Final Project Report

Energy Modeling Analysis: Peak Thermal Load Management Strategies

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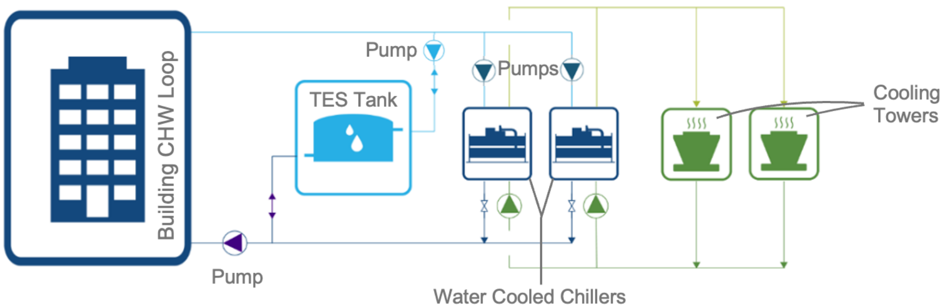

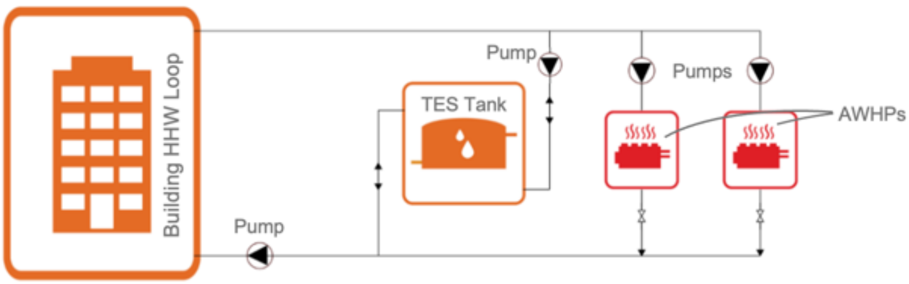

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CREDITS

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LEGAL NOTICE

EXECUTIVE SUMMARY

INTRODUCTION

This research project supports the development and implementation of California's Building Energy Efficiency Standards Title 24, Part 6 (Title 24) by providing insights into envelope and thermal energy storage (TES) design strategies along with their potential energy savings. A significant challenge in decarbonizing California's nonresidential building stock is addressing coincident peak electric demand during daily (morning and afternoon-evening) and seasonal (summer cooling and winter heating) periods. One approach is to employ building-level strategies that reduce (e.g. high-performance envelope) or shift (e.g. TES) building thermal loads to better synchronize with onsite or grid-supplied renewable energy generation. TES is not frequently used in California, with the most common usage being chilled water (CHW) ice storage. However, as space heating uses electrify, heating hot water (HHW) TES may be a valuable asset to minimize peak electric demand, reduce plant size, and support resiliency for buildings with hydronic space conditioning. This research effort is broken into two phases, this report covers Phase 2, which aims to quantify the peak demand, energy, and cost savings of two types of thermal load management strategies: TES and high-performance envelopes.

PROJECT DESCRIPTION

The Code Readiness research team (research team) completed a phased approach for this project. The initial *Technology and Market Assessment* phase (Phase 1) included a literature review and interview survey to identify key peak thermal load reduction and peak load management strategies. The research team identified seven leading strategies and summarized their regulatory, modeling, and market landscape, along with their benefits, barriers, and data gaps for each strategy.

Phase 2, documented in this report, builds on Phase 1 findings by using building energy modeling to quantify the energy and cost savings of two selected strategies: Primary TES, or sensible CHW and HHW tank storage for load shifting, and Envelope Backstop, a thermal load reduction measure with strong potential for inclusion in future Title 24 cycles.

The research team used building energy modeling software and an excel-based calculator to analyze TES energy and cost savings for both strategies across three tiers of envelope performance in two climate zones.

METHODS

Phase 2 examines TES potential in non-residential new construction buildings by utilizing two prototypes, the 2025 CBECC Large Office and ASHRAE 90.1-2022 Large Hotel. The analysis uses 2025 California Long-Term System Cost factors (LSC), specifically the non-residential electricity LSC factors, to compare energy savings and evaluate the long-term impact of energy costs in each evaluated climate zone, climate zone 10 (CZ10) and 12 (CZ12).

