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Development of a Simulation Testbed for Validating Optimal Thermal Energy Storage Operation Algorithms in Energy-Efficient Buildings

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Abstract

There has been growing attention on energy-efficient buildings with Thermal Energy Storage Systems (TESS), which are designed not only to reduce their energy consumption but also take advantage of time-of-use (TOU) prices to reduce energy costs by efficiently scheduling and shifting loads. This paper proposes two effective modeling solutions to simulate with and validate a specific optimal control algorithm designed to operate the TESS and HVAC systems. The proposed strategies are implemented on two widely used simulation platforms in the HVAC industry, EnergyPlus and Modelica, to represent the TESS and HVAC systems. The in-depth comparative analysis of these simulation platforms is provided highlighting their respective advantages and limitations. Then, the proposed approaches are demonstrated and discussed through case studies.

Introduction

With the increased emphasis on energy-efficient buildings, researchers are proposing various system solutions and control algorithms that not only improve building performance but also take advantage of TOU prices to reduce energy costs. One of the most common ways to do this is to use energy storage solutions that store energy during non-peak periods and then use it later. There is increasing adoption of TESS due to the following benefits. [James et al.2021]

- TESS are generally less expensive than battery electrical storage system (BESS), both in terms of capital and operational costs, for storage systems of the same capacity. [Odukomaiya et al.2021]
- The ability of TESS to provide a more favorable temperature for heat transfer at the outdoor coil of heat pump systems, can effectively support and facilitate the push for electrifying HVAC systems.

To utilize TESS more efficiently, researchers have proposed optimal control algorithms that use predictions of future weather conditions, building loads, and electricity prices to operate the TESS and HVAC system in a manner that minimizes peak energy demand and reduces operational costs. These algorithms generally determine charge/discharge rates and the resulting state of charge (SOC). They then determine the required predefined operating mode (charging, discharging, no action) and relay it to the TESS in the building [Tarragona et al.2021]. When validating the controller, prior studies utilized co-simulation with models to execute the optimal charge/discharge rates and evaluate the controller performance while taking into account other HVAC operation processes. However, these studies often focus on control over the predefined operation modes of HVAC systems rather than directly regulating the charging/discharging rates of the TESS. Furthermore, there is a noticeable gap in the literature that explores the capabilities and limitations of the simulation environments considered here when implementing co-simulation with MPC for the optimal control of TESS and HVAC systems.

To address the gap, this paper proposes two modeling methods to implement TESS simulation models to validate optimal controller. It identifies the merits and disadvantages of two widely used simulation environments (i.e., EnergyPlus and Modelica) and highlights significant requirements for modeling to be coupled with optimal controller. Then, it demonstrates the effectiveness of the proposed approaches and discusses potential areas for further enhancement.

Background

In this section, we begin with a brief overview of existing work related to TESS with a controller. Then, we describe the proposed optimal control algorithm designed for TESS. Lastly, we provide a comprehensive overview of the use of Modelica and EnergyPlus for co-simulation with optimal TESS control.

Existing work

Various studies explored controls for TESS and other energy storage assets in building conditioning. [Drees and Braun1996] studied a simple rule-based control algorithm using an office building simulation model. Similarly, [Kamal et al.2019] used a detailed model in EnergyPlus to study a rule-based controller that switches between operation modes. However, they focused on only controlling the operation modes and not the specific charging/discharging rates of TESS.

For researchers engaged in modeling, simulation, and control of building energy systems, there is also research that presents a compact list of all building energy systems modeling parameters and their significance on the model [Harish and Kumar2016].

As more intelligent methods, model predictive control (MPC) techniques have been applied [Kontes et al.2018, Raman et al.2020] and [Zhu, Cui, and Ni2022] suggested an enhanced mathematical model to improve the control of energy storage systems. [Baniasadi et al.2020] used physics-based prediction models to provide a control signal, and then studied the performance by comparing the control actions against a baseline case. [Beghi et al.2014] used a Simulink model for validating the MPC controller for TESS operation by controlling the outlet temperature.

Overall, researchers used a few different methods to validate their control algorithm. Some of these studies utilized detailed Modelica simulation models to assess HVAC controller performance in simulation-based frameworks, as emphasized in [Blum et al.2021]. Additionally, there are various free [eQuest] and commercial tools [HOMER, TRNSYS] for analyzing TESS that have not been considered here since they do not meet the larger project objectives, which require analysis of the DOE prototype building suite. [Yu et al.2023]

Optimal control algorithm for ice-based TESS

The optimal controller for TESS can be developed to target a specific objective, for example, to minimize the operation costs of energy systems that relate to the charging and discharging operation of TESS. The algorithm uses building thermal and electric loads, as well as weather conditions to determine the optimal charging and discharging rates of the TESS as shown in Figure 1. The controller can incorporate prediction models for the building thermal zones, the HVAC air loop, hot water, and chilled-water loop components, and the TESS with mathematical system equations using references including the EnergyPlus Engineering reference [EnergyPlusEngRef2023] and other past work [Yu et al.2023, Huang et al.2023a, Huang et al.2023b]. TESS can be effectively modeled using a State-Of-Charge (SOC) approach in the optimal controller as follows [Yu et al.2023]:

$$l_{tes}^{t} = l_{tes}^{t-1} + \frac{q_{tes,ch}^{t} - q_{tes,dis}^{t}}{Q_{tes}} \quad (1)$$

$$\underline{L}_{tes} \leq l_{tes}^{t} \leq \bar{L}_{tes} \quad (2)$$

$$0 \leq q_{tes,ch}^{t} \leq \min\left(C_{TESchiller},\ \bar{q}_{tes,ch}(l)\right) \quad (3)$$

$$0 \leq q_{tes,dis}^{t} \leq \min\left(q_{cool},\ \underline{q}_{tes,dis}(l)\right) \quad (4)$$

$$q_{cool} \leq Q_{basechiller}^{t} + q_{tes,dis}^{t} \quad (5)$$

$$P_{chiller}^{t} = f(q_{cool}^{t},\ q_{tes,ch}^{t},\ q_{tes,dis}^{t}) \quad (6)$$

where the dynamics of TESS are incorporated with the state-of-charge (SOC) level (l_{tes}^{t}) and charging/discharging rates ($q_{tes,ch}^{t},\ q_{tes,dis}^{t}$). The SOC level of TESS represents the percentage of the capacity (Q_{tes}). The charging/discharging rates of TESS are constrained by the available chiller capacity ($C_{TESchiller}$), thermal demand (q_{cool}), and thermodynamic limitations ($\bar{q}_{tes,ch}(l),\ \underline{q}_{tes,dis}(l)$) imposed by the mass flow and temperature within the loop. Chiller power consumption ($P_{chiller}^{t}$) is estimated based on the TESS charging/discharging rates in the optimization engine as in (6).

