
<td>91.1</td>
</tr>
<tr>
<td>Office 4</td>
<td>27.1</td>
<td>175.8</td>
</tr>
<tr>
<td>Office 5</td>
<td>19.2</td>
<td>87.3</td>
</tr>
<tr>
<td>Total</td>
<td>144.0</td>
<td>667.9</td>
</tr>
</tbody>
</table>

A water-water HP provides controlled flow rate (0.29L/s) of water for the radiant floor. The HP has a nominal coefficient of performance (COP) of 2.7 at 48.8°C test conditions (water temperature) for full load operation based on the HP data sheet.

Heating power to the radiant floor is calculated by using the flowrate ($\dot{m}$), specific heat of water ($c_p$), supply and return temperatures difference ($\Delta T$) as:

$$Q = \dot{m} \times c_p \times \Delta T$$ (1)

The sensors are included with the thermostat to measure slab temperature to protect the floor from overheating and to enhance comfort. According to the ASHRAE standard 55, the allowable floor temperature is 29 °C (ASHRAE 55 2017). In this case study allowable floor temperature is considered to be 26 °C.
Methodology

Grey-box models rely on physical knowledge about the system dynamics to define the model structure. Statistical methods are then used, and the unknown parameters are calibrated with measurement. These parameters may be directly linked to the physical properties of the building, given that the model structure correctly represents the physical behaviour of the system.

Thermal model

In this paper, the thermal modelling approach is based on the lumped parameter finite difference method and implemented in MATLAB. By performing a heat balance on the control volume, the differential equation of a node can then be written as (Athienitis and Santamouris 2002):

$$\sum_{j} U_{ij} (T_{i}^k - T_{j}^k) + \frac{C_{i}}{2} (T_{i}^{k+1} - 2T_{i}^{k} + T_{i}^{k-1}) + Q_{i}^k = 0$$

(2)

- $U_{ij}$: Conductance between nodes $i$ and $j$, W/K.
- $C_{i}$: Capacitance of the node ($C = \rho C_{p} A dx$), J/K.
- $Q_{i}$: Heat flow into the node, W.
- $\Delta t$: Time step, s.

Equation 3 calculates the heat provided by the floor heating system with proportional-integral control (PI controller) at each time step.

$$Q_{q_{he}} = k_{p} \left( T_{set}^{\infty} - T_{room,air}^{\infty} \right) + k_{i} \int\left( T_{set}^{\infty} - T_{room,air}^{\infty} \right) dt$$

(3)

With this methodology, it is possible to create a thermal network for office zones based on the electrical-thermal analogies as shown in Figure 7.

Table 3 provides an overview of thermal network parameter description (capacitors).

As shown in Figure 7, the inputs include: outdoor temperature ($T_{ext}$), solar gain ($q_{sol}$), internal heat gain ($q_{int}$), heat delivered by RF system ($q_{RF}$), and heat delivered by ceiling water-air HP ($q_{aux}$). We presented the details of these information in (Morovat et al. 2020).

The heat delivered by ceiling HP ($q_{aux}$) is calculated by multiplying measured power electricity by COP of the HP, and the output is indoor air temperature. The outdoor temperature and solar irradiance are obtained from Montreal weather data (Hydro-Québec 2020).

State – Space representations

State – Space representations describe systems of linear differential equation in a compact manner, as shown in Equation (4), where $x$ is the state matrix, $u$ is input, and $y$ represent output vectors.

$$\dot{x} = Ax + Bu$$

(4)

$$y = Cx + Du$$

In this approach, the temperatures of nodes with thermal capacitances are usually considered as the states of the system since they have certain physical meanings and they are relatively easy to measure (Candanedo et al. 2013).

In this paper, the objective of the model identification is to find the equivalent RC circuit parameters by minimizing CV(RMSE). Equation (5) (ASHRAE Guideline 2002) is used to calculate this index where $y_{i}$, $\hat{y}_{i}$, $n$ represent the measurements data, simulation results, a total number of observations and the average of all measurements, respectively.

$$CV(RMSE)\% = 100 \times \sqrt{\frac{\sum_{i=1}^{n}(y_{i} - \hat{y}_{i})^2}{n}}$$

(5)

In this study, the Python function SLSQP – which finds the minimum of a constrained nonlinear multivariable function – is used.

