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CRADA NFE-24-10403 Final Report – Optimizing Control for Efficient Load Shifting with Thermal Energy Storage in Existing HVAC Systems

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August 2025

OAK RIDGE National Laboratory

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Building and Transportation Science Division

CRADA NFE-24-10403 FINAL REPORT – OPTIMIZING CONTROL FOR EFFICIENT LOAD SHIFTING WITH THERMAL ENERGY STORAGE IN EXISTING HVAC SYSTEMS

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ABSTRACT

This project developed the integration of a direct-contact heat exchanger (DCHX) based thermal energy storage (TES) system with a chiller–air handling unit (AHU) plant to evaluate its potential for reducing building energy costs. Detailed physical models of the TES unit, building envelope, and HVAC components were developed alongside simplified control-oriented models to support both high-fidelity simulation and real-time optimization. Two control strategies were implemented and compared: a rule-based control (RBC) aligned with utility time-of-use (ToU) rates, and a model predictive control (MPC) framework leveraging forecasts of building load, weather, and internal gains.

Simulation results show that the RBC strategy reduced daily electricity costs by around 30% by shifting cooling production from on-peak to off-peak hours. In contrast, the MPC strategy achieved significantly greater performance, reducing daily operating costs by up to 44% and peak-hour costs by more than 60%. Both strategies maintained indoor thermal comfort within acceptable limits, with MPC further improving load distribution and reducing equipment cycling.

The outcomes confirm that TES integration, particularly when coordinated with advanced predictive control, can provide substantial cost savings and on-peak demand reduction. . These findings directly support the U.S. Department of Energy’s goals for grid-interactive efficient buildings and demonstrate the potential of TES-enabled HVAC systems for scalable deployment across the commercial building.

1. INTRODUCTION

The U.S. building sector accounts for approximately 40% of national energy consumption [1]. As the electric grid transitions toward cleaner but more variable distributed energy generation, the ability of buildings to shift, store, and manage thermal loads has become increasingly critical. Thermal energy storage (TES) integrated with heating, ventilation, and air-conditioning (HVAC) systems offers a promising pathway to achieve cost savings and grid flexibility by shifting demand away from high-cost peak periods.

TES has been investigated for decades as a means of reducing peak electricity demand, particularly through cold storage applications in commercial buildings. Conventional ice-on-coil and chilled-water systems are commercially available and have been deployed in utility demand response programs, but their adoption has been limited due to high first costs, system complexity, and relatively low efficiency during charge/discharge cycles.

To address these gaps, Shift Thermal developed a novel direct-contact heat exchanger (DCHX) technology that enables near-steady and high-rate heat transfer during charging and discharging processes. This innovation improves TES efficiency and provides greater operational flexibility compared to conventional systems. In collaboration with Oak Ridge National Laboratory (ORNL), this project evaluated the feasibility and benefits of integrating DCHX-based TES with building HVAC systems under multiple control strategies.

The specific objectives were to (1) develop and validate physical and control-oriented models of the DCHX-TES and HVAC system, (2) establish a co-simulation testbed to evaluate baseline and advanced control strategies, and (3) quantify the energy and cost benefits of TES integration. This report presents the methodology, simulation framework, and results of the study, and discusses the implications for broader deployment of TES-integrated HVAC systems in commercial buildings. The outcomes provide DOE and industry stakeholders with a validated pathway for advancing TES technologies that support energy efficiency and grid-interactive building strategies.

2. METHODOLOGY

The methodology of this study is designed to evaluate the performance of a TES-integrated chiller–AHU system using both detailed system modeling and advanced control strategies. The section first introduces the TES–chiller configuration and its operation modes (Section 2.1), followed by the development of physical and control-oriented models for the building, TES, and HVAC subsystems (Section 2.2). Finally, the implementation of rule-based control (RBC) and model predictive control (MPC) is presented (Section 2.3), providing the framework for subsequent performance comparison.

2.1 TES UNIT AND TES-CHILLER SYSTEM

In contrast to conventional ice-on-coil systems that suffer from ice adhesion and reduced heat transfer, Shift Thermal's DCHX design prevents ice from sticking to surfaces, allowing ice slurry formation and rapid, consistent charging/discharging performance [2]. Technology operates using a dual-fluid system in which oil and water remain immiscible within an open tank, creating two distinct layers. During charging, oil is cooled in a brazed-plate heat exchanger with chilled glycol from a chiller plant and then reintroduced at the bottom of the tank. As the cold oil percolates upward through the water layer, direct contact heat exchange occurs, cooling the water to its freezing point and forming ice. The ice rises to the oil–water interface, while the oil separates and returns to the top of the tank to repeat the cycle. This design allows for a close temperature approach, efficient ice formation, and continuous cycling until the ice mass breaches the surface and interrupts oil skimming. The use of immiscible fluids for direct contact heat exchange is the key innovation that enables stable, efficient, and scalable TES performance compared to conventional ice-on-coil systems.