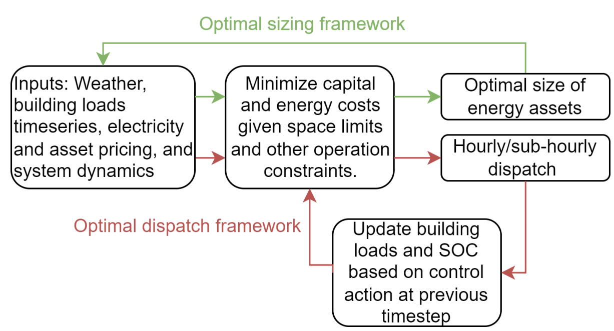


Figure 1: Optimal dispatch algorithm framework [Yu et al.2023]

At each time instant, the controller assumes a receding horizon (e.g., 24 hours). It then calculates a control action for the next timestep after optimizing an objective function and passes it to the system. It then reads measurements from the system again at the next timestep and repeats the optimization process before passing on the control action. The objective function can be energy cost minimization, peak demand reduction, comfort maximization, and more. The optimal controller provides the best solution considering specific objectives as well as the physical limits associated with the energy storage system. More details about the optimal controller can be found in the paper [Yu et al.2023].

Capabilities and limitations in EnergyPlus

EnergyPlus [EnergyPlusGetStart2023] is a building energy simulation engine developed to calculate the heating and cooling load of a building given information about the weather conditions, building geometry, HVAC system design, and operating parameters like various setpoints and internal heat gain. The HVAC systems, in particular, consist of loops of components that are constructed using pre-defined object classes in the tool. These object classes contain the calculations defined to generate the component outlet conditions given the inlet conditions. The operation of all these components is coordinated by subroutines programmed in the source code of EnergyPlus, allowing users to customize system behavior via the Energy Management System (EMS) capability, or the Functional Mockup Interface (FMI) protocol.

The program currently contains 4 different object classes for cold thermal energy storage: simple ice storage, detailed ice storage, simple chilled water storage, and detailed chilled water storage. Each of these objects represents a cold TESS which consists of a tank and a 3-way valve for controlling the outlet water temperature at a user-defined setpoint. The detailed models differ from the simple model in terms of an increased number of input parameters, as well as the calculations used for determining the effective charging and discharging rate based on the chilled water loop temperature measurements.

These objects are typically placed on the supply side of the plant loop, as shown in Figure 2. The charging and discharging operations are controlled by adjusting the outlet temperature setpoints for both the chiller and cold storage objects in the chilled water plant loop. Different combinations of the setpoints result in various operation modes, as summarized in Table 1 for a chilled water loop with an upstream chiller and a downstream cold storage object.

The problem is that these object classes therefore restrict the users' capability to control the charging/discharging rate accurately. The only viable way to do so in an EnergyPlus-only simulation might be to set up a method where we develop a numerical model for the plant loop that maps the relationship between the charging rate and the temperature setpoint for the thermal storage, given other loop conditions. Repeating this process for every new building and ice tank model makes it a significant challenge to implement MPC in practice. In addition to that, using the existing thermal storage objects in EnergyPlus restricts us to these types for all future experiments, and will make it harder to substitute them with other thermal storage types that may have different underlying mechanics.

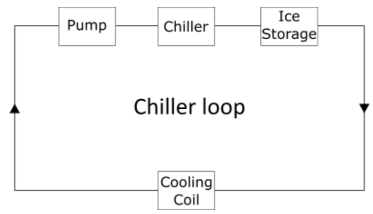


Figure 2: Schematic of a typical chiller loop with cold energy storage in EnergyPlus

Table 1: Chiller and cold storage setpoints for operation mode control in typical cold thermal storage use-cases. ([EnergyPlusInputOutput2023])

Operation Mode	**Chiller Setpoint (°C)**	**Storage Setpoint (°C)**
Charging ice storage tank	-5	7
Cooling with chiller only	7	99
Cooling with chiller & storage (Chiller fully loaded first)	7	7
Cooling with chiller & storage (Partial loads on chiller and cold storage)	10	7

Capabilities and limitations in the Modelica Buildings Library

The Modelica Buildings Library (MBL) [Wetter et al.2013] is an open-source library of energy simulation models for buildings and the HVAC domain, which has been developed using the Modelica modeling language. The Modelica language allows mathematical system equations for components to be programmed in their original algebraic notation, which is then compiled for all the components in a system at runtime and simulated over a time period using libraries of solvers for differential equations in the time domain.

This allows users to program a system of equations consisting of interdependent variables, and then pick one or some of them as input(s) for enforcing boundary condition(s). When the simulation is run, these inputs assume the required boundary value(s) and the remaining dependent variables are automatically determined and solved for. For example, the system of equations governing fan physics can be programmed with variables for the mass flow rate, pressure head, fan speed, and fan power. The same equation set can then be used for multiple fan models that accept an input signal for one of the above variables, and automatically solve for the others over time.

As for the chiller loop, the MBL currently has multiple components for air-cooled and water-cooled chillers, pumps, valves, and cold storage components like ice tanks. The ice tanks specifically use the same design parameters, input signals, and governing equations as EnergyPlus. The programmed variables include an internal variable for effective heat transfer rate and an input signal for the temperature setpoint to be tracked. Due to the nature of the Modelica language, they can be easily reconfigured to accept the effective heat transfer rate directly as an input, and then calculate the remaining system variables from it.