To complete the TES modeling analysis, the research team followed these steps:

1. **Generated building thermal loads:**
    a. Selected relevant and accurate model prototypes
    b. Identified model iterations
    c. Refined prototypes

   d. Ran models to generate baseline loads

2. **Generated TES energy and LSC savings:**
   a. Developed a TES simulator tool
   b. Sized the TES system
   c. Selected TES controls
   d. Sized each HVAC system
   e. Simulated TES for each model

3. **Analyzed results**

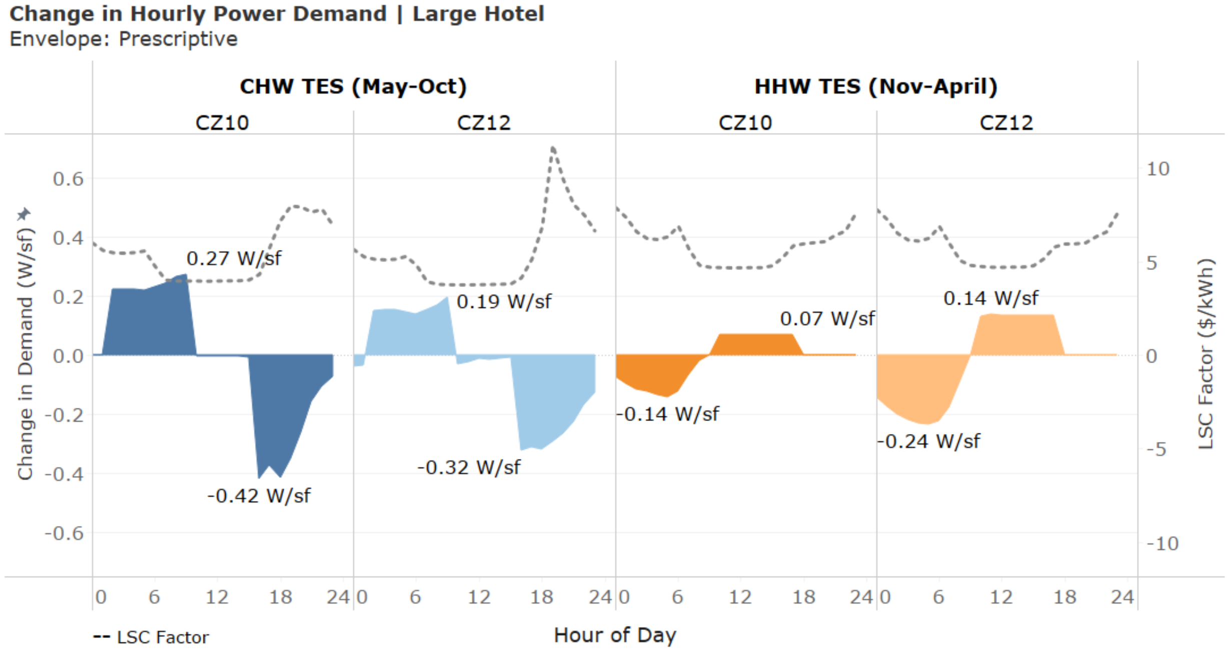
KEY FINDINGS

ENERGY AND COST SAVINGS

The research team evaluated the Large Office and Large Hotel prototypes in two representative California climate zones using a seasonal TES configuration. In this setup, the tank stores CHW during summer months (May-October) and HHW during winter (November-April). Below are the following key savings statistics:

	Large Hotel Seasonal TES Prescriptive Envelope		Large Office Seasonal TES Prescriptive Envelope	
	CZ10	CZ12	CZ10	CZ12
Annual Regulated Energy Savings (kWh)	14,468	35,877	20,306	61,205
Annual Regulated Energy Savings (%)	1.7%	4.2%	1.5%	3.9%
Regulated Energy LSC Savings ($)	$207,667	$393,463	$394,506	$788,095
Regulated Energy LSC Savings (%)	4.1%	7.6%	5.9%	9.8%
Winter Morning Peak Electric Demand Savings (W/sf)	0.14	0.24	0.46	0.69
Summer Afternoon Peak Electric Demand Savings (W/sf)	0.42	0.32	0.13	0.20

The following chart provides a visualization of the average peak electric demand impact of seasonal TES for the Large Hotel in each climate zone.