According to ASHRAE Guideline 14 (Measurement of Energy and Demand Savings), the model shall have a CV(RMSE) of not more than 30% relative to hourly calibration (measured) data (ASHRAE Guideline 14 2002).

Table 3: Low-order RC thermal network model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Envelope temperature node</td>
<td>$R_{t,c}$</td>
<td>Wall resistance, (K/W)</td>
</tr>
<tr>
<td>2</td>
<td>Indoor air temperature node</td>
<td>$R_{t,2}$</td>
<td>Resistance between wall and air node, (K/W)</td>
</tr>
<tr>
<td>3</td>
<td>Floor surface temperature node</td>
<td>$R_{t,3}$</td>
<td>Resistance between floor and air node, (K/W)</td>
</tr>
<tr>
<td>4</td>
<td>Pipe temperature node</td>
<td>$R_{t,4}$</td>
<td>Infiltration, (K/W)</td>
</tr>
<tr>
<td>5</td>
<td>Concrete temperature node (top)</td>
<td>$R_{t,5}$</td>
<td>Resistance between pipe and floor surface, (K/W)</td>
</tr>
<tr>
<td>6</td>
<td>Concrete temperature node (below)</td>
<td>$R_{t,6}$</td>
<td>Resistance between concrete and pipe, (K/W)</td>
</tr>
<tr>
<td>$T_{ext}$</td>
<td>Outdoor temperature, (°C)</td>
<td>$R_{t,6}$</td>
<td>Resistance in concrete, (K/W)</td>
</tr>
<tr>
<td>$T_{e}$</td>
<td>Ground temperature, (°C)</td>
<td>$R_{t,6}$</td>
<td>Resistance between ground and concrete, (K/W)</td>
</tr>
<tr>
<td>$Q_{sol}$</td>
<td>Solar gain, (W)</td>
<td>$C_{1}$</td>
<td>Envelope capacitance, (J/K)</td>
</tr>
<tr>
<td>$Q_{int}$</td>
<td>Internal gain, (W)</td>
<td>$C_{2}$</td>
<td>Effective Air capacitance, (J/K)</td>
</tr>
<tr>
<td>$Q_{aux}$</td>
<td>Heating power, (W)</td>
<td>$C_{3}$</td>
<td>Floor capacitance (top), (J/K)</td>
</tr>
</tbody>
</table>

| $C_{1}$ | Floor capacitance (below), (J/K) |

Figure 7: Thermal network RC model.
The RC model created has CV-RMSE equal to 12.57% and meet calibration requirements. We also presented more details about data analysis and important parameters in the school at (Morovat et al. 2020)

**Results**

**Control Scenarios for energy flexibility**

This paper evaluates the amount of heat modulated by the slab and the duration of the effect on the grid. This characterization will then be used to develop simple predictive control strategies to exploit the thermal storage potential, considering both energy consumption and thermal comfort. Other objectives in the future could include minimization of cost under diverse scenarios (demand charge penalty, fluctuations of energy price, utility-triggered cost incentive).

By analysing measured data in the offices, it was observed that the radiant floor temperature setpoint (21.8 °C) is at all times lower than the air temperature setpoint which is 23 °C in daytime, as shown in Figure 8a. Thus, the floor has a cooling effect, and it works as a sink of heat. Thus, two control scenarios in a cold winter day are evaluated and compared to the current operation of the building as a reference case. In the control strategies the following assumptions are considered:

- Maximum slab surface temperature set to be 26°C (upper limit of the concrete slab to guarantee thermal comfort);
- Operative temperature is considered as effective indoor temperature;
- The slab is charged during nighttime (unoccupied hours) and discharged during daytime (occupied hours);
- Slab temperature should be higher than air temperature for effective operation of the floor heating.

