Optimizing Heat Recovery with Storage: Control Validation and Sensitivity Analysis of the Time-Independent Energy Recovery Plant Using Modelica

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ABSTRACT

Heat recovery in large building central plants saves energy but traditionally requires simultaneous heating and cooling. The Time-Independent Energy Recovery (TIER) plant shifts this paradigm by integrating thermal energy storage (TES) to enable heat recovery regardless of concurrent demand, offering a highly efficient, space-saving solution to achieve California's energy goals. However, its integration of heat recovery chillers, cooling-only chillers, cooling towers, and trim air-source heat pumps (ASHPs) creates growing control and sizing complexity. To overcome this, this study employs high-fidelity Modelica dynamic simulation to validate TIER control sequences and optimize equipment sizing. We translated the written Sequences of Operation into executable Control Description Language (CDL) to test logic against sub-hourly loads. This verification workflow successfully identified and resolved critical vulnerabilities, such as thermal storage freezing and equipment short-cycling, in a virtual environment prior to physical deployment. Then, the study analyzes TIER plant performance across three simulated building types in three locations, and a real building load profile, ensuring variety in heating and cooling loads, and simultaneity factors and explores sizing rules for the TES and ASHP capacity. The analysis shows that the TIER plant operates equipment efficiently, leading to a plant SCOP of around 7.5 across all scenarios. The analysis also shows that Modelica-based simulation is a viable pathway to de-risk complex system design and control and identify optimal designs that maximize energy efficiency, minimize operational costs, and ensure robust operation in varied environmental conditions, thereby facilitating the broader adoption of such solutions for large buildings.

Introduction

Meeting ambitious goals for reducing energy costs for building owners and maintaining a reliable grid in the face of growing demand and changing net load patterns requires innovative HVAC solutions. For large commercial buildings, central plants are the core component where heating and cooling generation occurs. Thus, mechanical designers are designing innovative systems that aim to shift the paradigm from simple heating and cooling generation to comprehensive resource maximization, including methods for simultaneous heating and cooling, waste heat recovery, and energy storage utilization.

One recent innovative plant design called the Time-Independent Energy Recovery (TIER) plant (Gill 2021) combines all of these methods. TIER integrates heat recovery chillers (HRC), cooling-only chillers (CHI), a thermal energy storage (TES) tank to indirectly store heat using condenser water, cooling towers, and a "trim" heat source, such as an Air Source Heat Pumps (ASHP). Figure 1 shows a schematic of the TIER plant configuration simulated in the different scenarios.

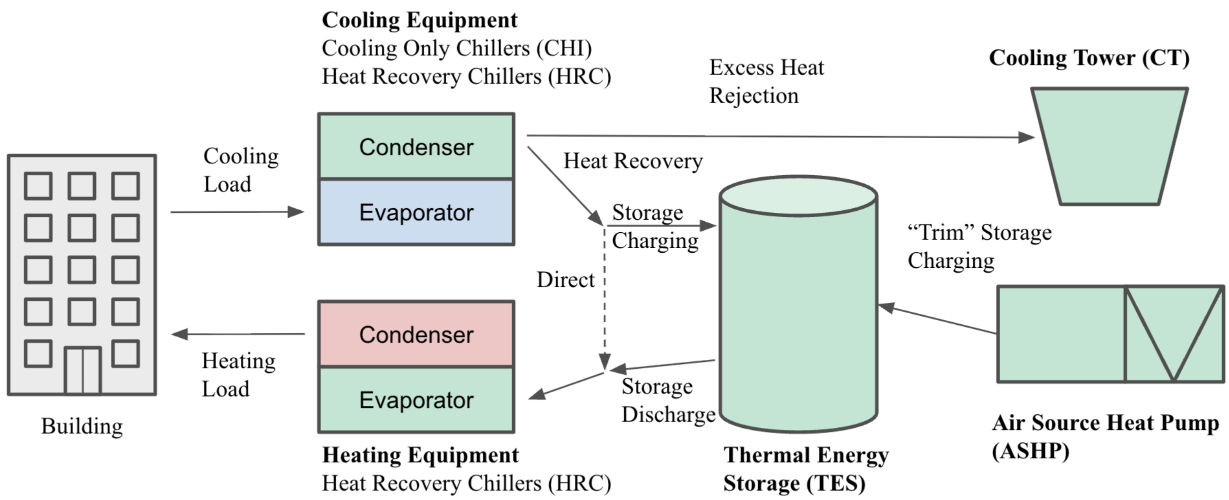

Figure 1: Schematic of TIER plant operating in simultaneous heating and cooling. TIER operates in 3 modes, 1) Direct heat recovery mode, in this mode the CHI reject heat to the condenser water loop and the HRC uses it to heat up the building, 2) Cascade heat recovery mode, where the CHI rejects heat in the storage and the HRC extracts it, 3) HRC can work in cooling mode if not engaged in heating mode. If excess heat needs to be rejected CT is engaged, and if the storage is depleting too quickly, the ASHP is engaged to charge it.

In standard heat recovery systems, waste energy can only be reclaimed when heating and cooling loads occur simultaneously, like in mode 1 described in Figure 1. By integrating TES, the TIER plant decouples this relationship. During the day, waste heat from cooling loads is transferred into the TES tank, raising the water to tepid temperatures (6–25 °C / 43–59 °F). While this water is too cool to heat the building directly, the HRCs are able to extract this stored energy to heat the building during periods of high heating demand, such as the mornings. Thus, the TES tank acts as a thermal battery and allows the HRC to provide heating during these periods with greater efficiency than conventional systems. In addition, the tepid TES tank temperature reduces tank heat lossesand allows the tank to operate across a wider temperature range, allowing the same amount of energy to be stored in a smaller volume. The HRC can also operate at higher supply water temperatures than the ASHP equipment, allowing them to be used with air-side terminal units designed for higher temperatures than ASHPs can provide. The ASHP is instead used to recharge the tank when it's close to the lower temperature limit. Furthermore, the tank can be charged during off-peak hours and utilized during on-peak hours to provide more efficient heating and cooling during on-peak hours, further reducing energy costs for building owners and peak electrical demand for the grid. When the tank temperature is too high the CTs reject the excess heat from the chillers. Lastly, the HRC can operate both in heating and cooling mode depending on the current building demand.