This TES unit is integrated with a chiller–AHU system to enable load shifting through carefully designed charging and discharging schedules. The system diagram is shown in Figure 1, and the operating modes are illustrated in Figure 2. The TES–chiller system (Figure 1) consists of an electric chiller supplying chilled water to the AHU cooling coil through a plate heat exchanger (PHX), a TES tank equipped with a DCHX, a primary distribution pump that circulates chilled water between the chiller/PHX and the AHU, and a TES loop pump dedicated to charging and discharging.

On the chiller side, two pumps are used: the main pump circulates heat transfer fluid (HTF) between the chiller, PHX, and cooling coil, while the AHU pump regulates the return HTF flow from the cooling coil outlet, mixing it with the PHX outlet flow to prevent excessively low water temperatures entering the cooling coil. Glycol is selected as the HTF between the chiller, PHX, and cooling coil. On the TES side (illustrated by the green line), oil is used as the HTF to transfer energy within the PHX.

Five operation modes can be achieved by this proposed system, as shown in Figure 2, including:

(1) TES charging (off-peak only): the chiller charges the TES via the PHX while meeting any coincident load.
(2) TES discharging (on-peak only): the AHU cooling coil is served from the TES through the PHX with the chiller off.
(3) Chiller-only cooling: baseline operation serving the AHU directly.
(4) Simultaneous cooling + TES charging: the chiller meets the load and diverts surplus capacity to charge the TES.
(5) Simultaneous cooling + TES discharging: the TES assists the chiller to shave peak demand.

The availability of multiple operating modes provides the flexibility required to adapt to dynamic building loads and electricity pricing. By coordinating the chiller and TES through these modes, the system can shift energy consumption to off-peak hours, reduce peak demand, and improve utilization of low-cost electricity. This operation is essential for enabling cost-effective load shifting and advancing operation goals in grid-interactive buildings.

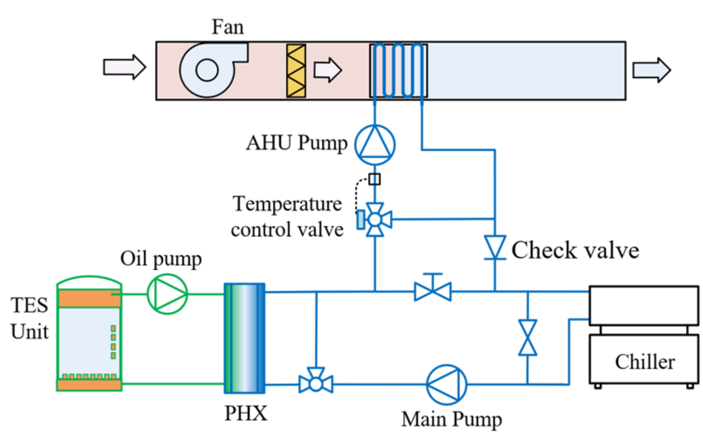
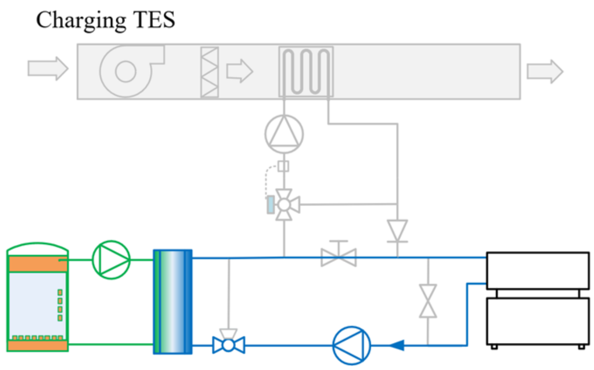
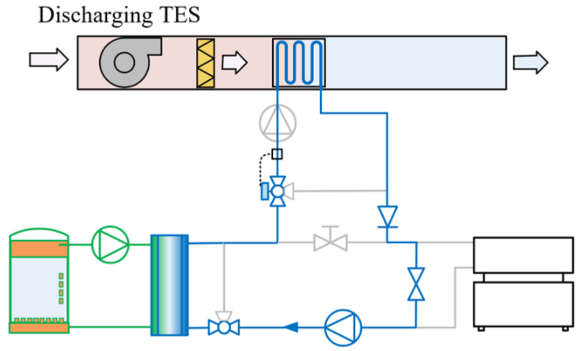


