Implementing Thermal Electric Storage in EnergyPlus through an OpenStudio Measure

Houssem Eddine Younes[1], François Laurencelle[2], Katherine D'Avignon[1]
[1]École de technologie supérieure, Montréal, Canada
[2]Centre de recherche d'Hydro-Québec, Shawinigan, Canada

Abstract

Building decarbonization requires intelligent deployment of electrical-source heating. Central electric thermal storage (cETS) devices can assist this effort while ensuring electric grid capacity is respected. This paper describes a novel use of OpenStudio's scripting facility - Measures - to implement a cETS device in an EnergyPlus simulation. The proposed Measure implements a data-driven regression model capable of representing a cETS units' heat losses and simultaneous charge/discharge capabilities. The Measure allows the device to be controlled for either load levelling or peak shifting. Punctual peak events, when building power demand must be further minimized or completely erased, can also be included through a schedule for demand response simulations. In order to demonstrate the functionalities of the control options provided, a case study is carried out using a readily available archetype model of a Quebec primary school and performance data gathered from experimental tests on the Steffes ThermElect Hydronic unit (model 9180). Results indicate that the structure of the proposed Measure is an effective method to model cETS devices, provided their performance characteristics have been documented. A preliminary version of this Measure has been made publicly available for use to all industry professionals at [21].

Introduction

As the global urgency to combat climate change continues to escalate, regions worldwide are actively seeking innovative strategies to cut greenhouse gas emissions and foster sustainable development. Many jurisdictions seek to reduce building emissions by shifting the heating needs of buildings away from the use of fossil fuels [1, 2, 3] through the use of electric heating alternatives such as heat pumps and electric boilers. However, such widespread electrification can lead to an increased demand for electricity during winter peaks, posing new challenges for electrical grids. Central electric thermal storage (cETS) systems have been successfully used for decades as a demand-side management strategy [4], to break the simultaneity of thermal needs and electric power demand [5] and reduce building electricity bills by leveraging dynamic electricity pricing options [6, 7]. cETS units come in both hydronic or forced-air versions and can be connected to either a hot water heating loop or a ventilation system, respectively. During off-peak hours, the cETS unit draws power from the grid, converts it into heat, which it stores in a thermal storage medium such as magnesite or ceramic bricks [8]. During peak hours, the cETS unit is discharged to meet heating loads and ensure comfort, without impacting the building's electric demand.

A major challenge preventing a wider adoption of thermal energy storage systems has been the limited information available to heating, ventilation and air-conditioning (HVAC) system designers and building operators about effective operation and control strategies that ensure the cost-effectiveness of the technology [9]. An analysis of several school buildings in Quebec using hydronic cETS units [10] revealed that building operators, even after a few years of operation, still lack the necessary data and tools to fully leverage the technology's potential. Designers interviewed pointed out that the absence of numerical models of cETS units limited their ability to test potential control sequences at the design stage. Instead, building operators selected trigger parameters, such as peak power demand limits or storage setpoint temperature, based on trial and error. This resulted in instances of insufficient discharge capacity or excessive heat losses, particularly during shoulder seasons and periods of prolonged inoccupancy. The study emphasized the necessity of providing designers with performance data and numerical models which could be used with whole building energy simulation to develop control strategies at the design stage.

Several numerical models of ETS units have been developed in the past for both forced-air [11, 12, 13, 22] and hydronic units [17, 24, 25]. Most models are physics-based, albeit using simplified representations of the thermal behavior of ETS, such as one-dimensional lumped capacitance models or exponential models with a single time constant, which capture the charging and discharging dynamics of ETS systems [8, 11, 12, 13, 24]. Some have explored the use of data-driven models such as regression-based models [17] or neural networks [22, 23]. Most would require complex adjustments to be implemented into the

building energy simulation programs most commonly used by industry professionals, as they rely on specialized software [7, 12] or training from large sets of operational data [22, 23]. The more easily accessible are TRNSYS types [11, 25] that do not include built-in device control strategies, leaving users to develop and implement their strategies separately.

To address these limitations, this paper proposes a control-oriented cETS model, using the EnergyPlus whole building simulation engine and the OpenStudio interface. EnergyPlus was chosen because of its modular structure, allowing the integration of user-defined models and performance maps, in addition to being open source, cross-platform and widely used in industry. OpenStudio was selected because it provides a graphical interface for users allowing them to more easily interact with the model in addition to having an online library of Measures (Building Component Library) allowing regular updates. Other alternatives that allow the creation of user-defined scripts, such as the Python EnergyPlus application programming interface (API), were tested as part of the model integration process. As their use would require a certain level of programming by the HVAC industry professionals who we hope will eventually use this model, they were not retained as the final mechanism through which the model should be disseminated to potential users.