However, the drawback with using the current version of the MBL (at the time of publication) is that it does not have any autosizing calculations akin to EnergyPlus. As a result, manual sizing of all the components in the model becomes necessary, for example, when conducting case studies across multiple scenarios (e.g., different locations), which restricts the practical adoption and widespread applicability of MPC and co-simulation. Apart from that, Modelica calculations are also computationally intensive and sometimes lead to non-convergence of variables during simulation, which potentially obstructs the feasibility of extensive case studies.

Proposed system modeling strategy

This section articulates specific requirements for system modeling to validate optimal dispatch algorithm in a simulation-based framework and proposes modeling strategies to achieve them.

System model requirements

To effectively validate the optimal dispatch algorithm, it is necessary for the model to accept the input charge/discharge rate signal, and then operate the TESS and the building HVAC systems accordingly. To meet our needs, the building energy simulation model should satisfy the following requirements:

1. The simulation model should contain local control loops that directly receive the required charge/discharge rates as input signals. They should then operate the TESS model to achieve it.
2. The simulation model should allow for the scaling of the energy storage capacity and types of TESS (including those that may not currently exist in the considered simulation environments, EnergyPlus and Modelica), thereby enabling system co-design experiments for most common scenarios. The simulation model should also be designed to accommodate multiple TESS instances within both chilled water and hot water loops.
3. The system modeling strategy for the charging loop of the TESS should enable the loop to run at a temperature that is independent of the operating temperatures of the other chilled water/hot water loops in the simulation model. This ensures that the charging loop can operate at the required temperature for any phase change-based TESS.
4. The model should have all necessary control loops for operating the other systems in the building energy simulation model. For instance, the zone temperature should be regulated within the thermal comfort limits, and the other loops in the system model should operate regularly, while interacting with the charging/discharging process of the TESS when required.

In addition to meeting the system-level requirements, the re-usability and wide adoption in the industry of the system model is highly desirable. Thus, it will be beneficial to incorporate EnergyPlus to make use of features like system autosizing.

Proposed strategy

Given the above system-level requirements as well as the capabilities and limitations of the selected simulation environments, we propose the following strategy.

The simulation model is set up to use an EnergyPlus building model for assessing the zone thermal loads and operating the required air loops to meet them and achieve their zone setpoints. The chilled water cooling coils and/or the hot water heating coils are integrated within secondary plant loops, being serviced by two primary plant loops each. One primary loop consists of a base chiller/boiler that meets the building thermal loads, which can be directly modeled in EnergyPlus. The other loop consists of a TESS object (e.g., ice storage tank), as well as a dedicated chiller/boiler for charging and discharging it. This loop may not necessarily exist in the same simulation environment. The thermal energy storage object is modeled to enable precise control over the charge/discharge rate.

Ideal heat exchangers can be used for heat transfers between the primary and secondary loops. For example, when the TESS primary loop is modeled in EnergyPlus, it can consist of the `HeatExchanger:FluidToFluid` object. In this case, the heat transfer from the TESS object will be applied on a `LoadProfile:Plant` object in the same loop.

If the TESS primary loop is modeled in a different simulation environment, the `LoadProfile:Plant` object can be placed directly in parallel with the coils in the secondary loop. The ideal heat exchange from the TESS primary loop to the secondary loop can be achieved through a data transfer during the co-simulation process.

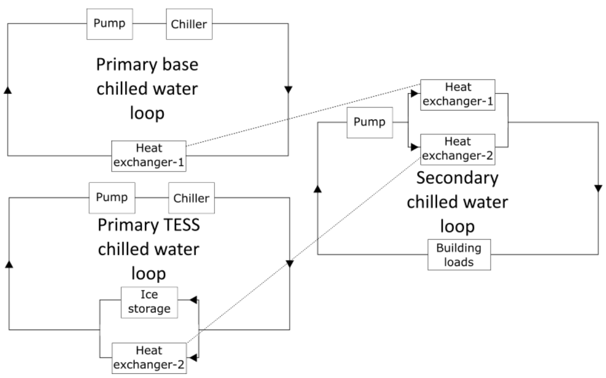


Figure 3: Modeling strategy for meeting system simulation requirements

The base primary loop operates to meet the thermal loads of the building during regular operation (no TESS use) and when the TESS is being charged. During the TESS discharging operation, heat transfer from the TESS to meet thermal loads is prioritized, with the base primary loop operating to meet any remaining loads.

The proposed approach can apply to both heating and cooling operations. This paper specifically focuses on cooling application with ice storage as TESS model. Figure 3 illustrates an example of this strategy applied to a chilled water loop with ice storage.

Method-1: Implementation of TESS in EnergyPlus

This section describes how the proposed modeling strategy can be implemented in a simulation model that uses EnergyPlus to simulate building thermal model, the base primary loop, and the TESS primary loop. The method is specifically described for a building model with two chillers and ice storage as an example.The following modifications are carried out to achieve the system detailed in Figure 3.

1. The primary chilled water loop with two chillers is split into two separate primary loops with one chiller each. While the primary loop with the base chiller stays as it is, the primary loop with the TESS-dedicated chiller adds a plant load profile object, `LoadProfile:Plant` to the demand side. This ideal object is used to impose the heat transfer from the TESS object via co-simulation.
2. An external interface to interact with the load profile object is set up using the `ExternalInterface:Actuator` object, which uses the `Power` control type available on it. Aside from that, multiple measurement interfaces are set up using the `EnergyManagementSystem:Sensor` class at various points within the primary and secondary chilled water loops. These are used to operate the EMS programs below.
3. EMS programs are implemented within the EnergyPlus model to manage the TESS chiller loop operations, by switching between 3 modes of operation when specific conditions are met, as shown in Figure 4. Setting the mode determines the operating status of the TESS chilled water loop components according to Table 2.

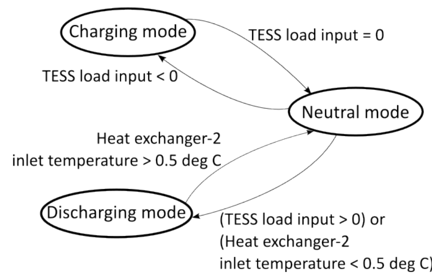


Figure 4: State machine chart for logic implemented in EMS

Aside from enabling the components according to Table 2, EMS programs are also written to determine the dispatch from the TESS chiller. The dispatch level is calculated based on the measured supply temperature of the TESS chiller and the required setpoint using Algorithm 1. Note that in EnergyPlus, a negative number indicates dispatch from the chiller object.