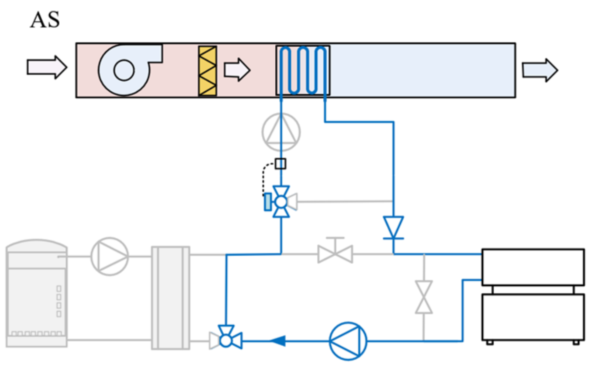
Figure 1: TES-chiller system diagram



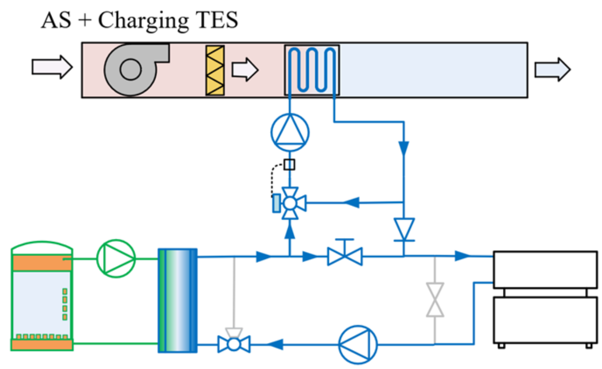
(a) TES charging mode



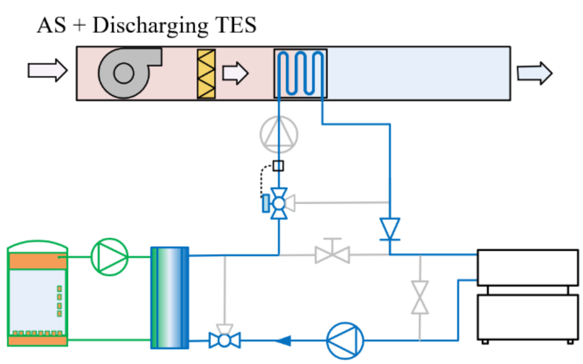
(b) TES discharging mode



(c) Chiller cooling mode



(d) Chiller cooling & TES charging mode



(e) Chiller cooling & TES discharging mode

Figure 2: TES-chiller system operation mode

2.2 PHYSICAL MODEL AND CONTROL-ORIENTED MODEL DEVELOPMENT

To evaluate the performance of the TES–chiller system and its control strategies, both physical and control-oriented models were developed. The physical models capture detailed thermodynamic and heat transfer processes, providing a high-fidelity representation of the building, TES, and HVAC components. In contrast, the control-oriented models are simplified but computationally efficient, enabling real-time optimization in advanced control schemes such as model predictive control (MPC). Together, these complementary models provide the foundation for co-simulation, system analysis, and the comparison of different control strategies.

This section describes the detailed system models developed for the study, including the building thermal model, the TES unit model, and the HVAC equipment model, across all relevant modes of operation. Moreover, the simplified control-oriented models were derived from the detailed physical models to enable efficient real-time optimization.

2.2.1 Thermal Energy Storage Modeling

The DCHX configuration ensures near-steady heat transfer between the working fluid and storage medium, overcoming the limitations of conventional ice-on-coil systems. Experimental data indicate stable PHX inlet and outlet temperatures during both charge and discharge. The model captures thermal dynamics across operating modes and provides a baseline for evaluating load-shifting potential.

2.2.2 Building Energy Modeling

The building was represented by a reduced-order resistance–capacitance (RC) model as shown in Figure 3 [3]. The parameter R represents the thermal resistance that governs heat transfer between adjacent temperature nodes in the RC model, including the equivalent outdoor air temperature ($T_{oa,eq}$), wall temperature (T_w), and thermal zone air temperature (T_z). Each thermal resistance is calculated by accounting for the relevant conduction and convection processes: window conduction, window convection, external wall conduction, internal wall conduction, and internal wall convection. Within the RC network, the thermal resistances associated with the walls and windows act in parallel, representing the multiple heat transfer paths that connect the outdoor environment to the indoor zone air.

The compact state–space form of the thermal zone dynamics can be expressed as:

$$\begin{bmatrix} \dot{T}_z & \dot{T}_{wall} \end{bmatrix}^T = \mathbf{f}_z(T_z,\ T_{wall},\ T_{sa},\ T_{oa},\ \dot{m}_a,\ Q_{rad},\ Q_{ig}) \quad (1)$$