The cETS model structure proposed uses regressions derived from experimental performance data to characterise the unit's thermal capacity (i.e. the maximum thermal output deliverable) $\dot{Q}_{max}$ and heat losses $\dot{Q}^t_{loss}$. The current version (v1.0.0) of the model implements performance data from the Steffes ThermElect hydronic unit (9180) [15], however, its structure can be easily customized to accommodate other brands of cETS units once their performance characteristics are documented. Model equations, control strategies as well as input-output variables are presented. Finally, the convenience of the cETS model is demonstrated through a test case using a primary school archetype building.

cETS model description

To implement the cETS model in EnergyPlus, a new user-defined object was created based on the PlantComponent:Userdefined (PCUD) object provided by the EnergyPlus library. This object was introduced in EnergyPlus version 7.1 to allow the creation of an equation-based central plant equipment without having to define a new module through modification and recompilation of the source code [16]. The PCUD object uses the Energy Management System (EMS) feature and the EnergyPlus Runtime Language (ErL) to define the component's inputs, outputs, the cETS model physical equations and connections to the plant loops as depicted in Figure 1.

The PCUD object consists primarily of two EMS programs: one to initialize plant equipment, and one to simulate thermal and electrical behaviour of the cETS system beyond EnergyPlus's warmup period. The former program includes the Erl scripts used to set values for the component size, control parameters and model constants. The latter program holds the main equations to calculate the cETS system's state of charge *SOC*, thermal output $\dot{Q}_{heat}$, heat losses $\dot{Q}_{loss}$, electric consumption $P_{electric}$, and control strategies.

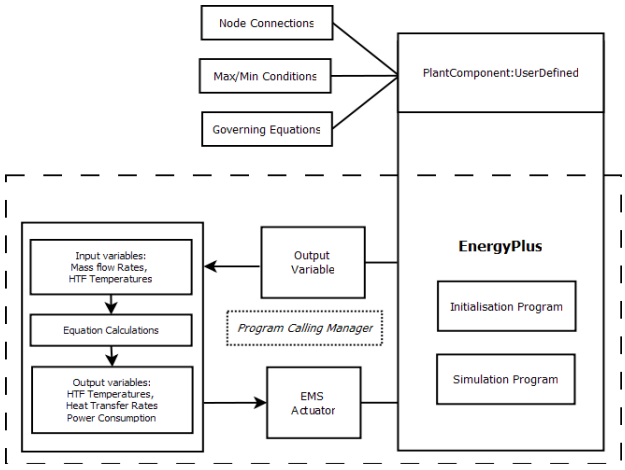

Figure 1: User-defined plant component operation in EnergyPlus, from [16]

Model energy balance

A forward finite difference model was implemented in the EMS program to simulate the charging and discharging of the cETS system. The model assumes one-dimensional heat transfer with one control volume (one node) representing all of the cETS's brick core. During operation, the cETS system average brick core temperature $\bar{T}_b$ is governed by the energy balance formulated in Equation (1), where M and C_p represent the total mass and specific heat of the brick core.

$$M \cdot C_p \cdot \frac{d\bar{T}_b}{dt} = P^t_{electric} - \dot{Q}^t_{heat} - \dot{Q}^t_{loss} \quad (1)$$

Equation (1) has been introduced in the EMS program in its explicit form so that the $\bar{T}_b$ is updated at the end of each simulation timestep t based on the electric input $P^t_{electric}$, heat output $\dot{Q}^t_{heat}$ and heat losses $\dot{Q}^t_{loss}$ calculated at the current timestep, as expressed in Equation (2).

$$\bar{T}^{t+1}_b = \bar{T}^t_b + \frac{t}{M \cdot C_p}(P^t_{electric} - \dot{Q}^t_{heat} - \dot{Q}^t_{loss}) \quad (2)$$

Timestep considerations

During simulation, EnergyPlus uses two different types of timesteps to ensure stability of zone air temperatures. The first is referred to as the "Zone time step", which is the default value defined by the user and used to update the contribution of surfaces and internal loads to the zone loads. The second timestep, called the "System time step" t_{sys}, is used to update the contributions of HVAC systems to the zone loads and ranges from one minute up to the zone time

step. Depending on zone air temperatures, EnergyPlus makes the decision to recalculate the overall model at t_{sys} until convergence checks are passed for all zones. As an HVAC component, the cETS model equations are also recalculated at the system time step t_{sys} until convergence is met, so $t = t_{sys}$ in all model equations. Several cETS model runs were executed to ensure model stability across a wide range of zone time steps (1 to 60 minutes). It was judged that the use of an explicit scheme, rather than implicit, was sufficiently stable given its relative simplicity, computational efficiency as well as the limitations imposed by the EnergyPlus runtime language [18].