![Temperature profile in different scenarios](image1)

**Figure 8:** Temperature profile in different scenarios

![Heat delivered to the thermal zones](image2)

**Figure 9:** Heat delivered to the thermal zones
Control scenario 1 (Reference case)
This control scenario is the current operation of the heating systems in offices and it is considered as the reference case. As shown in Figure 8(a), the slab setpoint temperature is constant (21.8 °C). The air setpoint temperature is 23 °C during daytime (occupied hours), and 21.8 °C in nighttime (unoccupied hours).

Figure 9 (a) presents the amount of heat delivered to the thermal zones. It is observed that in this scenario, the air system is the main heating system, and the radiant floor system is not in operation most of the time. From the graph it also can be observed that the peak load is during early morning, which is high peak for the grid as well.

With an appropriate control strategy, it is feasible to determine if there is an alternative control strategy that would improve the building operation, energy use, or peak demand. Therefore, two following control scenarios are investigated to reduce/shift the peak load and enhance energy flexibility of the building.

Control scenario 2
In this case, as shown in Figure 8(b), the slab setpoint temperature is increased to 26 °C to preheat the slab from midnight to 8:00 a.m. During occupied hours (from 8:00 a.m. to 5:00 p.m.) the slab setpoint temperature is 18 °C and after that it is increased to 22 °C. The air setpoint temperature is considered to be constant and equal to 20°C during both occupied and unoccupied hours.

From Figure 8(b), it can be observed that the operative temperature varies between 21 to 24 °C, which is in range of thermal comfort for occupants.

Figure 9(b) presents the heat delivered to the thermal zones based on control scenario 2. From the graph it can be observed that the radiant floor system is the main heating system and the heating load during occupied hours reduced significantly. The limitation of this control scenario is that the ventilation system is off, and it can causes the low air quality in the offices. Thus, the control scenario 3 takes into account the operation of forced air system during occupied hours.

Control scenario 3
In this control scenario, increasing air setpoint temperature to 23 °C during occupied hours is considered (refer to Figure 8(c)).

The proposed control strategy can achieve reductions in peak load of around 10 kW heat in the morning, and provide fresh air to the space by turning on the air system from 10:00 a.m. to 5:00 p.m. It should be noted that energy consumption in this flexible scenario is 133.5 kWh which is less than reference as usual case (136.6 kWh).

This information is used to assess the state of charge (SOC) of the slab (i.e., thermal storage in slab), and therefore, to estimate the flexibility associated to reducing peak load and energy consumption over peak periods.

State of Charge (SOC) of the slab
The state of charge (SOC) is used to explain the fraction of stored energy at time t compared to the total storage capacity (Reynders et al. 2018):

\[
SOC = \frac{E_{th}(t) - E_{th,min}(t)}{E_{th,max}(t) - E_{th,min}(t)}
\]

Figure 10 and 11 present the heat storage and State of Charge (SOC) of the slab in reference case and control strategy 3 (flexible case), respectively. It can be observed that in the reference case the slab cannot be fully charged.

Thus, the potential of thermal energy storage by the large thermal inertia of the slab is not used properly.

As shown in Figure 11, this large thermal inertia in slab can provide the flexibility to reduce peak loads and shift the heat production of RF system in time. By appropriate control strategy it is possible to fully charge the slab during unoccupied hours and discharge it when needed. This approach provides thermal load flexibility for the school and the smart grid, to manage electricity demand for a period when needed by the grid.

![Figure 10: Heat storage and State of Charge (SOC) of the slab - reference case](https://doi.org/10.26868/25222708.2021.30468)

![Figure 11: Heat storage and State of Charge (SOC) of the slab – flexible case](https://doi.org/10.26868/25222708.2021.30468)
Recent international efforts have recognized the need for a methodology to assess the flexibility for demand response in buildings. The following section presents a methodology for quantification of dynamic energy flexibility and its application in this case study.