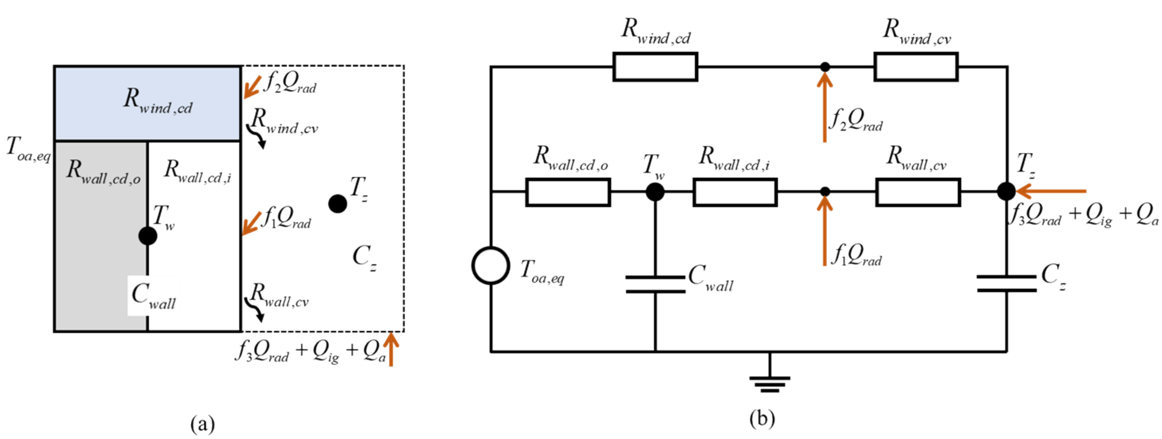


Figure 3: RC model of an existing research building

2.2.3 Chiller and AHU Modeling

The HVAC subsystem includes models for the chiller, fans, and pumps. The total power consumption is given in Eq. (2), consisting of fan power, pump power and chiller power. The power consumption of the fan and pump is represented by a third-order polynomial function of the air and water mass flow rates, respectively, as expressed in Eqs. (3)-(4). A detailed description of the physical model is provided in [4]. The chiller power consumption is based on the DoE2 simulation model [5], given by Eq.(5). This model relates chiller performance to part-load ratio, chilled water supply temperature, and condenser conditions, providing a validated approach for system-level energy analysis.

$$P_{total} = P_{fan} + P_{pump} + P_{chiller} \tag{2}$$

$$P_{fan} = \alpha_3 \dot{m}_a^3 + \alpha_2 \dot{m}_a^2 + \alpha_1 \dot{m}_a + \alpha_0 \tag{3}$$

$$P_{pump} = \gamma_3 \dot{m}_w^3 + \gamma_2 \dot{m}_w^2 + \gamma_1 \dot{m}_w + \gamma_0 \tag{4}$$

$$P = P_{ref} \times CAPFR(T_{sw}, T_{cws}) \times EIRFT(T_{sw}, T_{cws}) \times EIRFPLR(Q_{cc}, T_{sw}, T_{cws}) \tag{5}$$

2.3 CONTROL STRATEGIES

Effective control strategies are critical for realizing the full benefits of integrating TES with building HVAC systems. In this study, two approaches are implemented and compared: a conventional RBC strategy and an advanced MPC strategy. RBC provides a simple, schedule-driven benchmark that follows fixed rules aligned with time-of-use electricity rates, while MPC uses predictive models and forecasts to dynamically optimize system operation. The comparison highlights the trade-offs between simplicity, computational effort, and performance in reducing electricity cost, and establishes the performance gains achievable with advanced control.

2.3.1 Rule-Based Control

The RBC strategy was implemented for operating the TES–chiller system. RBC relies on fixed, predefined rules that schedule charging and discharging of the TES in accordance with the time-of-use (ToU) electricity tariff and expected building load profile. Unlike advanced control methods, RBC does not adapt to short-term variations in load, weather, or grid conditions, but instead follows preset schedules designed to reduce operating costs during on-peak hours. As shown in Figure 4, the RBC schedule divides the day into off-peak and on-peak periods according to the utility tariff. The off-peak windows (19:00–08:00 and 08:00–14:00) are prioritized for chiller operation and TES charging, while the on-peak window (14:00–19:00) is reserved for TES discharging to offset peak cooling demand. The 24-hour evaluation duration can be divided by several time slots:

(1) Off-peak Period 1 (19:00–00:00): The 3-stage chiller operates to meet cooling loads.

(2) Off-peak Period 2 (00:00–08:00): The chiller operates to meet cooling loads and charge the TES whenever capacity is available. Three operation options are available: (i) chiller-only AS cooling, (ii) TES charging, and (iii) simultaneous cooling and TES charging.

(3) Off-peak Period 3 (08:00–14:00): The TES may continue charging if storage capacity remains, while the chiller serves the building load directly. Two operation options are available: (i) chiller-only cooling and (ii) TES charging.

(4) On-peak (16:00–19:00): The TES discharges to supply the AHU cooling coil, reducing chiller operation and shifting demand away from high-cost hours. Three operation options are available: (i) chiller-only cooling, (ii) TES discharging, and (iii) simultaneous cooling and TES discharging.