Thermal output and heat losses

Thermal capacity (i.e. maximum thermal output deliverable) $\dot{Q}^t_{max}$ and heat losses $\dot{Q}^t_{loss}$ of the cETS unit are assumed to be primarily functions of the *SOC*, which could be reasonably well approximated by $\bar{T}_b$ as in [12]. $\dot{Q}^t_{max}$ is calculated through Equation (3) where ΔT_{max} is the maximum possible temperature elevation induced in the heat transfer fluid (HTF) passing through the unit. Inlet fluid properties ρ_f and $C_{p,f}$ as well as HTF volume flow rate $\dot{V}$ are calculated by EnergyPlus at each t_{sys} and retrieved through internal EMS variables. ΔT_{max} is determined through a polynomial of the form of Equation (4), based on $\bar{T}_b$ for the current timestep t. Coefficients a, b and c have presently been fixed based on the studied cETS unit; they could become inputs in future model versions, as performance data from other cETS units become available.

$$\dot{Q}^t_{max}, = \left(\rho_f \dot{V} C_{p,f}\right) * \Delta T_{max} \quad (3)$$

$$\Delta T_{max} = a \cdot (\bar{T}^t_b)^2 + b \cdot \bar{T}^t_b + c \quad (4)$$

At a given t_{sys}, the actual thermal output of the cETS system $\dot{Q}^t_{heat}$ is determined as the minimum between the load requested from the cETS by the central plant loop manager $\dot{Q}^t_{demand}$ and the unit's available thermal capacity $\dot{Q}^t_{max}$, modulated by a user defined discharging authorization schedule. During runtime, the schedule values are mapped to a discharging authorization variable $Auth^t_{DIS}$, using an EMS sensor object. The value of the $Auth^t_{DIS}$ variable at each t_{sys} can be described through Equation (5) where $t_{DIS,s}$ and $t_{DIS,e}$ are the discharging start and end times, respectively.

$$Auth^t_{DIS} = \begin{cases} 1 \ if \quad t \in [t_{DIS,s}, t_{DIS,e}] \\ 0 \ else \end{cases} \quad (5)$$

The 9180 unit forces $Auth^t_{DIS}$ to 0 once a threshold brick temperature T_{min} is attained. This function was included in the model to avoid $\bar{T}^t_b$ getting too low. The actual heat delivered by the cETS system $\dot{Q}^t_{heat}$ is then obtained by Equation (6).

$$\dot{Q}^t_{heat} = Auth^t_{DIS} * min[\dot{Q}^t_{max}, \dot{Q}^t_{demand}] \quad (6)$$

The outlet HTF temperature $\bar{T}^t_{HTF,outlet}$ is calculated through Equation (7) and reported by the model using an EMS actuator.

$$\bar{T}^t_{HTF,outlet} = \bar{T}^t_{HTF,inlet} + \dot{Q}^t_{heat}/\left(\rho_f \dot{V} C_{p,f}\right) \quad (7)$$

The cETS inlet HTF temperature $\bar{T}^t_{HTF,inlet}$ is calculated by EnergyPlus at each timestep t and retrieved by the cETS model through an EMS internal variable. Finally, when the cETS is not asked to provide heat, $\bar{T}^t_{HTF,outlet}$ is set equal to $\bar{T}^t_{HTF,inlet}$ and the overall volume flow rate passing through the cETS unit is forced to zero.

Heat losses

Thermal losses $\dot{Q}^t_{loss}$ are calculate through Equation (8), as a function of $\bar{T}^t_b$, effective heat loss coefficient UA_{eff} and the ambient temperature T^t_{amb} of the thermal zone in which the cETS system is located.

$$\dot{Q}^t_{loss} = UA_{eff} * (\bar{T}^t_b - T^t_{amb}) \quad (8)$$

Electric consumption and control strategies

The electrical input $P^t_{electric}$ from Equation (1) is calculated at each timestep t and is the result of the control strategy and model parameters chosen by the user. The two storage strategies supported by the model are load levelling and peak shifting. They can also be combined, with both strategies applied concurrently to the same cETS unit.

In the peak shifting strategy, the cETS system charges according to a user-specified charging authorization schedule containing values of either 0 or 1. During runtime, the schedule values are mapped to a charging authorization variable $Auth^t_{CH}$, using an EMS sensor object. The value of $Auth^t_{CH}$ are fixed through Equation (9), with $t_{CH,s}$ and $t_{CH,e}$ respectively the charging start and end times.

$$Auth^t_{CH} = \begin{cases} 1 \ if \quad t \in [t_{CH,s}, t_{CH,e}] \\ 0 \ else \end{cases} \quad (9)$$

Under the load levelling strategy, the electric consumption of the cETS system is modulated by a load levelling control signal λ^t_1, to maintain the building total electric demand $P^t_{building}$ under a user-specified threshold P^t_{max}. λ^t_1 is calculated thorugh Equation (10), while P^t_{max} is defined by a schedule, enabling the user to specify different values on a monthly, daily and timestep basis. $P_{nominal}$ is the cETS unit's electric consumption when all its heating elements are activated simultaneously. Available power to charge the cETS is determined by the difference $P^t_{max} - P^t_{building}$.

$$\lambda^t_1 = min\left[1, \frac{max(0, P^t_{max} - P^t_{building})}{P_{nominal}}\right] \quad (10)$$

Regardless of the operating strategy used, the electric consumption of the cETS system is modulated according to how close the brick setpoint temperature is to the desired

setpoint. The setpoint brick temperature T_{sp}^{t} is calculated at each timestep *t* as a function of the instantaneous outdoor air temperature T_{OA} as shown in Figure 2.