In Algorithm 1, *ReqdDis*(W) represents the required dispatch from the TESS chiller to regulate the measured

Table 2: Components operated during different operation modes (✓: Used, X: Not used)

Operation mode	TESS chiller	Heat exchanger-2
Charging	✓	X
Neutral	X	X
Discharging	X	✓

Algorithm 1 EMS program for TESS chiller dispatch

$ReqdDis \leftarrow C_p \times Flowrate \times (TSup - TSupSet)$
$ActDis \leftarrow -min(ReqdDis, TESSChiCap)$

chiller outlet temperature *TSup*(°C or K) at the setpoint *TSupSet*, given the measured mass flowrate of chilled water in the TESS loop *Flowrate*(kg/s). The actual dispatch rate *ActDis*(W), which is the smaller value between the required dispatch rate and the TESS chiller capacity, and is negative to conform with EnergyPlus conventions, is passed to the TESS chiller. C_p represents the specific heat capacity of water (4200 J/(kg*K)).

Co-simulation setup

The EnergyPlus model is converted into an FMU using an open-source converter [EnergyPlusToFMU2021], and the co-simulation experiment is setup using the open-source FMPy Python library for running FMUs as shown in Figure 5. A Python program is set up to read the measurements from the EnergyPlus FMU and pass them to the optimal control algorithm. The algorithm then uses these measurements, and along with the anticipated cooling load and weather conditions for the next timestep, calculates a control action that optimizes the objective functions. This control action is then passed to the Python object for the TESS, which determines the maximum allowable heat transfer using the calculations for the Simple Ice Storage Model in [EnergyPlusEngRef2023]. The calculations are adapted to use the required heat transfer rate as an input, and then determine the outlet temperature and actual heat transfer rate iteratively. This actual heat transfer rate is then sent back to the EnergyPlus FMU, and the co-simulation is advanced by one timestep. This process is repeated till the experiment stop time.

This technique precludes variable convergence between the EnergyPlus FMU and the TESS object, thereby requiring simulation timesteps that are a small fraction of the charging cycle time. That is satisfied here, since the charging cycle time is of the order of 16 hours, whereas the timestep is only 10 minutes long.

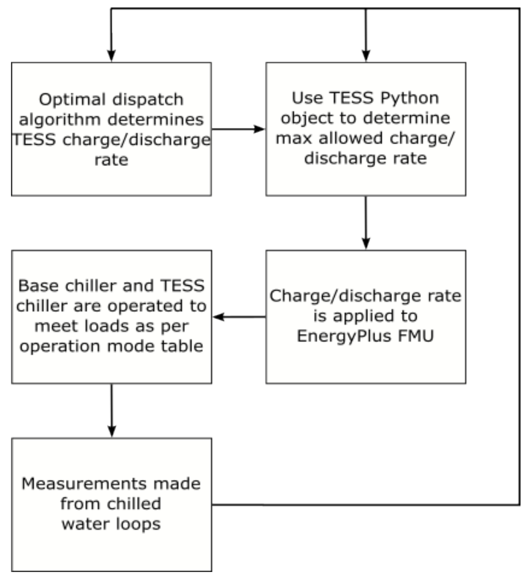


Figure 5: Process flow for Method-1 co-simulation

Method-2: Implementation of TESS in Modelica

An alternative approach to achieving a similar physical system configuration is to use Modelica models for representing the thermal storage tank, as well as the complete TESS with all associated plant loops. This TESS model is used to simulate the charging operation using the TESS-dedicated chiller/boiler, and the discharging operation to help meet the thermal loads in the building. Additionally, an EnergyPlus model is used to determine the loads from the thermal zone, and simulate the operation of the base chiller/boiler to meet the remaining loads in the building.

This section illustrates this approach specifically using a TESS model with an ice storage tank in Modelica, coupled with a building model in EnergyPlus.

Ice storage tank model in Modelica

The existing Modelica model in the MBL for the ice tank [CurrentModelicaIceTank2023] implements a baseclass `Buildings.Fluid.Storage.Ice.Tank` that allows the users to pick one of the myriad variables as an input, and then use that to determine the remaining dependent variables. An existing use-case of the baseclass exists in `Buildings.Fluid.Storage.Ice.ControlledTank`, which uses the ice tank outlet temperature setpoint as the independent variable. This baseclass is used to develop the ice storage model that meets our requirements.

We first add an input signal for the required charge/discharge rate as the independent variable, as shown in Figure 6. Next, we redefine the heat transfer rate limits defined in the block *limQ_flow* to correctly apply the constraints on it based on the inlet water temperature, the phase change temperature in the ice tank, as well as the required heat transfer rate. The constraints are described in Algorithm 2.

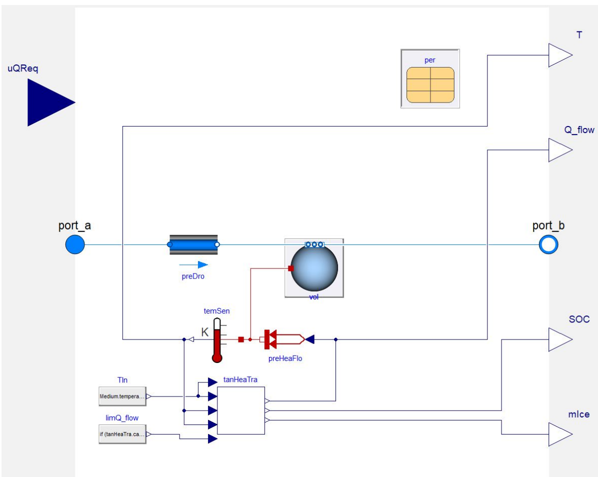


Figure 6: Modelica model for ice storage tank

Algorithm 2 Ice tank heat transfer limits

$QMax \leftarrow m\_flow \times C_p \times (TFre - TIn)$
if $(uQReq < 0)\&(TIn > TFre)$ **then**
  $limQ\_flow \leftarrow max(QMax, uQReq)$
else if $(uQReq > 0)\&(TIn < TFre)$ **then**
  $limQ\_flow \leftarrow min(QMax, uQReq)$
else
  $limQ\_flow \leftarrow 0$
end if