**Thermal load flexibility**

The requirements of smart grid load flexibility raised the need of building energy flexibility study. The dynamic energy flexibility can be defined as the capability of a building to reduce or increase its electricity demand for a period when needed by the grid.

Equation 7 calculates the average BEFI under implementation of the flexibility strategy and the reference as-usual profile. We presented the details of this approach in a previous study (Athienitis et al. 2020).

$$BEF I(t, DT) = \frac{\int_{t}^{t+DT} P_{ref} dt - \int_{t}^{t+DT} P_{flex} dt}{Duration \ time \ of \ flexibility}$$

where $BEFI$ is the average Building Energy Flexibility Index at time $t$ for duration $DT$.

Flexibility available may be quantified using a model to establish the power demand difference between reference case ($P_{ref}$) with a flexible case for 1 hour, or a few hours. If this flexibility strategy is applied to the offices, the hourly BEFI that can be provided to the grid is as shown in Figure 12.

As can be observed in this graph, by applying control scenario 3 (flexible case), available hourly BEFI that can be provided to the grid during peak hours (in the morning and evening) is positive, which indicates the value of power reduction available compared to the reference case. During off-peak hours (night time) the BEFI is negative which shows higher power demand for charging the slab and preheat the offices. According to Figure 12, an energy flexibility of around 9 kW in the morning and around 5 kW in the evening can be provided to the grid when needed. It should be noted that BEFI at time $t$ may vary according to time of notice and a notice prior to signal may allow to precondition the building to maximize available flexibility when needed.

**Conclusion**

This paper focused on office zones in a school building in Quebec, Canada, to measure and analyse performance, develop a control-oriented model, verify/validate the model, and use this model to assess the energy flexibility potential of the office zones. The office zones are equipped with integrated geothermal heat pump, floor heating system, forced air system, and concrete slab as a thermal energy storage.

A data-driven grey-box model was developed to describe the relationship between (a) the geothermal heat pump system, (b) the thermal storage in the concrete slab, and (c) the temperatures of the indoor air and the concrete slab surface.

The modelling results were analysed to develop the flexibility strategy through the estimation of the state of charge (SOC) of the concrete slab and a Building Energy Flexibility Index (BEFI) to quantify energy flexibility and enable interaction between building, aggregators, and utilities.

Results show that by charging the floor heating mass during the nighttime and discharging it during the morning critical demand hours, the office zones can use maximum SOC of the concrete slab and provide an energy flexibility of 25% during on-peak hours relative to a reference (as-usual, current default) profile. The charging/discharging rates could be adjusted according to predicted heating loads to reduce bills and enhance building energy flexibility in its interaction with the grid.

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References


Nomenclature

<table>
<thead>
<tr>
<th>BEFI</th>
<th>Building Energy Flexibility Index (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Thermal capacitance (J/K)</td>
</tr>
<tr>
<td>Dt</td>
<td>Time duration (seconds or hours)</td>
</tr>
<tr>
<td>P</td>
<td>Electric power (W)</td>
</tr>
<tr>
<td>QSG</td>
<td>Solar gain (W)</td>
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<tr>
<td>QBG</td>
<td>Internal gain (W)</td>
</tr>
<tr>
<td>Qaux</td>
<td>Heating power (W)</td>
</tr>
<tr>
<td>R</td>
<td>Thermal resistance (K/W)</td>
</tr>
<tr>
<td>S</td>
<td>Solar radiation (W)</td>
</tr>
<tr>
<td>T</td>
<td>Temperature (ºC)</td>
</tr>
<tr>
<td>Tb</td>
<td>Bottom zone temperature (ºC)</td>
</tr>
<tr>
<td>Tn</td>
<td>Outdoor temperature (ºC)</td>
</tr>
<tr>
<td>TSP</td>
<td>Setpoint temperature (ºC)</td>
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Subscripts

<table>
<thead>
<tr>
<th>Flex</th>
<th>Flexible case</th>
</tr>
</thead>
<tbody>
<tr>
<td>ref</td>
<td>Reference case</td>
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<tr>
<td>SP</td>
<td>Setpoint</td>
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