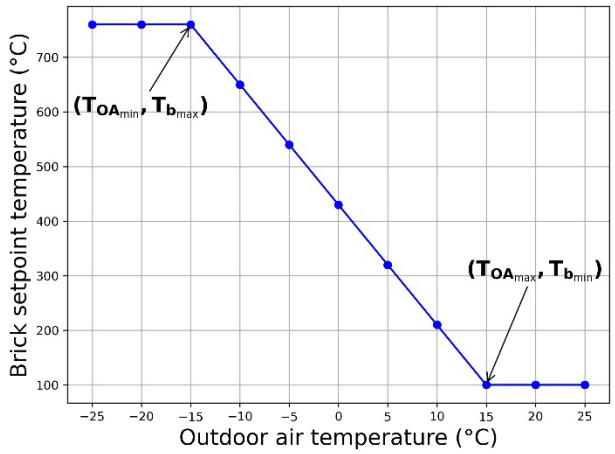

Figure 2: Example of T_{SP} as a function of T_{OA}

Parameters $T_{OA,min}$ and $T_{OA,max}$ represent the minimum and maximum outdoor air temperatures used to determine the maximum and the minimum brick setpoint temperatures, $T_{b,max}$ and $T_{b,min}$ respectively. Between $T_{OA,min}$ and $T_{OA,max}$, the setpoint temperature is determined from a linear relationship and expressed by a combination of Equations (11), (12) and (13).

$$T_{sp} = \begin{Bmatrix} T_{b,max}\ if & T_{OA} \leq T_{OA,min} \\ T_{b,min}\ if & T_{OA} \geq T_{OA,max} \\ a * T_{OA} + b & else \end{Bmatrix} \quad (11)$$

$$a = \frac{T_{b,max} - T_{b,min}}{T_{OA,min} - T_{OA,max}} \quad (12)$$

$$b = T_{b,max} - \frac{T_{b,max} - T_{b,min}}{T_{OA,min} - T_{OA,max}} * T_{OA,min} \quad (13)$$

At each timestep *t*, a brick setpoint temperature control signal λ_2^t is calculated using a proportional control relationship represented by Equation (14) where k_p is the controller's proportional gain and u_b is the controller's offset.

$$\lambda_2^t = min\left[1, max(0, k_p \cdot (T_{sp}^t - \bar{T}_b^t) + u_b\right] \quad (14)$$

Coefficient k_p determines how fast the cETS charging system reaches the desired setpoint temperature, while u_b was added to maintain the setpoint temperature by preventing large decreases in brick core temperature that occur due to heat losses. Although some cETS units do not feature a proportional controller, it was added to the model to ensure simulated charging behaviour and short cycling of heating elements resembled those occurring in real settings even with the larger simulation timesteps.

Combining all control signals, the resulting electric power consumption $P_{electric}^t$ is calculated with Equation (15).

$$P_{electric}^t = Auth_{CH}^t \cdot min(\lambda_1^t, \lambda_2^t) \cdot P_{\text{nominal}} \quad (15)$$

The parameters activated in Equation (15) will depend on the strategy utilized. Under a purely peak shifting strategy, the cETS system will charge only when authorized by $Auth_{CH}^t$, but no limit will be placed on its peak power (λ_1^t is always equal to 1). Under load levelling, the magnitude of the charging power will depend on how much power is available for charging (λ_1^t is active) but no specific charging schedule is implemented ($Auth_{CH}^t$ is always equal to 1). In the case both load levelling and peak shifting strategies are applied concurrently, the cETS unit will charge according both $Auth_{CH}^t$ and λ_1^t.

Implementing cETS model as an OpenStudio Measure

To facilitate use and dissemination of the cETS model, we leveraged the OpenStudio (OS) interface by packaging the EMS code as a Measure. OS Measures consist of programs written in the Ruby language, that can access and leverage the OS model and application programming interface (API) to create or make changes to a building energy model. Some use cases for OS Measures include the automatic creation of prototype buildings, adding energy conservation measures and automating model alterations to building envelope, schedules, central plant equipment, etc. [19]. In the context of cETS modelling, the Measure automates the insertion of the ErL code to the baseline EnergyPlus model through a graphical interface, where the user can specify initial conditions and control parameters of the cETS system.

The Measure inputs include the following:

[Name]: This input field defines a unique user-assigned name for an instance of the cETS unit. Any reference to this component by another object will use this name. A maximum of 40 characters can be used as the name of a particular cETS system.

[Plant Loop]: Hot water loop where the cETS will be added.

[Existing equipment]: This input is used when another central heating equipment already exists on the [Plant loop] specified by the user. It determines the equipment that the cETS system will operate with, to meet the plant heating demand. The model currently allows for the operation of cETS system with electric or fossil fuel boilers.

[Location]: This input specifies the location of the cETS system relative to the equipment selected in the [Existing equipment] input. The options available are *Parallel*, *Upstream* or *Downstream*. The *Parallel* option is suitable when the plant loop's load distribution scheme is uniform, meaning that the heating load is divided evenly between the central equipment. The *Upstream* and *Downstream* options are used to establish the priority of the cETS system when connected in series with another equipment. The series configuration is used with a sequential load distribution scheme.