In Algorithm 2, *uQReq*(W) represents the required charge/discharge rate (positive is charging, negative is discharging). *TFre*(K) represents the freezing temperature of the media in the ice storage tank. *QMax*(W) represents the maximum viable heat transfer rate, assuming the outlet chilled water temperature is at *TFre*. *TIn*(K) and *m_flow*(kg/s) represent the temperature and mass flowrate of the tank inlet chilled water temperature. *limQ_flow*(W) represents the limits on the heat transfer rate based on the required operation mode and the inlet water temperature, and is used in the iterative calculations to determine the actual heat transfer. C_p is the specific heat capacity for water (4200 J/(kg*K)).

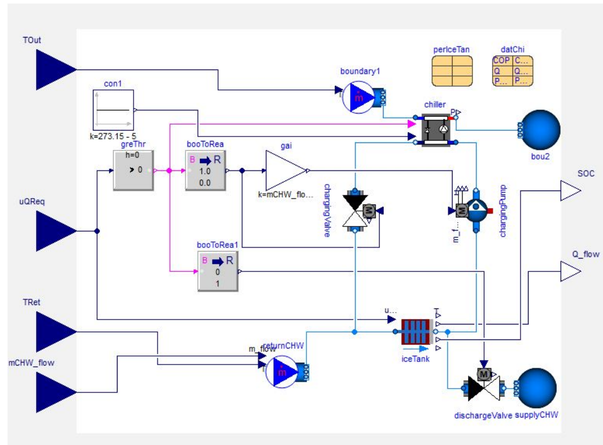


Figure 7: Modelica model for TESS

TESS system model in Modelica

The ice tank model described in the previous subsection is integrated into a complete system that manages the charging and discharging operation, as shown in Figure 7.

The system consists of an ice tank that is operated using two separate loops for the charging and discharging operations. The charging loop consists of a chiller to supply chilled water and a pump to circulate it. The discharging loop consists of an ideal fluid source that is used to replicate the tank inlet conditions at the inlet of the `LoadProfile:Plant` object in the modified EnergyPlus model, as shown in Figure 8.

The charging loop is operated when the system receives a positive signal (>0) on the `uQReq` input interface. The charging valve is opened while the discharging valve is closed. The charging pump is operated to circulate the chilled water, and the chiller is operated to maintain a constant supply temperature (e.g., -5 °C). The calculated heat transfer and the resultant SOC are passed on to the plant load profile object through the respective output interfaces.

The discharging loop is operated when the system receives a negative signal (<0) on `uQReq`. The charging valve is closed and the discharging valve is opened. The inlet conditions (temperature and mass flowrate) on the plant load profile object in the modified EnergyPlus model are replicated by the ideal fluid source. Again, the calculated heat transfer and the resultant SOC are passed back to the EnergyPlus model.

Modifications to the EnergyPlus model

The modifications to the EnergyPlus model in this approach are simpler than those discussed in Method-1.

The model is modified by adding a branch with a `LoadProfile:Plant` object to the demand side of the chilled water loop, as in Figure 8 for example. Additionally, external interface objects are added in a similar manner to Method-1.

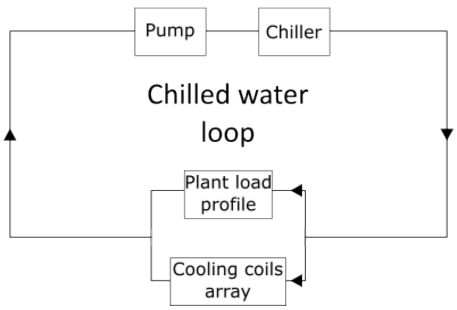


Figure 8: Modified chilled-water plant loop in EnergyPlus prototype model for secondary school building

Co-simulation framework

The proposed co-simulation framework follows the process shown in Figure 9.

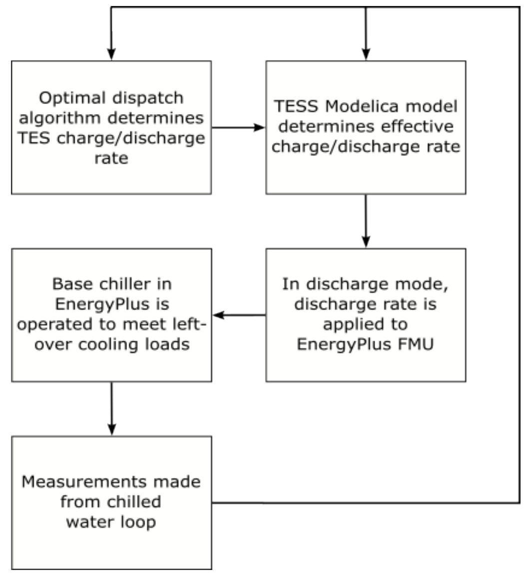


Figure 9: Process flow schematic for co-simulation method-2

The optimal control algorithm receives measurements from the EnergyPlus model for the air loop and various plant loops, along with estimates for the anticipated building loads and outdoor air conditions. It then calculates optimal charge/discharge rates that are then passed on to the TESS Modelica model. The TESS model then tries to achieve the required heat transfer rate, and the effective heat transfer rate is passed on to the `LoadProfile:Plant` object in the EnergyPlus model. The EnergyPlus model operates the building HVAC equipment to meet the building thermal loads, while also accounting for the thermal discharge by the TESS. This simulation process is then repeated for each timestep.

Demonstration: Method-1

Case study conditions

The simulation case study involves using DOE large office building prototype models for various locations and propagating the model changes across them. Then, they are simulated with the electricity price rates (e.g., time-of-use (TOU), flat rates, demand charge), anticipated cooling loads, and weather conditions to compare the performance of the optimal controller across various climate zone locations against a baseline scenario.