Despite its potential to lower operating costs and reduce peak electrical demand, the TIER plant is exceptionally complex to design, size, and control. It requires continuous modulation between various operating modes, such as cascading cooling, direct heat recovery, tank charge/discharge, and excess heat rejection, based on instantaneous building loads, ambient weather conditions, and the state of charge of the TES. Ensuring stable supply temperatures, avoiding equipment short-cycling, and preventing potentially catastrophic failures, such as freezing the TES or evaporator coils during peak heating events, demands sophisticated, multilayered control logic. This inherent complexity warrants the use of dynamic models and simulations to develop, verify, and improve upon control sequences with significantly greater speed and lower risk than in the field. Incorporating modeling into the research and design processes, including controls design and sizing optimization, will be key to de-risk the deployment of the TIER plant and other emerging complex systems at-scale, prove their performance benefits across a diverse set of operating conditions, and unlock their full potential for advanced economic energy management (Wetter et al. 2016, 2024; Akesson 2025).

Considering such modeling and simulation, conventional building energy modeling tools, such as EnergyPlus, generally employ load-based simulation approaches that idealize HVAC and control behavior, rather than representing control sequences and HVAC dynamics explicitly. Furthermore, these tools generally have limited ability to build or customize models of new systems with complex architectures. Meanwhile, the emergence of equation-based, object-oriented, acausal modeling enables modeling and simulation of explicit control logic and HVAC system dynamics. One such language with extensive usage in the auto and aerospace industries and growing usage in the energy and building industries is Modelica (Mattsson and Elmqvist 1997). For building and district-level HVAC modeling and simulation, the open-source Modelica Buildings Library (MBL) (Wetter et al. 2014) represents one of the largest, most robust open-source Modelica libraries, containing component and system models that can be used to build conventional and novel HVAC system models coupled with explicit control logic at local-loop and supervisory levels. Furthermore, the development of the Control Description Language (CDL) as a subset of the Modelica specification (Wetter et al. 2022), now further specified in a new national standard, ASHRAE 231:2026, enables the digital specification of HVAC control logic, in CDL, that can be simulated with Modelica models and exported into a neutral JSON format ready for machine-to-machine translation directly to existing commercial control products. This capability further bridges the gap between design and real-world operation, providing a direct pathway to field implementation that minimizes commissioning time and operational risk.

Given the potential for the TIER design to provide central plant heating and cooling with superior energy management, its significant complexity in control requirements and equipment sizing limiting its ability to be deployed at-scale with low operational risks and proven performance across diverse operating conditions, and the emergence of modeling capabilities with Modelica and CDL to address these challenges, the objectives of this paper are threefold:

1. Validate the complex TIER control sequences using Modelica and CDL. By translating Sequences of Operation written in English into executable CDL code, the actual control logic is tested with a dynamic Modelica model of the TIER system against realistic building loads to identify and correct any issues, verify stability, and ensure system reliability prior to field deployment.

2. Conduct a simulation-based, comprehensive sensitivity analysis of the performance of the TIER plant using the Modelica model and validated control logic in CDL across diverse California climates (San Francisco, Sacramento, and Los Angeles) and varied load profiles, including hospitals, large offices, and hotels. This analysis will explore various equipment sizing heuristics, specifically optimizing the joint relationship between TES tank volume and ASHP capacity, to identify optimal, robust designs that maximize energy efficiency, minimize peak demand, and guarantee reliable performance under a wide array of environmental conditions.

3. Demonstrate the capability for dynamic modeling with Modelica and CDL to be incorporated into design and deployment processes to optimize and de-risk novel HVAC systems that are emerging to meet new energy management objectives.

Methods

The TIER plant is inherently hard to design and control. High fidelity simulations, such as the ones using the Modelica language, provide a necessary tool to explore these complex interactions, refine control strategies, analyze design trade-offs, and evaluate the overall performance and cost-effectiveness of different TIER configurations. The MBL v12.0 TIER plant model (Buildings.DHC.Plants.Combined.AllElectricCWStorage[1]) was used as the template for this simulation study. All the parameters to size the equipment in each scenario are a function of the yearly peak loads currently simulated, and for more details, users can consult the Model's documentation and inspect the Modelica model itself. The major differences between the model used in this study and what is available in Building v12.0 are the CHI and HRC performance maps, which are adapted from E+ to work at higher temperature lifts and were supplied by Taylor Engineers for this study, and the supply heating setpoint used in this study of 51.7 °C (125 °F).

The Methods section is divided into two: Control Sequence Validation explaining the validation process of the control sequences using Modelica and CDL, and System Level Simulation and Sensitivity Analysis presenting the case study and scenarios under analysis.

Control Sequence Validation

Due to the complexity of the main controller module, which includes numerous inputs and outputs, each submodule is validated separately. The validation workflow involves comparing the Sequence of Operation (SOO) specification, model documentation, code implementation, and simulation validation. Figure 2 shows as an example the simulation validation of the tank cycle controller submodule.