[Charging schedule]: Schedule used to authorize the charging process of the cETS system ($Auth_{CH}^t$).

[Discharging schedule]: Schedule used to authorize the discharging process of the cETS system ($Auth^t_{DIS}$).

[Pead demand schedule]: Schedule that sets the peak electric demand authorized for the building (P^t_{max}).

[Initial brick temperature]: Defines the initial brick temperature.

[Maximum target brick temperature]: Defines $T_{b,max}$. Default value is 760°C.

[Minimum outdoor air temperature]: Defines $T_{OA,min}$ corresponding to $T_{b,max}$. Default value is -15°C.

[Minimum target brick temperature]: Defines $T_{b,min}$. Default value is 100°C.

[Maximum outdoor air temperature]: Defines $T_{OA,max}$ corresponding to $T_{b,min}$. Default value is 15°C.

[Mass flow rate]: Defines maximum mass flow rate passing through the ETS system. Default value is 1.86 kg/s.

[Ambient zone name]: Defines the thermal zone where the cETS system will be located. This input is used to identify T^t_{amb} for $\dot{Q}_{loss}$ and its impact on zone air temperature.

Priorities

The Measure allows for the cETS to be rapidly integrated to an existing plant loop, letting the sequential load distribution scheme define how the storage complements other central equipment such as boilers. Given that plant operation schemes are not accessible through the OpenStudio GUI, users may choose to alter the default sequential load distribution scheme logic by modifying equipment ranks in the plant operation scheme object within the EnergyPlus text input data file (IDF) (see the 'Simulated Case' section).

cETS unit performance characteristics

Current performance data used in the cETS model is documented in Table 1 along with the source of the values. The cETS unit considered is the Steffes ThermElect Hydronic unit, model 9180. Parameters *a*, *b*, *c* and UA_{eff} stem from experimental and operational data collected from units installed at the Laboratoire des technologies de l'énergie of Hydro-Québec.

Table 1: ETS unit performance characteristics used in v1.0.0

Parameter	Value	Reference
a	$-1.05 \cdot 10^{-5}$	
b	$2.32 \cdot 10^{-2}$	
c	-0.188	
C_p	0.92 kJ/kg·°C	[17]
M	2350 kg	[15]
$P_{nominal}$	80 kW	[15]
T_{min}	93°C	[15]
UA_{eff}	4,5 W/K	

Simulated case

To demonstrate the use of the cETS Measure, two test cases are presented using conventional operating strategies: Peak shifting and load levelling. The cETS model used for demonstration has a maximum heating capacity of 80 kW and 440 kWh of energy storage capacity, representative of Steffes's 9180 model [15].

A prototype building representing a primary school in Quebec based on the work done by [20] was used. The building has two floors and a footprint area of 1000 m^2. It contains 10 classrooms, an office, a gymnasium, a cafeteria, two bathrooms, one mechanical room and two corridors for a total floor area of 1640 m^2. Construction materials used in [20] were chosen to reflect buildings built in Quebec between 1945-1965. These include external and internal walls with U-values of 0.811 W/m^2·K and 2.511 W/m^{2}K, respectively. The building has a window-to-wall ratio of 41% with a glazing U-value of 3.52 W/m^2·K. The lighting power density is set to 14.35 W/m^2 for each classroom and 8 W/m^2 for other spaces. The equipment's power density is set to 11 W/m^2. This baseline building has a hot water loop with a central electric boiler with 156 kW nominal capacity, heating water to 85°C, which is circulated by a constant speed pump with a rated mass flow rate of 3.45 kg/s towards hydronic radiators providing space heating to each zone. The building does not have a centralized ventilation system, however two outdoor air units, used for the gymnasium and cafeteria zones are used to extract and supply warm air using an electric heating coil.

In Case 1, the peak shifting strategy, the cETS is used to shift the electric consumption associated with heating from peak periods to off peak periods. The cETS charges between 8 PM and 6 AM and discharges from 6 AM to 10 AM and 4 PM to 8 PM. A separate EMS program based on the PlantEquipmentOperation:UserDefined object was added in the IDF file to redefine the priorities of heating equipment based on peak and off-peak schedules. Priority is given to the boiler during off-peak periods to allow sufficient charging of the cETS unit. During peak times, priority is transferred to the cETS unit, allowing it to provide heating from the energy already stored, while the boiler acts as an auxiliary to meet any demand exceeding the cETS unit's maximum capacity.

In Case 2, the load levelling strategy, the cETS unit is charged and discharged throughout the day without a specific schedule ($Auth^t_{CH}$= $Auth^t_{DIS}$=1) so the boiler always has priority. The cETS unit modulates its electric consumption so that the total building demand remains under a limit of 130 kW through P^t_{max}. In this case, the electric boiler nominal capacity is manually reduced to 50 kW as the auto-size feature is unusable due to the cETS model being integrated through EMS code rather than in the EnergyPlus source code as a new module.