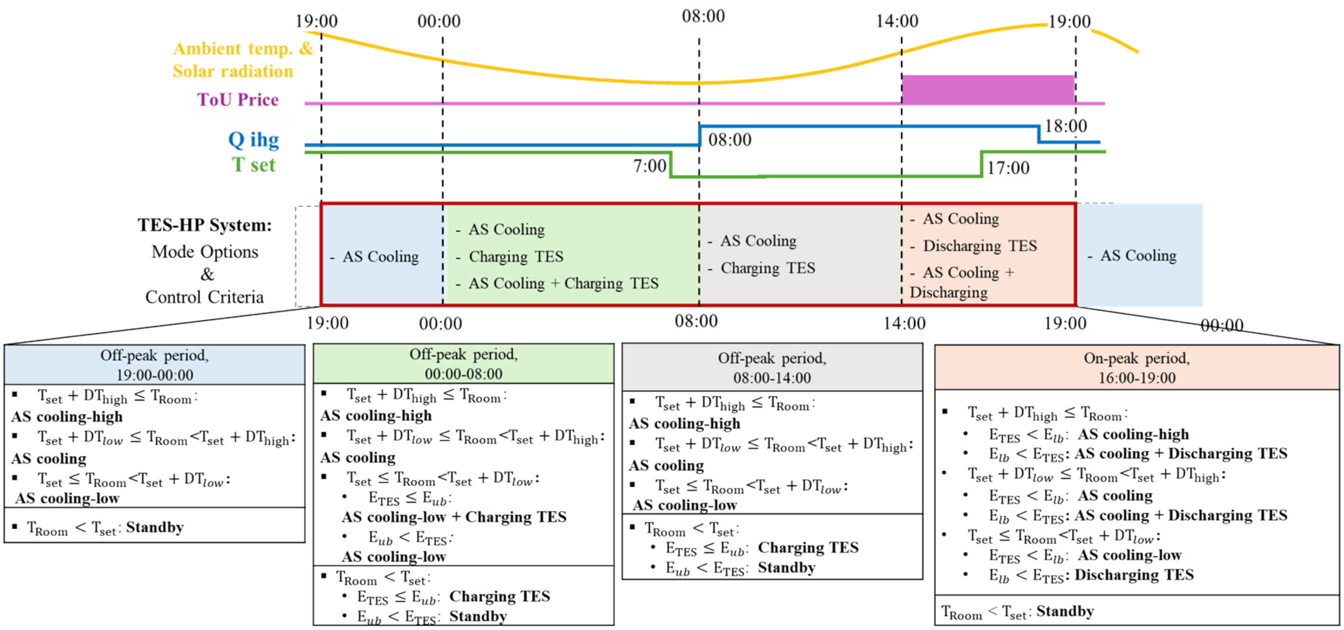


Figure 4: RBC control logic

The control inputs include weather conditions, ToU price, internal heat gain and building thermostat setpoint. ToU price defines the high-cost peak window (14:00–19:00) and drives the RBC scheduling logic. Q_{ihg} represents the building's internal load from occupants, lighting, and equipment. In the RBC framework, this load signal triggers cooling demand that it must be satisfied either by the chiller or by TES discharge, depending on the ToU period. In the simulation, it increases at 08:00, marking the transition between Off-peak Period 2 and Off-peak Period 3. Thermostat setpoint T_{set} defines the indoor comfort constraint. It is higher during the night and is lowered between 7:00 to 17:00 to reflect occupied hours and stricter comfort requirements. More detailed temperature profiles and their effect on system operation are presented in the Results section.

2.3.2 Advanced Control

The MPC framework was implemented as an advanced strategy for optimizing TES–chiller system operation. Unlike rule-based control (RBC), which follows fixed schedules, MPC dynamically adjusts charging and discharging decisions by forecasting building loads, weather conditions, internal heat gains, and ToU electricity prices. By solving an optimization problem in real time, MPC identifies the control actions that minimize operating cost and maintain thermal comfort.

As shown in Figure 5, the MPC controller integrates forecast disturbances (weather data, ToU tariff, internal gains, and temperature setpoints) with a reduced-order RC building model and a TES–HVAC control-oriented model. At each time step, the system state variables (x) and disturbance inputs (d_k) are updated. The optimizer then evaluates candidate mode options (u) against the objective function and system constraints, selecting the control action that minimizes cost over a defined prediction horizon. Only the first step of the optimal sequence is applied; the process repeats as forecasts are updated.