The baseline scenario is represented by a large office building prototype model that does not have TESS, thereby providing a comparison point to effectively demonstrate the additional flexibility and energy cost savings achieved with the use of storage systems.

The case study is run for 3 different locations - Boston, MA, San Diego, CA, and El Paso, TX - each of which has distinct climates and electricity prices, with representative prices as shown in Figure 14. The simulations are run for 1 week each from the 8^{th} of August through the 15^{th} of August.

Results

The simulation results indicate the successful operation of the chilled water loop components as per the experiment requirements. Figure 10 shows the operation of the base chiller and the TESS discharge to meet the overall cooling demand for the scenario run for Boston. The EMS program for chiller dispatch operates the base chiller to successfully meet any cooling loads that are not being met by the discharge cooling energy transferred to the secondary loop through heat exchanger-2.

Figure 11 specifically shows the TESS discharge performance. In the first subplot, it is clear that the discharge value applied on the `LoadProfile:Plant` ob-

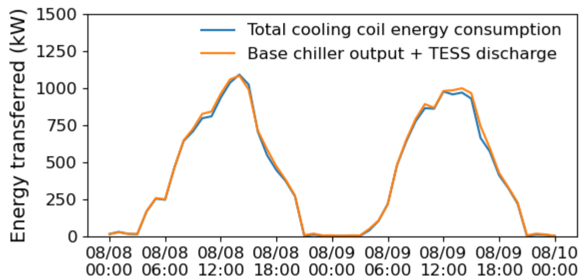


Figure 10: Comparison of combined output from base chiller and TESS discharge against cooling coil loads

ject ("Measured-Ice tank") closely mirrors the required discharge rate from the controller ("Required"). However, it can also be seen that the discharged cooling energy may not always be transmitted to the secondary loop ("Measured-Ice tank"). This is because of the cut-off temperature that is used to switch the discharging mode to the neutral mode, as defined in Figure 4. It is observed that the heat exchanger does not transmit the cooling energy whenever the measured chilled water temperature ("Supply-side") is over the cutoff temperature ("Cut-off") as shown in the third plot of Figure 11. This process does not necessarily affect the overall energy consumption since the heat discharged can be used by the loop in subsequent timesteps for charging or discharging, though the user is cautioned against drawing conclusions from other variables like the temperature at those timesteps. Further experiments with EMS variable logging are required to identify the reason behind the failure to apply the required TESS discharge to the `LoadProfile:Plant` object at lower discharge rates, even when the chilled water temperature is lower than the discharge cut-off temperature, as shown at the time instants "08-09 00:00" and "08-09 21:00".

Apart from that, the controller can reduce the peak power demand and energy cost across all 3 scenarios, as summarized in Table 3. Figure 12 shows the operation of the TESS over a representative single day. It shows a greater preference for using TESS when there are significant changes in the electricity price over a day, as observed in Figure 14 for El Paso and San Diego.

Demonstration: Method-2

Case study conditions

For this experiment, we use one of the same building models used in the Method-1 case study, which is the large office building prototype model for Boston. Due to a paucity of time, a complete co-simulation with the optimal dispatch controller was not carried out. Instead, an open-loop simulation is set up using time-series data from the Method-1 experiment for the dates between the 8^{th} of August to the 10^{th} of August, which is run at timesteps of 1-minute intervals. This data is fed into the Modelica TESS model through the input interfaces, and measurements are made from it. Note

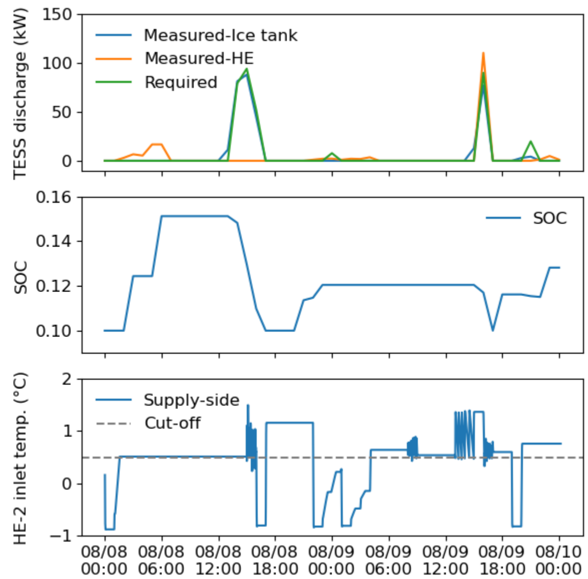
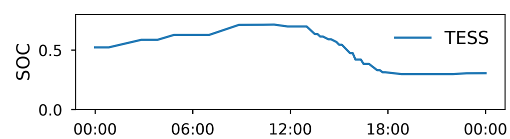
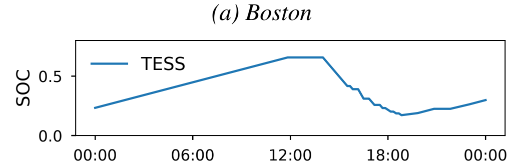


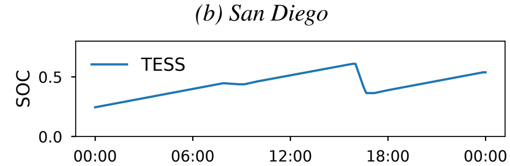
Figure 11: TESS discharge performance in Method-1



(a) Boston



(b) San Diego



(c) El Paso

Figure 12: TESS operation across locations

that these input signals do not exactly match the required charge/discharge rates from the experiment for Method-1 reported above.

Results

The results are shown in Figure 13. In the first subplot, we can see that the simulation model can respond to the control signal and achieve the required operation mode almost immediately, which is an advantage of the separate charging and discharging loops modeled in Modelica. The exact rate for charging is always met, while the discharge rate is constrained by the modeled storage physics which depends on the SOC observed in the second subplot. The immediate change in operation mode is also apparent in the third subplot. When the system switches to discharging, the tank inlet temperature immediately approaches the temperature of the secondary chilled water loop, which is used for TESS discharge. Similarly, when it switches to charging, the tank inlet immediately drops below the freezing temperature of the ice tank media.