In both operating strategies, the plant loop's design temperature difference is 11°C and the hot water setpoint temperature is set to 82°C. Furthermore, the load distribution scheme in both strategies is to set "Sequential Load", which allows the EnergyPlus plant loop manager to sequentially load the central plant equipment to their available capacities according to their priority, until the heating demand is fully met. Finally, the simulation zone time step was set to 10 minutes.

Results and discussion

Figure 3 shows simulation results under Case 1 (peak shifting).

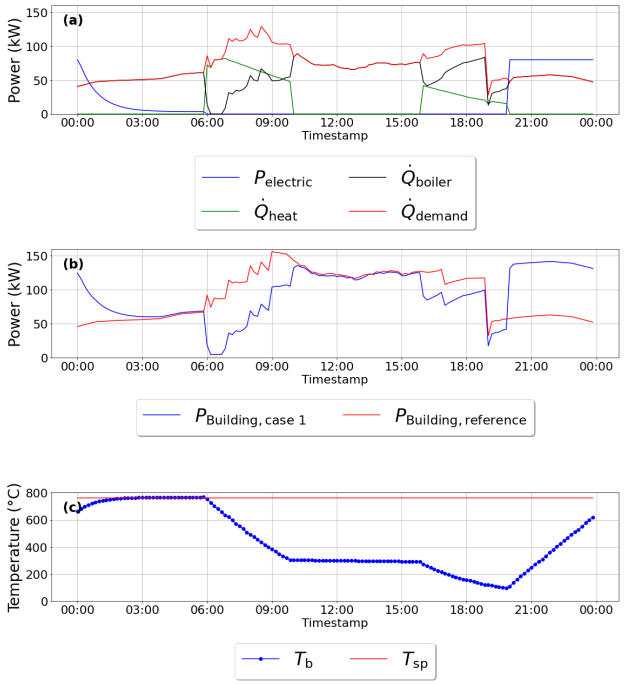

Figure 3: Modelling results for Case 1 (peak shifting)

Prior to 6 AM, the electric boiler operates to meet the building's heating demand and the cETS system is gradually charged (Figure 3a) while it's allowed by $Auth_{CH}^{t}$ and until T_{sp} is reached (Figure 3c). Between 6 and 10 AM, the cETS has priority to meet the heating demand and the boiler becomes an auxiliary. Figure 3a shows that the cETS can provide 80 kW of heating at the start of the peak period. The boiler is completely shut-off at the start of the peak period (i.e. $\dot{Q}_{boiler} = 0$) which reduces $P_{building}$ compared to the reference case (Figure 3b). As the ETS is discharged, $\bar{T}_b$ decreases (Figure 3c), and the heating demand $\dot{Q}_{demand}$ cannot be met by the cETS only, the boiler is therefore activated to fill the rest of the demand.

Between 10 AM and 4 PM, the cETS is neither charging nor discharging and priority is given to the electric boiler. During this time, $\bar{T}_b$ primarily decreases due to heating losses (Figure 3c). Between 4 and 8 PM, priority is once again given to the cETS, however having depleted most of its stored energy, the cETS is not able to meet the load alone, and the boiler is activated throughout most of the peak period.

In this test case, two 80 kW ETS units should have been considered to completely offset the boiler electricity use and shift the entire demand during peak periods. Similarly, $Auth_{CH}^{t}$ and $Auth_{DIS}^{t}$ should be optimized to realize the full potential of the strategy. This demonstrates the usefulness of the cETS model to adequately select unit sizing and cETS operating strategy, at the design stage. Facilitating the change of heating equipment priorities as a function of peak and off-peak times will be important for any peak shifting strategy, whether through thermal storage or otherwise. In future work, the EMS program could be included as a separate Measure to allow more configurations to be tested by users.

Figure 4 shows simulation results under Case 2, the load levelling case. Prior to 6 AM, the cETS's electric consumption is limited due to the small drift between the $\bar{T}_b$ and T_{sp} (Figure 4c), mostly caused by heat losses and the minimal heating contribution from the cETS, since $\dot{Q}_{demand}$ is largely met by the boiler (Figure 4a).

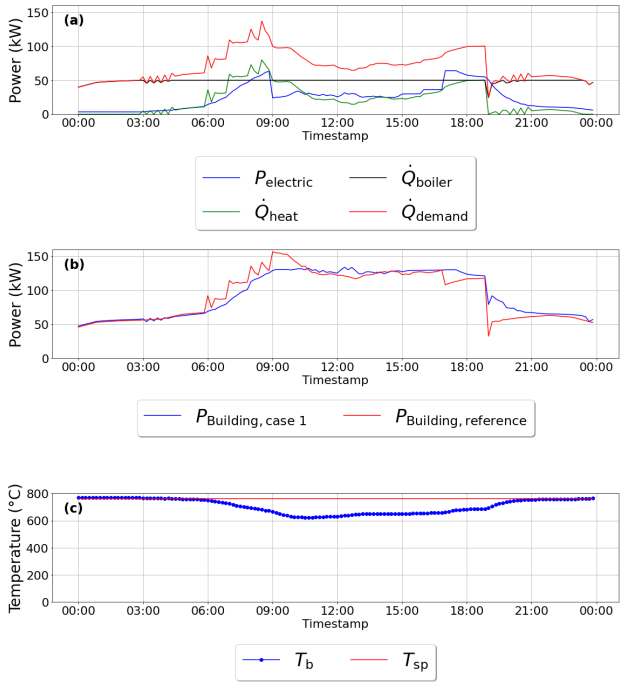

Figure 4: Modelling results for Case 2 (load levelling)