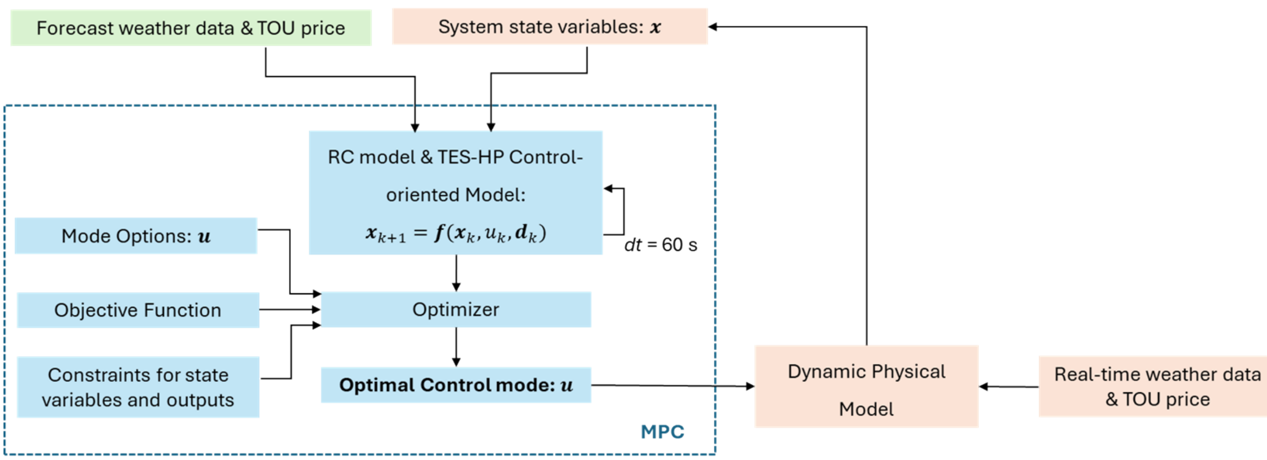


Figure 5: Structure of MPC in co-simulation

The disturbance signals considered in this study for certain days at Oak Ridge, TN, are illustrated in Figure 6. Outdoor air temperature and solar radiation determine the external load on the building envelope. Hourly ToU prices provide a signal to the MPC, allowing it to schedule TES charging during low-cost periods and shift load away from high-cost hours.

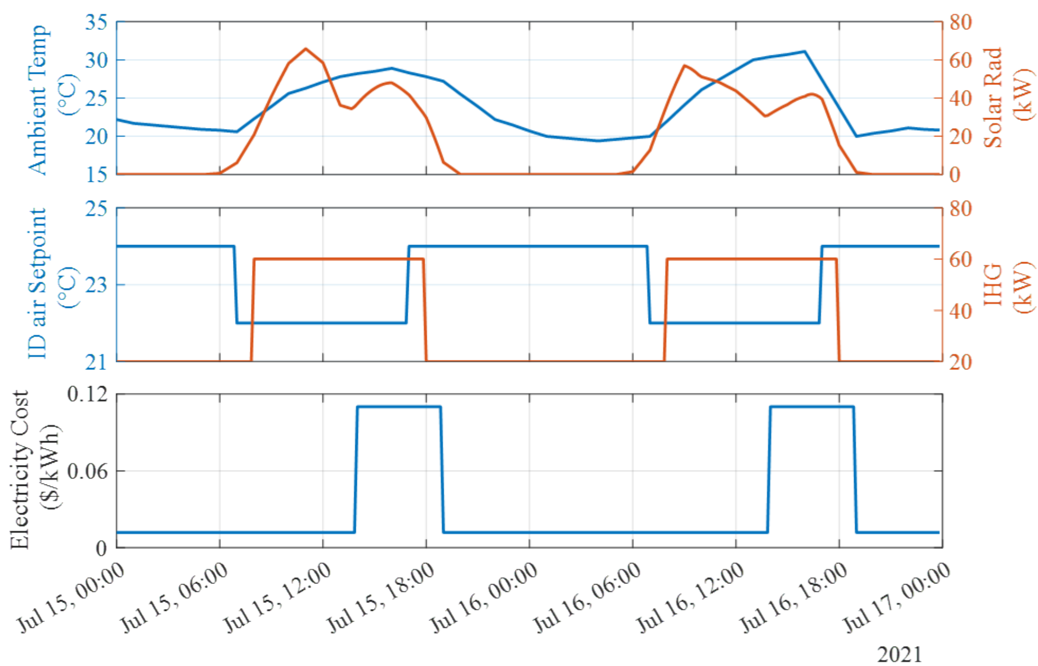


Figure 6: Disturbance of the MPC used in this study: weather data, ID setpoint, IHG and ToU price.

3. LOAD-SHIFTING RESULTS AND DISCUSSION

This section presents the simulation results of the baseline system compared with the TES-chiller system operated under RBC and MPC. Results are analyzed in terms of electricity cost reduction and thermal comfort performance.

The effectiveness of RBC and MPC strategies in reducing electricity costs was evaluated against the baseline chiller-only system. Figure 7 shows the operating mode schedules for each case, while Figure 8 and Figure 9 present the corresponding indoor temperature, cooling load, power, TES state-of-charge, and cumulative cost profiles.

As illustrated in Figure 7, the baseline system operates the chiller continuously to meet building loads, including during peak hours. By contrast, RBC shifts operation by charging TES during off-peak hours (00:00–08:00 and 08:00–14:00) and discharging during the on-peak period (14:00–19:00). MPC further improves this strategy by dynamically scheduling charging and discharging according to both forecast load and price signals, resulting in smoother operation and greater use of TES during high-cost periods.