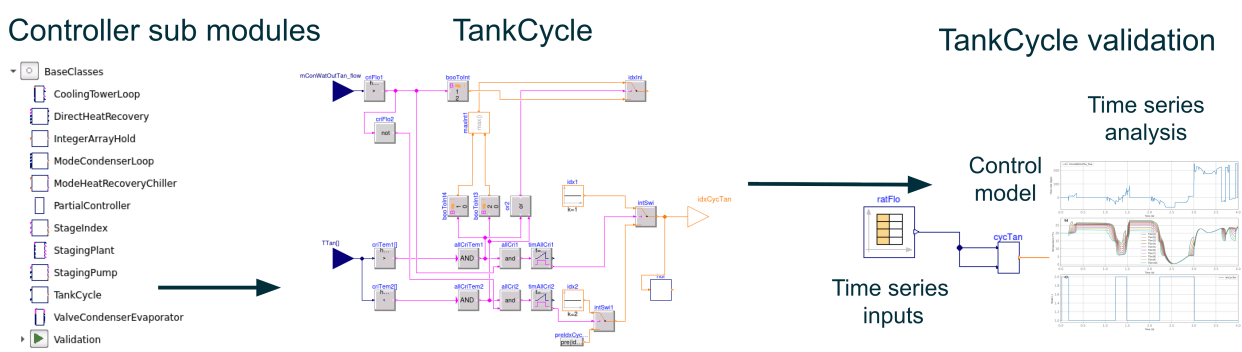

Figure 2: Controls validation example TankCycle sub module.

Each submodule was tested using simulation outputs generated from simulation of the full plant model using an example model provided in the MBL (Buildings.DHC.Plants.Combined. Validation.AllElectricCWStorage), which has a simplified load input for four days of simulation. Figure 3 shows the heating and cooling load for the example model.

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[1]https://simulationresearch.lbl.gov/modelica/releases/v12.0.0/help/Buildings_DHC_Plants_Combined.html#Buildings.DHC.Plants.Combined.AllElectricCWStorage

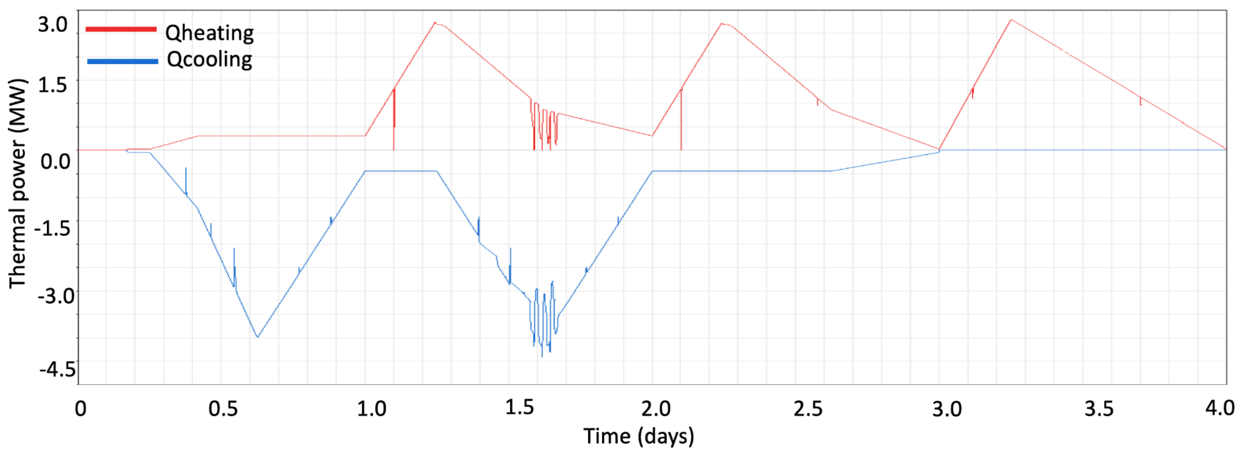

Figure 3: Heating and cooling loads of the four-day plant simulation used for control validation.

System-Level Simulation & Sensitivity Analysis

To evaluate the performance of the TIER plant across diverse environmental and operational conditions, the study includes a matrix of simulated load scenarios spanning three California climate zones and three building types. The selected climates, San Francisco (Climate Zone 3), Los Angeles (Climate Zone 6), and Sacramento (Climate Zone 12), represent the primary climate diversity across large urbanized areas in California where the TIER plant is highly applicable. Within each climate, the authors used E+ (Crawley et al. 2000) simulated load profiles from the Department of Energy prototype ASHRAE 90.1 2022 buildings for a Large Office (46,000 m^2, 500,000 sqft), a Hospital (22,000 m^2, 237,000 sqft), and a Large Hotel (11,000 m^2, 118,000 sqft). The team chose these building types based on an analysis of two key metrics: their annual heating-to-cooling ratios and their simultaneous heating and cooling hour ratios, as shown in Figure 4. This selection provides a comprehensive distribution of load characteristics, capturing both heating- and cooling-dominated buildings, as well as varying potentials for leveraging the plant's time-independent heat recovery capabilities. Finally, in addition to these nine simulated scenarios, the study incorporates one measured historical load profile derived from operational data of an office-laboratory (8,000 m^2, 86,000 sqft) building from the Lawrence Berkeley National Laboratory (LBNL) campus to verify that the identified trends and control performances remain valid under realistic load patterns.

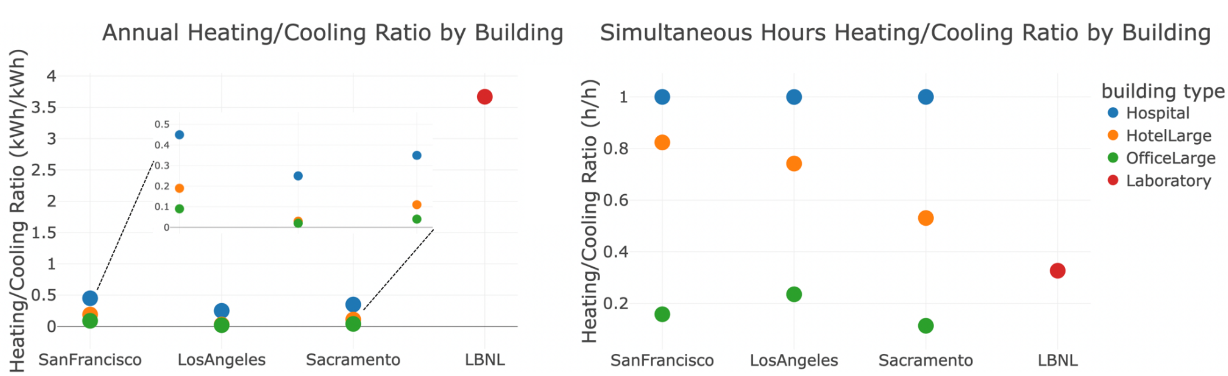

Figure 4: Annual ratio between space heating and space cooling energy load (left plot), with zoomed in view for simulated load profiles, and ratio of hours during the year when simultaneous heating and cooling demand are present (right plot). These values are plotted for all the different climates and buildings.