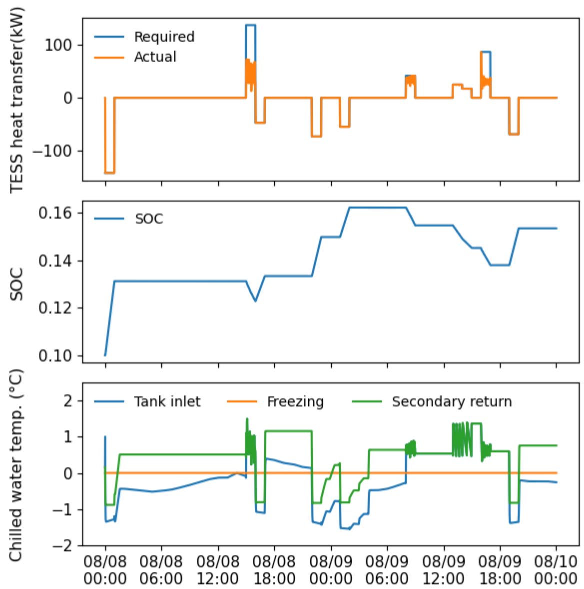


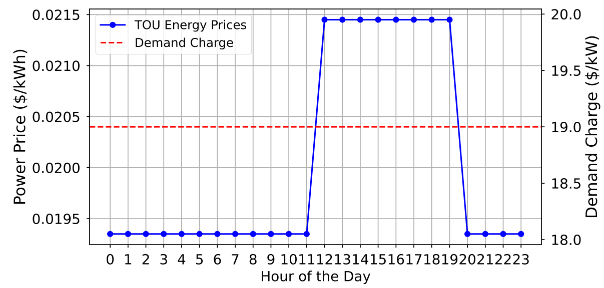
Figure 13: TESS performance in method-2

Discussion

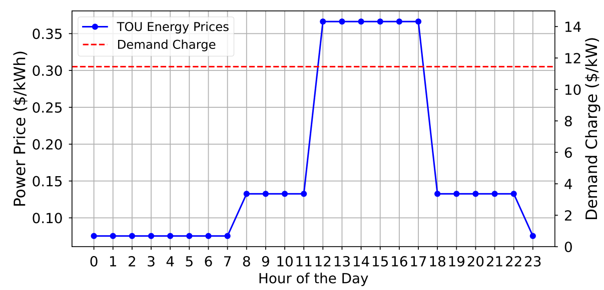
The two methods demonstrated in this paper are both able to meet the requirements for a simulation model for use in building-grid experiments.

Method-1 provides a simulation model that is entirely based on EnergyPlus and Python, both of which are well-established and mature open-source tools. While a standard EnergyPlus building model may require a lot of modifications to make it compatible with this approach, the use of EnergyPlus ensures that the simulation is robust and does not run into any convergence issues. Also, the user needs to ensure that the ice storage tank model needs to be accurately modeled in Python. In the future, a library of ice storage tank models could be made available for users, potentially using libraries that enable acausal system modeling.

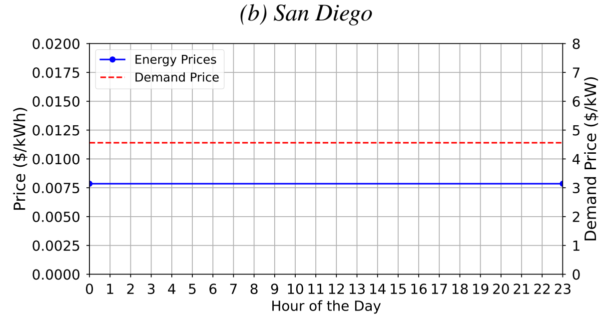
Method-2 provides a simulation model that is composed of components made with Modelica, EnergyPlus, and Python. The number of modifications required on the EnergyPlus model in this method is much fewer, with the only necessary changes being the addition of



(a) Boston



(b) San Diego



(c) El Paso

Figure 14: Electricity price rates for a commercial building in various locations [Yu et al.2023]

Table 3: Energy and cost benefits over one-week operation, when Method-1 simulation model is co-simulated with optimal dispatch controller

		Boston	**San Diego**	**El Paso**
Energy usage (total, peak)	w/o TESS	220MWh, 1815kW	195MWh, 1570kW	244MWh, 1891kW
	w/ TESS	228MWh, 1796kW	199MWh, 1480kW	247MWh, 1866kW
	Savings	-8MWh, 19kW	-4MWh, 90kW	-3MWh, 25kW
Energy charge	w/o TESS	$4439	$36786	$1915
	w/ TESS	$4589	$36866	$1940
	Savings	$(-150) (-3.4%)	$ (-80) (-0.2%)	$(-25) (-1.3%)
Demand charge	w/o TESS	$34487	$17975	$8623
	w/ TESS	$34126	$16946	$8511
	Savings	$361 (1.1%)	$1029 (5.7%)	$112 (1.3%)
Total operation cost saving		$211(0.5%)	$949 (1.7%)	$87 (0.8%)

a `LoadProfile:Plant` object on the demand side of the chilled water secondary loop, along with the necessary objects for the co-simulation interface. The Modelica model for the TESS enables the user to create any required configuration that is not dependent on any pre-programmed component models, plant loop conventions, or simulation subroutines, unlike EnergyPlus. It also does not rely on any user-programmed models for the ice storage tank in Python. However, there are a few disadvantages to this method. Since the Modelica model solves differential algebraic equations (DAEs) to obtain a solution, it runs into convergence issues if the input signals change by a large extent in a short span of time. Also, if a customized TESS configuration is to be implemented, the FMU must be generated again, which may require the use of proprietary Modelica compilers.

There are some inherent disadvantages to both methods due to the use of EnergyPlus. The `LoadProfile:Plant` object in EnergyPlus does not place any physical or numerical constraints on the heat transfer rate. Therefore, the user has to ensure that the flowrate through the chilled water loop is sized according to the expected nominal heat transfer from the TESS. If not, it may result in the simulation crashing due to very high or low temperatures caused in the chilled water loop by the heat transfer.