Starting at 6 AM, as $\dot{Q}_{demand}$ increases beyond the boiler's capacity and with both $Auth_{CH}^{t}$ and $Auth_{DIS}^{t}$ always active, the cETS is gradually discharged while being charged to compensate for the decrease in its stored energy. As $P_{building}$ reaches its peak around 9 AM (Figure 4b), the cETS's electric consumption is shaved to maintain the overall demand at the 130 kW threshold. This results in a 26 kW electric power reduction during the peak period, and a relatively flat electric profile between 6 AM and 19 PM

compared to the reference case. At the end of the building's occupancy period, the cETS takes advantage of the available electric power to recharge, which results in an increase of $P_{building}$ compared to the reference case (Figure 4b). While this example shows the possibility of peak power savings, it illustrates how much the performance of the load levelling strategy depends on the choice of P_{max}^{t} and the necessity for thorough investigation of operating strategies at the design stage. As P_{max}^{t} can be adjusted on a monthly, daily or timestep basis, this further demonstrates the pertinence of the proposed Measure, allowing the additional tests needed to determine the optimal levels at which the building electric demand can be levelled without impacting thermal comfort.

Table 2 presents a summary of the peak day results for all simulated cases. Compared to the reference case, the building energy consumption $E_{building}$ from Cases 1 and 2 was slightly higher (~1%), given the additional electric consumption $E_{electric}$ by the cETS unit due to heat losses. Unlike a boiler, the cETS unit incurs heating losses which, even during periods of low heating demand, must be compensated by the charging process making $E_{electric}$ greater than Q_{heat}. Careful selection of control parameters is therefore needed for a balanced operation, ensuring reliability of the cETS unit while reducing inefficiencies. In both test cases however, the excess energy consumption of the ETS unit is reasonable and serves to guarantee sufficient discharging power with minimal heat losses. The ETS heating energy losses Q_{loss} were between 10 and 13 % of the energy consumed for Cases 1 and 2 respectively. The lower efficiency in Case 2 can be explained by the activation of $Auth_{CH}^{t}$ throughout the day, leading to relatively higher losses particularly when the building is unoccupied.

Table 2: Case study summary results

	Ref. Case	Case 1	Case 2
$E_{building}$ [kWh]	2224	2250	2255
$P_{building}$ [kW]	156	141	130
Peak time	9:00 AM	9:40 PM	12:20 PM
Q_{demand} [kWh]	1726	1717	1688
Q_{heat} [kWh]	N/A	376	507
Q_{boiler} [kWh]	1726	1341	1178
$E_{electric}$ [kWh]	N/A	415	578
Q_{loss} [kWh]	N/A	45	73

The heating energy required by building loads Q_{demand} was equal to the sum of contributions of the cETS unit Q_{heat} and the boiler Q_{boiler}. However, in both cases Q_{demand} was slightly reduced compared to the reference case, which may be attributed to Q_{loss} contributing partially to the building's internal heat gains.

Finally, the peak demand $P_{building}$ was successfully shifted in Case 1 from 9 AM to 9:40 PM and reduced to 141 kW (a 10% reduction). This reduction is a byproduct of the chosen charging schedule and control parameters, as it is not the primary purpose of the peak shifting strategy. In Case 2, $P_{building}$ remained relatively flat at 130 kW throughout the peak period yielding a 15% reduction relative to the reference case.

Conclusion

This paper presented a novel approach to modelling and implementing central Electric Thermal Storage (cETS) systems using an OpenStudio Measure and the EnergyPlus platform. The Measure allows for the selection of different control strategies (peak shifting, load levelling, scheduled demand response events) and various operating scenarios (boiler and cETS system priorities). A preliminary version of the Measure [21] has been made publicly available : https://zenodo.org/records/10215082.

To demonstrate the functionalities of the control options provided, a simulation case study was carried out using a readily available primary school archetype model. Case results led to both a shift and reduction of peak building demand with only a minimal increase in building energy use. Results highlighted how valuable such a model is to adequately size thermal storage devices, select operating strategy and trigger parameters such as P_{max}^{t} or T_{sp}, at the design stage.

Preliminary results from simulation cases presented in this paper indicate that the structure of the proposed Measure is a promising method to model cETS devices. It should be modified to include the performance map of other of cETS such central forced-air units and units of different capacity, provided their performance characteristics have been documented.

Issues hindering the use of thermal storage devices and demand-management strategies (DMS) in both OpenStudio and EnergyPlus were highlighted. Using an OS Measure to implement the cETS model prohibits using the auto-size feature. Defining priorities of heating equipment based on peak and off-peak schedules, a requirement of many DMS, should also be facilitated. Further research is needed to facilitate the simulation of thermal storage devices by industry professionals during HVAC system design so that operating strategies may be optimized to mitigate peak electricity demand while maintaining building comfort and achieving decarbonization targets.