The researchers sized the primary generation equipment, consisting of three cooling-only chillers (CHI) sized to meet peak cooling demand and two heat recovery chillers (HRC) sized to meet the peak heating demand of each specific building profile, with each unit sharing an equal fraction of that peak capacity. Conversely, the sizing of the thermal energy storage (TES) tank and the auxiliary ASHP represents a coupled design trade-off. To evaluate this relationship, the sensitivity analysis defines TES capacity based on the hours of operation it can sustain under peak demand with three storage durations: a small 15-minute buffer tank, a nominal 3-hour storage tank, and a large 8-hour load-shifting tank. For each of these storage scenarios, the ASHP is sized not for the instantaneous peak, but to satisfy the integrated net energy deficit during the worst-case 24-hour heating day of the year. The required ASHP thermal power capacity $\dot{Q}_{ASHP}$ is therefore:

$$\dot{Q}_{ASHP} = \frac{E_{deficit\_24h} - E_{TES}}{24}$$

Where $E_{deficit\_24h}$ is calculated by taking the 24-hour integrated heating demand minus the concurrent heat recovery, and E_{TES} is the usable energy capacity of the TES tank. This approach links the TES peak time duration to the ASHP size, allowing the study to explicitly quantify the operational impacts of substituting active heat pump capacity with passive thermal water storage across the different scenarios.

The combination of three simulated climates and building types, a real building at LBNL site, and three ASHP-TES sizes, leads to 30 yearly simulation scenarios to be analyzed.

To help verify the overall plant operation in an automatic way, a new template Modelica model for plant requirements was developed using the Modelica Requirements Library (Otter 2025). Integrated directly into the plant model during simulation, this template enables the systematic, automated verification of the controller's operation against defined requirements across the simulation scenarios. This facilitates the debugging of complex systems by automatically checking and reporting whenever simulation results fail to meet specified operational limits, such as those relating to successful load satisfaction (e.g., if supply temperatures fall out of a defined range) or safe equipment behavior (e.g., excessive cycling). Table 1 reports the operational requirements monitored automatically through the Modelica Requirements model. A total of 80 requirements were monitored for each simulation scenario. At the end of each simulation, a .html file is generated highlighting how many requirements were violated and at what time during the simulation.

Table 1. Operational requirements verified by the Modelica Requirements model. Stable operation checks if the variable under consideration undergoes excessive oscillations.

	Minimum On/Off Times	Values Within Safety Bounds	Setpoint Tracking	Stable Operation
Equipment (CHI, ASHP, HRC)and Plant-level)	On/Off signal	Supply and Return Temperatures	Supply Temperature and dT Supply - Return	Supply Temperature
TES		Internal Temperatures	Average Temperature	
Pumps	On/Off signal	Flow Rate and Head		Flow Rate and Head
Valves				Position

Results

The results section is organized as follows. First, the Validating Controls and De-risking the Design section details the translation of written Sequences of Operation into executable code, demonstrating how dynamic simulation catches critical system failures and enables automated debugging prior to physical deployment. Then, the TIER Performance and Sensitivity Analysis section evaluates the plant's thermodynamic performance across diverse California climates, load profiles, and TES-ASHP sizing scenarios.

Validating Controls & De-risking the Design

As an example of control block validation we report how the tank setpoint operation is implemented. The tank works with two modes, each corresponding to a temperature band (25 °C - 15°C) for the first mode and (15 °C - 6 °C) for the second mode. These temperature levels make the CHI condenser and HRC evaporator to work with nominal ~10 °C between supply and return, while allowing for a wider temperature range in the tank (25 °C - 6 °C) increasing the actual energy capacity. Figure 5 shows the test results from the four days of simulation to validate the control logic to support these two modes.