AVERAGE DAILY PEAK DEMAND SAVINGS: LARGE HOTEL, CZ12 & CZ10 (PRESCRIPTIVE)

NEED FOR TES CONTROLS ADVANCEMENT

The 2025 LSC factors indicate that carbon emissions and energy costs in California are lowest midday during sunny, hot days when solar PV offsets energy demand and highest during summer evenings and winter mornings. Historically, CHW and ice TES has been used to shift electrical loads from peak to off-peak hours, charging the TES at low electricity prices in the evening, and discharging during high prices during the afternoon. However, increased solar generation and grid electric batteries are pushing grid peak demands and prices beyond 6 p.m. on hot summer days, creating a controls challenge where peak thermal capacity and peak electric costs no longer align.

As TOU rates evolve TES controls will need the capability to be easily re-commissioned, and potentially enhanced to actively respond to real-time building and grid utility signals, to deploy TES at the optimal time. Research should be done to standardize TES control capabilities and strategies for building operators and designers when selecting and evaluate advanced integrated TES controls.

SIZABLE ENERGY SAVINGS FROM HHW TES

While CHW TES is widely used in California, the findings from the HHW TES analysis suggest this technology provides an opportunity to reduce peak heating demand and downsize electric heating equipment and lower a buildings annual operational energy cost.

PERFORMANCE PATH COMPLIANCE CONSIDERATIONS

The Title 24 performance compliance pathway permits various envelope trade-offs with other energy systems such as HVAC and lighting. This study's findings indicate sizable TES savings, which could allow excessive design flexibility in the performance pathway. Introducing TES into compliance software without safeguards on the extent of energy cost savings could lead to unintended scenarios of lower performance building envelopes. The research team recommends further investigation into an envelope backstop and TES front-stop to encourage performance compliance that prioritizes energy efficiency.

Recommendations

Title 24 Enhancements

To accelerate TES adoption in California, the research team recommends the following updates to Title 24:

1. **Incorporate HHW TES into compliance software and ACM:** Add a compliance option for HHW TES to nonresidential buildings for hydronic hot water heating loops to enable basic control strategies and functionalities similar to those defined for CHW TES.
2. **Update internal gains assumptions in ACM:** Update internal gains assumptions for nonresidential buildings by space types based on modern sources of heat gains for equipment, improving the accuracy of the average assumptions used for compliance.
3. **Establish an envelope backstop to complement TES:** The current Title 24 nonresidential performance compliance pathway for energy efficiency allows for a wide range of envelope trade-offs. With the introduction of accurate TES to compliance software there is a risk of increasing the ability to trade-off a high-performance envelope with high-efficiency HVAC systems with TES. The research team recommends the development of an envelope backstop that limits envelope trade-offs to mitigate this concern.
4. **Set limits on excessive energy trade-offs from TES:** Consider a prescriptive compliance credit limit to apply to thermal and electrical shifting technologies like TES to limit excessive energy trade-offs between building systems.
5. **Expand TES compliance options:** The current Title 24 compliance software allows for CHW thermal storage. Expand upon this configuration, allowing for other technologies such as ice storage and phase-change materials, to provide more compliance options.

Recommended Research

TES proved to have peak demand, energy, and LSC cost savings under the developed control scenarios for the selected large building prototypes in CZ10 and CZ12. While the savings are promising, further research is needed to scale TES adoption and refine cost-effectiveness in various applications. The research team recommends the following areas for further investigation:

1. **Define minimum TES configuration and control requirements** to optimize charge and discharge scheduling across multiple utility rate structures currently available compared to the long-term forecast rates of LSC.
2. **Conduct cost-effectiveness analyses:** Identify the smallest TES system size that remains cost-effective for large nonresidential buildings. Large in this context should be defined as building size or plant capacity to enable cost effectiveness in projects and a minimum TES size.