Conclusion

The paper identified a gap in two specific building energy modeling tools for simulating and validating TESS with optimal dispatch control. Requirements for such a simulation model were identified, and a modeling strategy was proposed. The proposed modeling strategies were implemented and tested using the developed optimal dispatch controller [Yu et al.2023]. The Modelica model proposed in Method-2 responded faster and more consistently to the required charge/discharge rate. The other merits and demerits of the two modeling strategies were also discussed.

Future work aims to understand the lack of system response observed in certain instances in the experiment on Method-1 simulation model, and to perform a complete co-simulation experiment for the model created in Method-2.

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References

Baniasadi, Ali, Daryoush Habibi, Waleed Al-Saedi, Mohammad A.S. Masoum, Choton K. Das, and Navid Mousavi. 2020. “Optimal sizing design and operation of electrical and thermal energy storage systems in smart buildings.” *Journal of Energy Storage* 28:101186.

Beghi, Alessandro, Luca Cecchinato, Mirco Rampazzo, and Francesco Simmini. 2014. “Energy efficient control of HVAC systems with ice cold thermal energy storage.” *Journal of Process Control* 24 (6): 773–781. Energy Efficient Buildings Special Issue.

Blum, David, Javier Arroyo, Sen Huang, Ján Drgoňa, Filip Jorissen, Harald Taxt Walnum, Yan Chen, Kyle Benne, Draguna Vrabie, Michael Wetter, et al.

2021. "Building optimization testing framework (BOPTEST) for simulation-based benchmarking of control strategies in buildings." *Journal of Building Performance Simulation* 14 (5): 586–610.

CurrentModelicaIceTank. 2023. Current Modelica Ice Tank Model. `https://github.com/lbl-srg/modelica-buildings/commit/92ba91902790c0d25aba64774a9da2385d9cf02a`.

Drees, Kirk H., and James E. Braun. 1996. "Development and Evaluation of a Rule-Based Control Strategy for Ice Storage Systems." *HVAC&R Research* 2 (4): 312–334.

EnergyPlusEngRef. 2023. EnergyPlus Engineering Reference. `https://energyplus.net/assets/nrel\_custom/pdfs/pdfs\_v23.2.0/EngineeringReference.pdf`.

EnergyPlusGetStart. 2023. EnergyPlus Getting Started Document. `https://bigladdersoftware.com/epx/docs/23-1/getting-started/index.html`.

EnergyPlusInputOutput. 2023. EnergyPlus Input Output Reference Document. `https://bigladdersoftware.com/epx/docs/23-1/input-output-reference/`.

EnergyPlusToFMU. 2021. Available online at `https://simulationresearch.lbl.gov/fmu/EnergyPlus/export/`.

eQuest. eQuest Energy Simulation Tool. `https://doe2.com/equest/index.html`.

Harish, VSKV, and Arun Kumar. 2016. "A review on modeling and simulation of building energy systems." *Renewable and sustainable energy reviews* 56:1272–1292.

HOMER. HOMER grid design tool. `https://homerenergy.com/products/pro/index.html`.

Huang, Bowen, Sen Huang, Xu Ma, Srinivas Katipamula, Di Wu, and Robert Lutes. 2023a. "Stochastic scheduling for commercial building cooling systems: considering uncertainty in zone temperature prediction." *Applied Energy* 346:121367.

Huang, Sen, Bowen Huang, Srinivas Katipamula, and Xu Ma. 2023b. "Simulation-based assessment on stochastic load scheduling for building cooling systems." *Science and Technology for the Built Environment* 29 (2): 212–222.

James, N, S Kaur, F Brown, M Bianchi, J Vidal, and D Hun. 2021. Thermal Energy Storage Systems for Buildings Workshop: Priorities and Pathways to Widespread Deployment of Thermal Energy Storage in Buildings,(2021).

Kamal, Rajeev, Francesca Moloney, Chatura Wickramaratne, Arunkumar Narasimhan, and D.Y. Goswami. 2019. "Strategic control and cost optimization of thermal energy storage in buildings using EnergyPlus." *Applied Energy* 246:77–90.

Kontes, Georgios D, Georgios I Giannakis, Víctor Sánchez, Pablo de Agustin-Camacho, Ander Romero-Amorrortu, Natalia Panagiotidou, Dimitrios V Rovas, Simone Steiger, Christopher Mutschler, and Gunnar Gruen. 2018. "Simulation-based evaluation and optimization of control strategies in buildings." *Energies* 11 (12): 3376.

Odukomaiya, Adewale, Jason Woods, Nelson James, Sumanjeet Kaur, Kyle R. Gluesenkamp, Navin Kumar, Sven Mumme, Roderick Jackson, and Ravi Prasher. 2021. "Addressing energy storage needs at lower cost via on-site thermal energy storage in buildings." *Energy Environ. Sci.* 14:5315–5329.

Raman, Naren Srivaths, Karthikeya Devaprasad, Bo Chen, Herbert A. Ingley, and Prabir Barooah. 2020. "Model predictive control for energy-efficient HVAC operation with humidity and latent heat considerations." *Applied Energy* 279:115765.

Tarragona, Joan, Anna Laura Pisello, Cèsar Fernández, Alvaro de Gracia, and Luisa F. Cabeza. 2021. "Systematic review on model predictive control strategies applied to active thermal energy storage systems." *Renewable and Sustainable Energy Reviews* 149:111385.

TRNSYS. TRNSYS system simulation tool. `https://www.trnsys.com/index.html`.

Wetter, Michael, Wangda Zuo, Thierry S. Nouidui, and Xiufeng Pang. 2013. "Modelica Buildings library." *Journal of Building Performance Simulation* 7 (4): 253–270.

Yu, Min Gyung, Xu Ma, Bowen Huang, Karthik Devaprasad, Fredericka Brown, and Di Wu. 2023. Enhancing Building Energy Efficiency through Advanced Sizing and Dispatch Methods for Energy Storage.

Zhu, Jianzhong, Xiaobo Cui, and Weidong Ni. 2022. "Model predictive control based control strategy for battery energy storage system integrated power plant meeting deep load peak shaving demand." *Journal of Energy Storage* 46:103811.