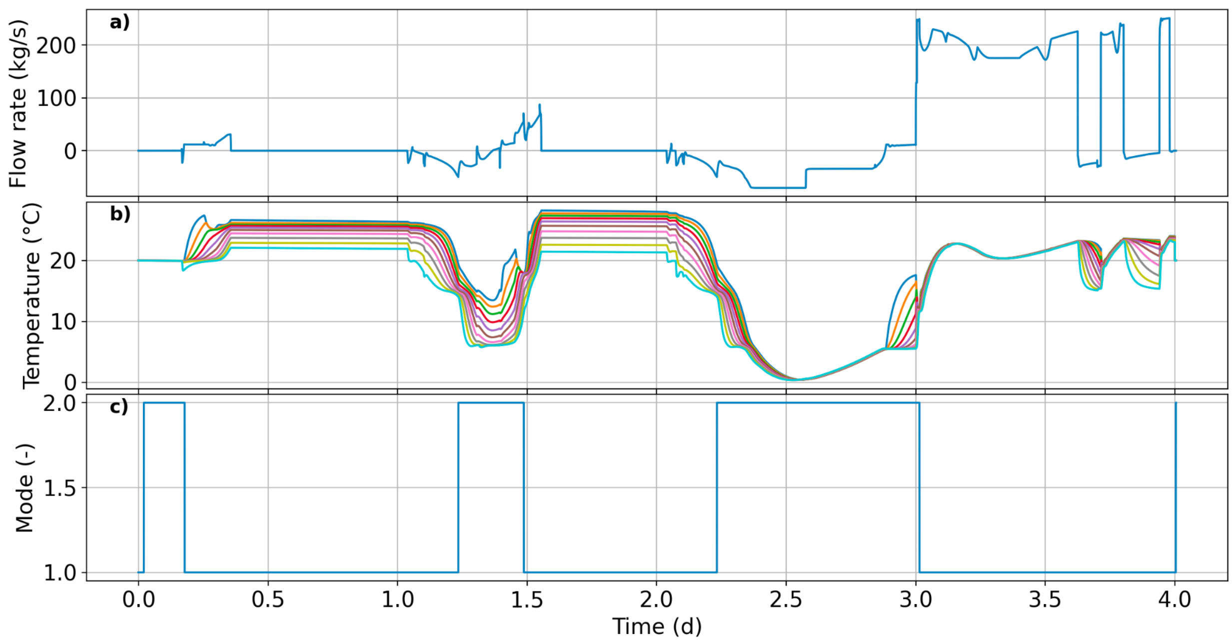

Figure 5: Tank operating mode change validation. Plot a), top, shows the flow rate from the Tank bottom (positive when outflow), plot b) shows the temperatures inside the tank, and plot c) indicates the current tank cycle mode.

SOO/Documentation Expectation: The first tank mode (higher temperature setpoint 25-15 °C) is activated whenever all of the following conditions are true:

- All tank temperature sensors measure a value higher than the mean setpoint value of the second tank cycle for 5 min.
- The flow rate out of the lower port of the tank is positive (tank is charging) for 5 min.

The second tank mode (lower temperature setpoint 15-6 °C) is activated whenever both of the following conditions are true:

- All tank temperature sensors measure a value lower than the mean setpoint value of the first tank cycle for 5 min.
- The flow rate out of the lower port of the tank is negative (tank is discharging) for 5 min.
- The minimum runtime of each tank cycle is fixed at 30 min.

Simulation Results and Confirmation: The simulation results confirm that the Tank Cycle control module determines the tank cycle mode according to the SOO, seen in plot c). In fact, the index transitions between 1 and 2 based on the tank temperatures (i.e. between 1 and 1.5 days in) seen in plot b) and the direction of flow into/out of the lower tank port and timings are consistent with the criteria for activating each cycle.

However, during the validation analysis, a control failure was identified where the tank bypass valve logic failed to maintain minimum flow rate through the condenser loop when CHI is turned off. In fact, Figure 6 bottom plot shows the valve position, red line, and condenser loop flow from the CHI, blue line, to be zero. The top plot shows the controller failing to engage the ASHP to reheat the tank because the temperature sensor intended to trigger the ASHP to turn on, red line in top plot, was positioned in a section of the hydronic circuit that became hydraulically isolated from the HRC. Notice its temperature remains unchanged due to this isolation while the temperature in the Tank and HRC evaporator drops until it freezes the pipes.

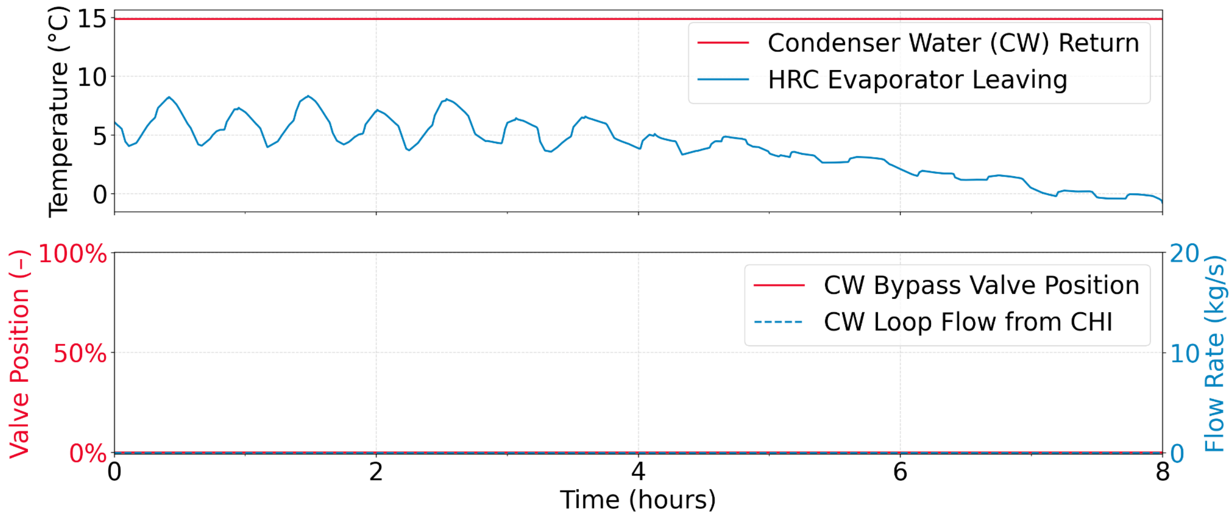

Figure 6: Simulation stopping with error due to tank not charging properly leading to pipe freezing. Top plot shows HRC evaporator leaving temperature (blue), CHI condenser water return line (red), and ASHP setpoint (orange). The center plot shows the bypass valve position of the CW loop on the left, and CW water flow from CHI.

In addition to the submodule-specific validation, through the execution of the 30 simulations run in the sensitivity analysis, two main operational issues were identified that would have been impossible to detect using traditional steady-state analysis. First, the plant demonstrated a vulnerability during large transient load changes, particularly when shifting rapidly from a high cooling demand to a low cooling demand. Under these conditions, the plant remains temporarily locked in heat rejection mode, and if a sudden concurrent heating demand arises, the HRCs can become thermally starved and freeze before the system can successfully stage down CHIs and begin drawing stored energy from the tanks.

The second operational issue is that while the default PID control loops performed adequately across most baseline scenarios, an average of 79% of the operational requirements were satisfied across the scenarios. The remaining 21% of violations were driven by varying transient magnitudes across the different climate and load scenarios, leading to oscillatory equipment behaviors and working temperatures that fell temporarily outside of the safe operating range. The .html output allowed us to narrow down what variables to look at and quickly verify if the behavior required further investigation. Figure 7 reports an example of the Modelica Requirements output.