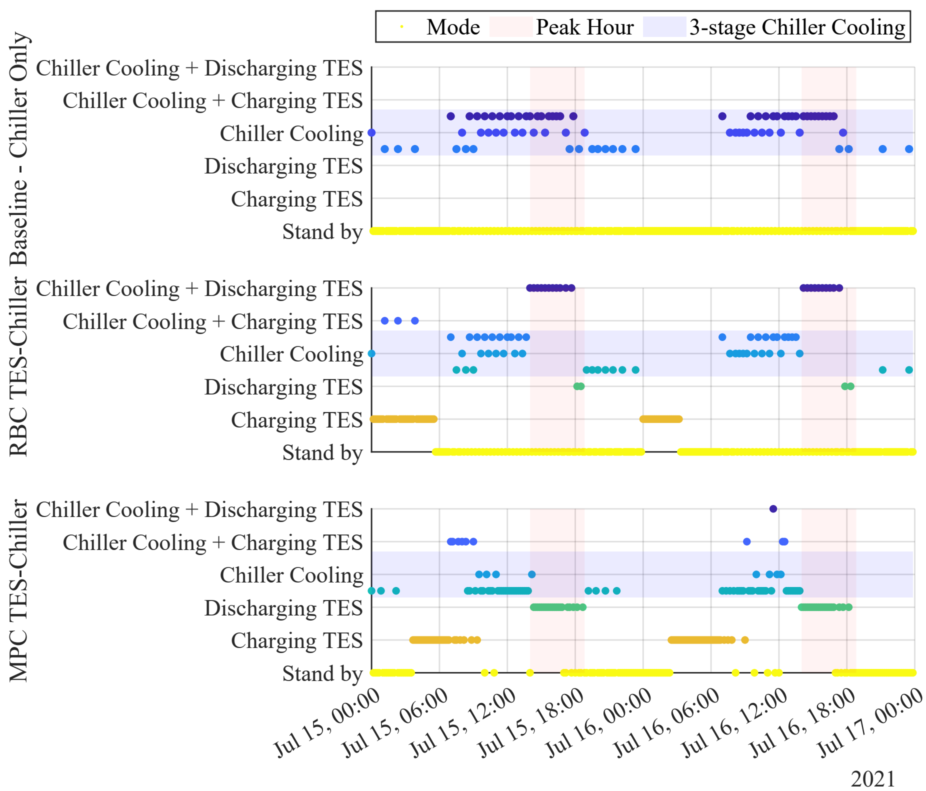


Figure 7: System operation mode of the baseline, RBC-TES system, and MPC-TES system.

Figure 8 shows that all three strategies maintained indoor air temperature within the comfort setpoint range. Cooling load patterns remained similar across cases, though MPC slightly reduced chiller cycling by better coordinating TES discharge with load peaks.

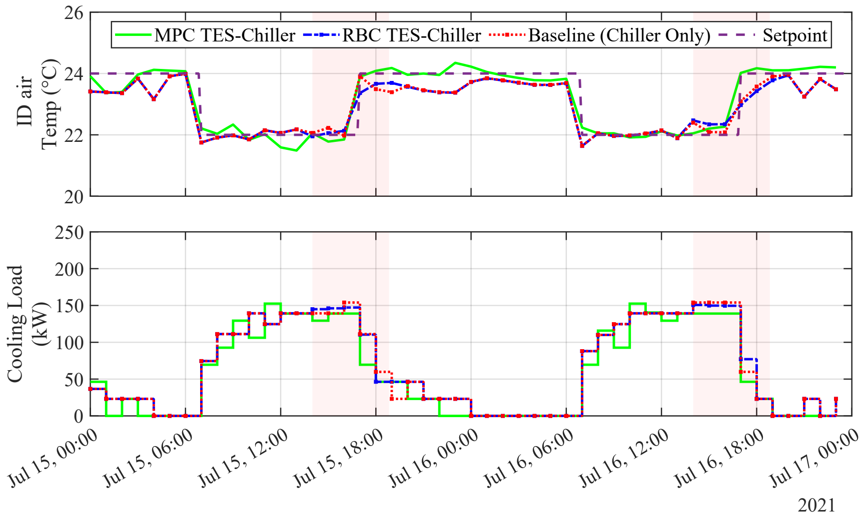


Figure 8: Building thermal comfort and cooling load of the baseline, RBC-TES system, and MPC-TES system

As shown in Figure 9, the RBC strategy reduced total power consumption during the on-peak window by shifting a portion of the cooling load to off-peak nighttime hours. MPC achieved even greater reductions by aligning TES discharging more precisely with the highest-cost periods. Compared to RBC, MPC scheduled TES charging later in the day, selecting charging periods that maximized economic benefit based on forecasted loads and tariff signals. This resulted in flatter power profiles, more efficient TES utilization, and significantly lower cumulative electricity costs.