Acknowledgement

The authors would like to acknowledge the financial support provided by Mitacs through the Mitacs Accelerate program and Mitacs Globalink Fellowship program.

References

1. Gouvernement du Québec, Plan pour une économie verte 2030: Politique-cadre d'électrification et de lutte

contre les changements climatiques. 2020: Bibliothèque et Archives nationales du Québec.

2. Ministry of Economic Affairs and Employment, Finland's Integrated Energy and Climate Plan, in Publications of the Ministry of Economic Affairs and Employment. 2019, Ministry of Economic Affairs and Employment: Helsinki.
3. Patronen, J., E. Kaura, and C. Torvestad, Nordic heating and cooling: Nordic approach to EU's Heating and Cooling Strategy. TemaNord. 2017, Copenhagen: Nordisk Ministerråd. 110.
4. Molina-Garcia, Á., et al., A Physically based Load Model of Residential Electric Thermal Storage: Application to LM Programs. International Journal of Power and Energy Systems, 2004. 24.
5. Xu, G., et al. Experimental and Numerical Study of an Electrical Thermal Storage Device for Space Heating. Energies, 2018. 10.3390/en11092180.
6. Syed, A.M., Electric Thermal Storage Option for Nova Scotia Power Customers: A Case Study of a Typical Electrically Heated Nova Scotia House. Energy Engineering, 2011. 108(6): p. 69-79.
7. Moffet, M.A., et al. Central electric thermal storage (ETS) heating systems: Impact on customer and distribution system. in PES T&D 2012. 2012.
8. Cooke, W.B.H., R.H.S. Hardy, and M.T. Sulatisky, Thermal Energy Storage in Forced-Air Electric Furnaces. IEEE Transactions on Industry Applications, 1980. IA-16(1): p. 127-133.
9. Ihm, P., M. Krarti, and G.P. Henze, Development of a thermal energy storage model for EnergyPlus. Energy and Buildings, 2004. 36(8): p. 807-814.
10. D'Avignon, K., Stockage thermique et exemplarité de l'État: Résultats de l'étude, constats et recommandations. 2022, École de technologie supérieure. p. 91.
11. Bedouani, B.Y., et al., Central electric thermal storage (ETS) feasibility for residential applications: Part 1. Numerical and experimental study. International Journal of Energy Research, 2001. 25(1): p. 53-72.
12. Date, J., et al., Development of reduced order thermal dynamic models for building load flexibility of an electrically-heated high temperature thermal storage device. Science and Technology for the Built Environment, 2020. 26(7): p. 956-974.
13. Janssen, N.T., R.A. Peterson, and R.W. Wies, Generalized Heat Flow Model of a Forced Air Electric Thermal Storage Heater Core. Journal of Thermal Science and Engineering Applications, 2017. 9(4).
14. Li, Y., et al., Grey-box modeling and application for building energy simulations - A critical review. Renewable and Sustainable Energy Reviews, 2021. 146: p. 111174.
15. Steffes Corporation, ThermElect Hydronic - Owner's and Installer's Manual. 2021.
16. T.Jones, A. and D. P.Finn, Ground Source Heat Pump Modelling With Thermal Storage - Simulation and Integration Issues in EnergyPlus, in International Building Performance Simulation Association. 2013: Chambéry, France.
17. Moreau, A., Intégration du stockage thermique dans les réseaux autonomes : modélisation d'un appareil de chauffage central avec accumulation thermique. 2015, IREQ.
18. Ellis, P., P. Torcellini, and D. Crawley, Simulation of Energy Management Systems in EnergyPlus. 2007. 1346-1353.
19. Roth, A., D. Goldwasser, and A. Parker, There's a measure for that! Energy and Buildings, 2016. 117: p. 321-331.
20. Vanroy, K., Developing a Prototype Building Energy Model for a Quebec Primary School and Assessing the Importance of Detailed HVAC System Modeling. 2022, Polytechnique Montréal.
21. Younes, H.E., K. D'Avignon, and F. Laurencelle, ltsb-étsmtl/ETS-Openstudio-Measure. 2023, Zenodo. https://doi.org/10.5281/zenodo.10215082
22. Roberge, M. A., Lamarche, L., Kajl, S., and Moreau, A., 1997, "Model of Room Storage Heater and System Identification Using Neural Networks," CLIMA 2000 Conference, Brussels, Belgium, Aug. 30–Sept. 2, Vol. 265, pp. 265–277.
23. Ji H, Yang J, Wang H, Tian K, Okoye MO, Feng J. Electricity Consumption Prediction of Solid Electric Thermal Storage with a Cyber–Physical Approach. Energies. 2019; 12(24):4744.
24. Belzile, P., Kajl, S., Rousse, D., & Dutil, Y. (2012). Electrical thermal storage optimization for demand side management. Innostock 2012.
25. Thermal Energy System Specialists, LLC. (2022). Type 1344 and 1369. TESSLibs 18 – HVAC Library Mathematical Reference. P. 321-326