80.0 % of TIER_sf_hot requirements are satisfied at time = 3.1536e+07 s

Requirements violated (16 of 80)

Observation	Requirement	First violation at	Description
chiller	plantRequirement.chiReq[1].reqdTSupRetEqu.req	207297 s	This chiller supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
cooling plant	plantRequirement.cooPlaReq[1].reqdTSupRetEqu.req	207297 s	This cooling plant supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
heat recovery chiller	plantRequirement.heaChiReq[1].reqdTSupRetEqu.req	182446 s	This heat recovery chiller supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
heat recovery chiller	plantRequirement.heaChiReq[2].reqdTSupRetEqu.req	2.89076e+06 s	This heat recovery chiller supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.
heating plant	plantRequirement.heaPlaReq[1].reqdTSupRetEqu.req	185846 s	This heating plant supply and return temperature difference should be between 4K and 20K once the equipement is active for 10 min.

Figure 7: Modelica Requirements .html sample output for the Hotel in San Francisco with nominal TES. The first line in green shows the percentage of constraints satisfied, followed by a table with the requirements that were violated, the monitored variable, the simulation time at the first violation, and a description of the requirements.

TIER Performance & Sensitivity Analysis

This section presents a comprehensive evaluation of the TIER plant's thermodynamic performance, operational robustness, and sizing sensitivity across all the 30 scenarios. The analysis assesses the system's ability to operate equipment at favorable part-load efficiencies and quantifies the impact of diverse California climate zones and building load profile size on the overall heat recovery potential with nominal TES size. Then, the study explores the impact of the trade-offs between thermal energy storage (TES) volume and active air-source heat pump (ASHP) capacity.

Figure 8 shows that the TIER plant operates equipment at reasonable partial load ratios. As seen in the Chiller (CHI) and HRC subplots, the lead equipment (e.g., CHI_1 and HRC_1) has distribution of median load fractions dictated by the range of the scenario loads, with climates and buildings with lower cooling load leading to lower median CHI_1 operation, and the same is true for heating demand and HRC_1 operation. Conversely, the lag equipment (e.g., CHI_2/3 and HRC_2) is tightly clustered at higher load fractions (0.5 to 0.8), apart from the Laboratory building. This outcome is a combination of the TIER plant properly implementing its staging control, and the fact that the simulated loads are almost never zero, allowing a smooth transition between stage ups and downs of the plant.

The ASHPs exhibit a wider range of median load fractions that are highly dependent on the distribution of heating and cooling loads. The Laboratory building in LBNL is heating dominated so a lot of trim heat is required, while the Hospital in Los Angeles has a year-round cooling demand, leading the ASHP to seldom operate. The high median load fractions observed for the TES demonstrate that the tank always operates near the upper value of the temperature setpoint band. It currently is 25 °C for mode 1 and 15 °C for mode 2.

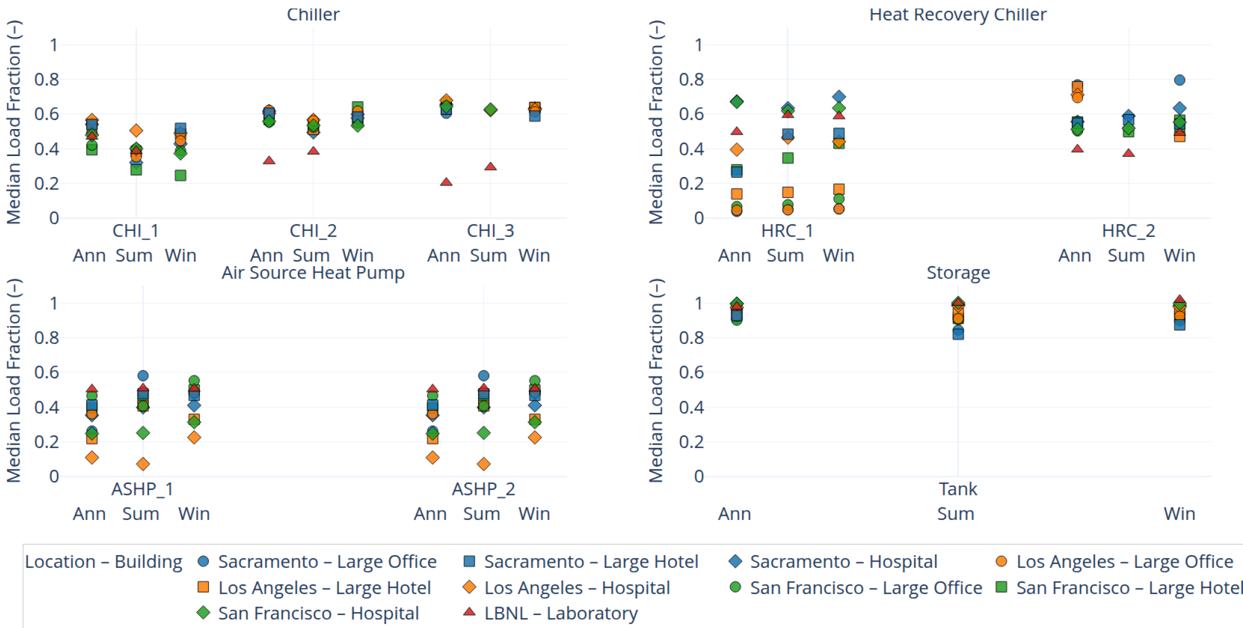

Figure 8: Distribution of median load fractions for the primary generation equipment (Chillers, HRCs, ASHPs) and thermal energy storage across simulated California climates and building types for the nominal thermal storage size (3h of peak load) for the whole year (Ann), Summer (Sum) and Winter (Win).