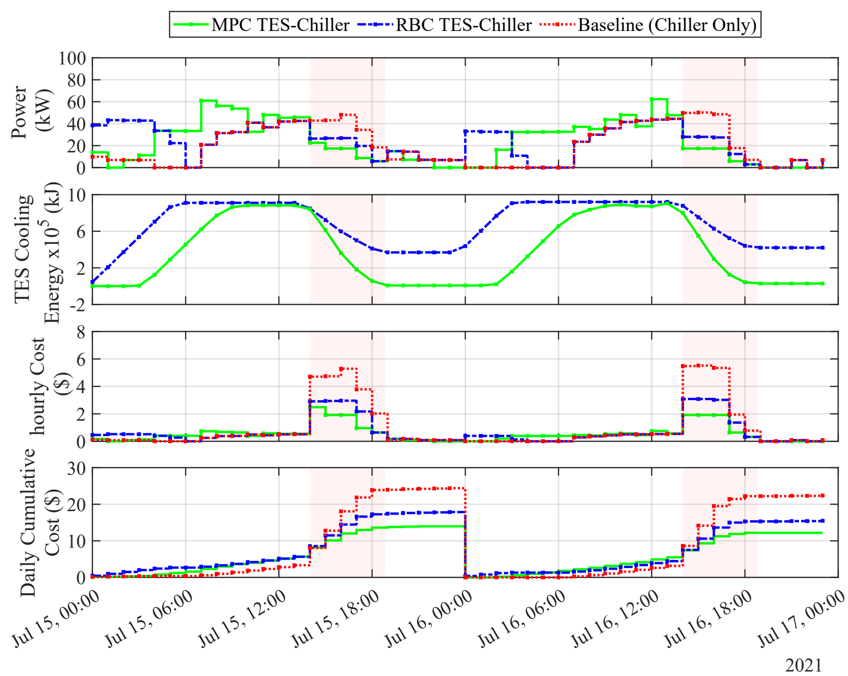


Figure 9: Hourly power consumption, TES stored energy, hourly electricity cost and accumulated cost of the baseline, RBC-TES system, and MPC-TES system

Table 1 and Table 2 summarizes daily electricity costs and peak hour electricity costs, respectively, consistent with the profiles shown in Figure 9. RBC based TES-Chiller system can reduce daily costs by 27% to 31% on the selected days, and MPC can achieve 36% to 40% on the selected days. During peak hours, MPC delivered the greatest benefit, achieving up to 61% cost reduction compared to the baseline case.

Table 1: Daily electricity cost comparison

System	Date	Building load (kWh)	Power Consumption (kWh)	Cost ($)	Cost Reduction (%)	Cost/load ($/kWh)	Cost/load Reduction (%)
Baseline	15-Jul-2021'	1688.3	506.8	24.4	--	1.4E-02	--
Baseline	'16-Jul-2021'	1471.3	448.6	22.4	--	1.5E-02	--
RBC	'15-Jul-2021'	1702.8	625.9	17.9	-27%	1.0E-02	-27%
RBC	'16-Jul-2021'	1476.6	483.0	15.5	-31%	1.0E-02	-31%
MPC	'15-Jul-2021'	1513.5	576.1	14.0	-43%	9.2E-03	-36%
MPC	'16-Jul-2021'	1325.7	518.7	12.2	-46%	9.2E-03	-40%

Table 2: Peak hour electricity cost comparison

System	Date	Building load (kWh)	Power Consumption (kWh)	Cost ($)	Cost Reduction (%)	Cost/load ($/kWh)	Cost/load Reduction (%)
Baseline	15-Jul-2021'	603.7	186.7	3.4	--	5.7E-03	--
Baseline	'16-Jul-2021'	545.0	173.4	3.2	--	5.8E-03	--
RBC	'15-Jul-2021'	595.0	105.6	1.9	-43%	3.3E-03	-43%
RBC	'16-Jul-2021'	550.3	98.7	1.8	-43%	3.3E-03	-44%
MPC	'15-Jul-2021'	523.2	71.9	1.3	-62%	2.5E-03	-56%
MPC	'16-Jul-2021'	486.5	60.9	1.1	-65%	2.3E-03	-61%

4. CONCLUSIONS

This project developed computer models to assess the performance of integrating a direct-contact heat exchanger (DCHX) based thermal energy storage (TES) system with building HVAC operation under both rule-based control (RBC) and model predictive control (MPC). Through a combination of detailed physical modeling, control-oriented model development, and co-simulation, the study quantified the economic and grid benefits of TES when coordinated with advanced control strategies.

RBC achieved daily electricity cost reductions of around 30%, while MPC delivered significantly greater savings of up to 44% across the evaluated days. During peak hours, MPC achieved cost reductions exceeding 61%. Both strategies maintained indoor temperatures within comfort bounds, demonstrating that cost reduction did not compromise occupant conditions. These results confirm that TES-integrated HVAC systems can play a significant role in reducing building operating costs and supporting load shifting. RBC provides a simple, low-complexity pathway for near-term deployment, while MPC demonstrates the added value of predictive, optimization-based strategies for long-term grid-interactive buildings. The recommended future work includes experimental validation of the DCHX TES system under real-world conditions, MPC development to multi-objective optimization (reducing operation cost, improving thermal comfort and reducing peak gird load), and integration with distributed energy generation and utility demand response programs.

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