Figure 9 shows how a building's inherent "simultaneity factor" dictates the effectiveness of the TIER plant. The left plot shows the heat recovery ratio calculated by the ratio between the total yearly heat used by the HRC evaporator minus the ASHP trim heat, divided by the heat used by the HRC condenser corresponding to the yearly building energy load. The middle and right plots show the total plant SCOPs, which include all the heating and cooling energy provided during the year in the numerator, and the electrical consumption of the plant in the denominator. The middle plot does not include pump energy in the denominator, while the right plot does. As expected, Hospitals, which operate 24/7 and have high internal loads, achieve higher heat recovery rates and high Plant SCOPs across all climates. However, the heat recovery ratio drops significantly for the Large Office scenarios, and in Sacramento, it approaches zero. In standard commercial buildings during cold winter weather, there is typically little to no mechanical cooling load because cold outdoor air (via airside or waterside economizers) provides all the cooling the building needs. Sacramento experiences colder winter temperatures than Los Angeles or San Francisco. Because the economizers satisfy the winter cooling loads in the Sacramento office, the chillers remain off and do not reject any waste heat into the TES tank. Consequently, when the office requires significant morning warm-up heating, the tank has no recovered heat to offer, forcing the plant to rely on the less-efficient trim ASHPs. However, the economizer control logic could be updated to accommodate HRC operation, and the ASHPs can still leverage the tank’s thermal storage to modify the operating hours to more efficient times of the day, or to reduce ASHP peak loads (and size smaller, cheaper equipment), a control strategy to be studied in future work. Note also, that the overall SCOP for the Large Office is still higher in Sacramento than in San Francisco and this is due to the warmer Summers in Sacramento leading to a more frequent use of the efficient cooling only chillers.

Analyzing the LBNL laboratory scenario shows a lower SCOP compared to the simulated building archetypes. This reduction is primarily driven by its highly heating-dominated load profile, which limits the availability of recoverable cooling waste heat and forces the plant to rely more heavily on less efficient ASHP heating rather than highly efficient HRC. However, when evaluating the Plant SCOP inclusive of pump energy, the performance gap between the real load profile and the simulated buildings narrows. This convergence occurs because the simulated building load profiles rarely drop to zero, forcing those modeled plants into continuous, year-round operation, while the real load from the LBNL building does drop to zero at times. This continuous baseline load in the simulated buildings results in constant pump recirculation across the primary and secondary hydronic loops to maintain minimum flows and setpoints.

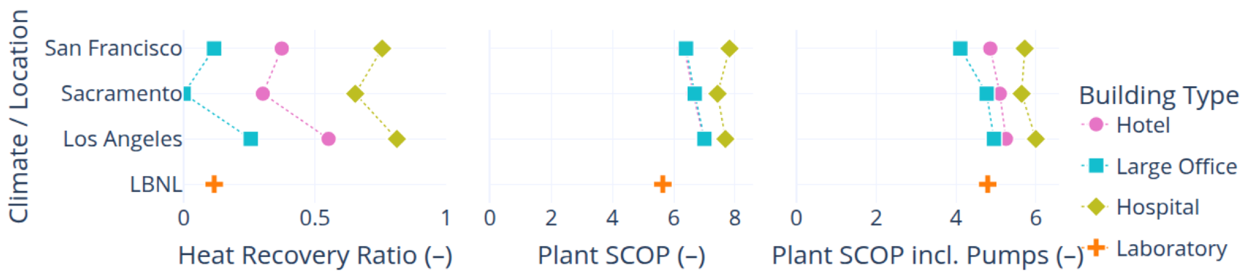

Figure 9: Sensitivity of the Heat Recovery Rate (left), Plant Seasonal Coefficient of Performance (SCOP) of primary generating equipment only (middle), and SCOP with pumps (right) across California climate zones (San Francisco, Sacramento, Los Angeles) and representative building types for the nominal thermal storage size (3h of peak load).

Moving to the sensitivity analysis on the tank and ASHP capacity, Figure 10 shows that across all evaluated climates and building types, TES volume and ASHP capacity share an inverse relationship that correlates to the plant's peak electrical demand. Because the amount of heat required to warm a building over a 24-hour peak design day remains constant, the combined capacity of the recovered heat (stored in the tank) and the trim ASHPs must collectively satisfy this daily deficit.

Across the subplots, when the plant is configured with a "Small" buffer-style tank, the recovered heat is quickly exhausted. This forces the plant to rely heavily on the ASHPs to satisfy instantaneous heating loads. Because ASHPs operate at lower efficiencies and draw maximum power during cold peak winter conditions, this reliance causes spikes in peak electrical demand.

Conversely, expanding the TES tank to a "Large" (8-hour) capacity maximizes the volume of "free" recovered heat that can be harvested from the building's daytime cooling loads and deployed independently of time, reducing peak demand. The data shows that across all simulated buildings (Hospitals, Hotels, and Offices), upgrading to a large tank consistently reduces the required ASHP electrical energy and flattens the peak demand. For instance, in the Large Office scenarios, while overall energy use remains relatively flat, the peak demand drops by up to 30% when shifting from a small to a large tank, as the trim ASHP merely trickles heat into the tank over a 24-hour period rather than fighting the instantaneous morning peak.

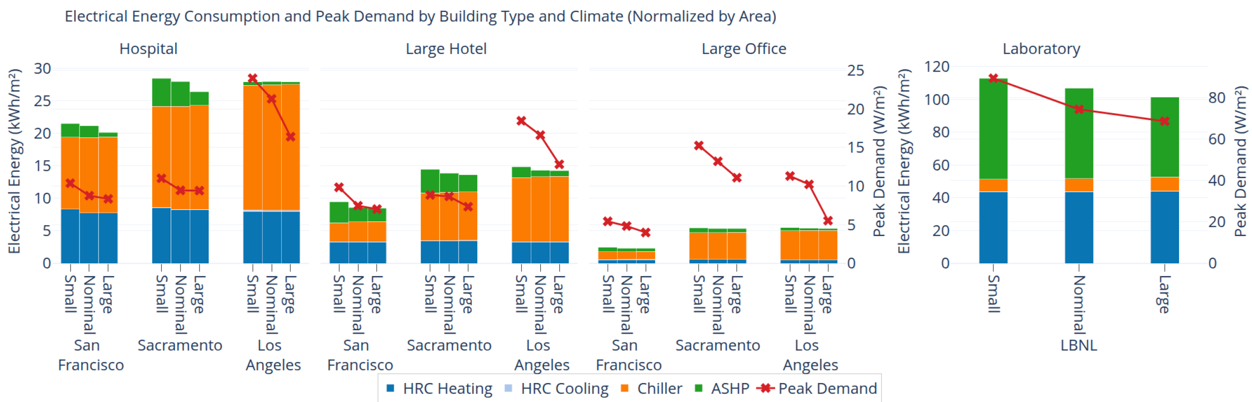

Figure 10: Operational trade-offs of equipment sizing rules, comparing Small (15-minute), Nominal (3-hour), and Large (8-hour) TES capacities across three building types for the different climates and building types on the left side, and real laboratory building on the right side. Stacked bars represent annual electrical energy use by equipment type, while the red line indicates peak electrical demand.

Discussion: Identifying Optimal Designs and the Value of Dynamic Simulations

Optimal TIER Configurations and Equipment Sizing

The data indicate that maximizing the TES capacity up to the 24-hour design load limit represents the most robust configuration across nearly all evaluated California climates and building types. The large storage allows the plant to maximize the capture of waste heat, operate primary equipment at highly efficient partial load ratios, and drastically reduce peak electrical demand and ASHP sizing. However, this analysis does not take into account trade off economics between ASHP and TES capacity, and space constraints for such large TES tanks. To deal with this Taylor Engineers explored the idea of using the fire prevention water tanks as TES in (Gill 2021).

This study's sensitivity analysis focused on the joint relationship between TES tank volume and ASHP capacity, while the strategic sizing of the primary generation equipment, the CHI and HRC is equally important. The selection of the precise number and capacity of these primary units is dictated by a facility's space constraints, capital budgets, and load shapes. Furthermore, our simulations showed that the HRCs rarely engaged in cooling mode. This occurred because the baseline sizing rule conservatively scaled the cooling-only chillers to independently satisfy the absolute peak cooling demand. To maximize resource and capital efficiency, cooling-only chillers should be downsized to cover only the net peak cooling demand, that is, the peak cooling demand minus the concurrent cooling capacity provided by HRCs not operating in direct heat recovery mode (CHW-to-HW). Determining this net peak, however, is not straightforward. On a cooling design day with no heating load, every HRC can run in cascading cooling mode at high EER, maximizing the reduction in required chiller capacity since high EER leads to higher cooling capacity for the HRCs. By contrast, on an intermediate day with a lower peak cooling load but some simultaneous heating demand, a portion of the HRCs must operate in direct heat recovery and, therefore, at a lower EER and simultaneous cooling capacity, leaving more of the remaining cooling load needing to be met by the chillers and potentially driving up the required chiller capacity for that load. The optimal sizing therefore depends on the interaction of several factors: the coincidence of heating and cooling loads, the allocation of HRCs between cascading cooling and direct heat recovery, and the EER differential of the HRCs between these two modes. This complexity is a strong argument for sizing the chillers through annual simulation rather than from peak-load calculations alone.Lastly, this conservative chiller sizing benefited the integrity of the current study; the simulation models presently have very optimistic performance for HRCs operating in cooling mode because the curves were tuned to reflect HRC performance with high lifts in heating mode. Had the HRCs been forced to operate extensively in cooling mode without corrected performance maps, it would have likely resulted in artificially inflated SCOP for the overall plant.

The Value Proposition for Industry

Beyond thermodynamic optimization, this study highlights the commercial value of dynamic simulation for the HVAC industry and the Modelica libraries. Complex central plants like TIER introduce more implementation risks. Real-world applications underscore this challenge; for instance, project partner Taylor Engineers has experienced long and tedious field commissioning processes during physical TIER plant deployments. These field challenges have included coil freezing events, and have required extensive control sequence updates and careful control loop tuning (Cheng et. al 2026).

The Modelica workflows demonstrated in this study prove that these exact operational vulnerabilities can be mitigated in a virtual environment long before a plant is physically constructed. By translating complex, written sequences of operation directly into executable CDL, engineers can subject the control logic to realistic, sub-hourly building loads. Coupled with the automated Modelica Requirements Library, this workflow systematically flags control instabilities, and helps to safely tune controllers. Establishing this unbroken digital thread from design intent to physical field controllers provides a reliable, scalable pathway to safely bring complex advanced energy systems to market. Ultimately, this dynamic simulation approach drastically reduces costly field commissioning time, eliminates human programming translation errors, and shields facility owners from the financial risk of catastrophic equipment failure.

Conclusions

This study successfully employed high-fidelity dynamic simulation to help bridge the gap between design intent and physical operation for the highly complex TIER plant. By translating written sequences of operation into executable code, the analysis formally validated the system's control logic, identifying and resolving critical operational vulnerabilities in a virtual environment to fundamentally de-risk field deployments. Furthermore, the sensitivity analysis established that a larger TES tank allows the plant to fully capture available waste heat independent of concurrent loads, and reduce peak electrical demand.

Follow-up studies will focus on tuning the TIER plant controllers to actively leverage the TES system for demand flexibility. Future simulations will evaluate predictive, rule-based pre-cooling and pre-heating strategies designed to respond dynamically to utility price signals, thereby optimizing the timing of the plant's energy draw to further minimize operational costs and alleviate peak strain on the utility grid. Additionally, subsequent research will incorporate a comprehensive techno-economic analysis that evaluates the optimized TIER plant against more traditional central plant configurations, such as conventional boiler-and-chiller systems, standard air-source heat pump designs, and consider air side heat recovery.

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AI-assisted tools used: LBNL cborg https://cborg.lbl.gov/.
Used for: writing and coding.
Extent: drafting sections and generating code.
Human review: The authors reviewed and verified all content, calculations, and citations.