3. **Conduct field studies** on TES control strategies and maintenance to better understand operational costs and challenges.
4. **Identify standardized TES attribute terminology,** such as TES charging and discharging functionalities, to streamline use and education of those terms.
5. **Develop design guidelines** for incorporating HHW and CHW TES plant equipment sizing at peak demand. Specifically, guidance and methods for considering HHW where peak load assessment is typically done for a steady state condition only.
6. **Explore whole-building thermal performance targets** beyond the prescriptive envelope criteria. Building on Phase 1 findings, evaluate how energy codes could adopt flexible whole-envelope performance metrics or efficiency compliance credits.

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DEFINITIONS AND ACRONYMS

Acronym	Meaning
ACM	Alternative Calculation Method Reference Manual
AWHP	Air to Water Heat Pump
CEC	California Energy Commission
CHW	Chilled Water
CHW Plant	Chilled Water system plant that provides chilled water to the building hydronic loop and TES. In this report, this refers to the chillers, cooling towers, and associated equipment (primary and secondary pumps).
CW	Condenser Water
CO2	Carbon Dioxide
CZ10	CEC Climate Zone 10
CZ12	CEC Climate Zone 12
DOE	U.S. Department of Energy
HHW	Heating Hot Water
HHW Plant	Heating Hot Water system plant that provide hot water to the building hydronic loop and TES. In this report, this refers to the air to water heat pumps and associated equipment (primary and secondary pumps).
LSC, LSC $	Long-Term System Cost Rate is the CEC-projected present value of costs to California's electric energy system over a 30-year period. In this report all references to LSC savings or LSC $ use the unit 30-year net present value $/kWh.
NPV	Net Present Value
TDV	Time Dependent Value Cost Rate of the CEC-projected present value cost of California's electric energy system over time. This metric was used in 2019 and previous code cycles and replaced by LSC.
TES	Thermal Energy Storage
Title 24	Title 24, Part 6 Building Energy Efficiency Standards
PNNL	Pacific Northwest National Laboratory
SF	Square Feet
SHW HP	Service Hot Water Heat Pump
SCHW	Secondary Chilled Water
SHHW	Secondary Heating Hot Water

INTRODUCTION

This research project supports the development and implementation of California's Building Energy Efficiency Standards Title 24, Part 6 (Title 24) by providing insights into envelope and thermal energy storage (TES) design strategies along with their potential energy savings. A significant challenge in decarbonizing California's nonresidential building stock is addressing coincident peak electric demand during daily (morning and afternoon-evening) and seasonal (summer cooling and winter heating) periods. One strategy involves employing building-level strategies that reduce or shift building thermal loads, such as HVAC energy use, to better synchronize with onsite or grid-supplied renewable energy generation.[1]

While experts recognize thermal load reduction and peak thermal load management practices, such as TES, as beneficial, their exact energy savings potential remains under-researched. This second phase of the overarching Code Readiness *Peak Thermal Load Management* project addresses that gap by simulating energy usage in prototype buildings with varying envelope performance and TES systems.

This report presents the simulation results, outlines potential energy and cost savings, and provides recommendations for Title 24 enhancements. Additionally, it identifies further research efforts needed to advance codes and standards that facilitate peak electric demand management.

PROGRAM BACKGROUND

PG&E's Code Readiness, a sub-program to the Codes and Standards Program, supports the development, adoption, and implementation of California's building and appliance energy codes through long-range planning and data collection. The subprogram aligns with long-term climate and energy goals to identify key regulatory opportunities within California's energy codes and standards framework, then develops strategies to fill data gaps and overcome obstacles to successful adoption and implementation. The Code Readiness Program prioritizes energy performance, cost-effectiveness, feasibility, and code compliance data to inform regulatory advocacy.

The Code Readiness research team (research team) shown in Table 1 developed and implemented this study on *Peak Thermal Load Management*.

TABLE 1. RESEARCH TEAM

Company	Role
Pacific Gas & Electric (PG&E)	Project Sponsor, Program Administrator
2050 Partners	Project Manager, Program Implementer
A2 Efficiency	Technical Lead
Glumac	Building Energy Modeling Consultant

[1] Thermal loads can be defined as the amount of heat energy that must be added or removed from a space to maintain the desired room temperature.

Research Overview

This study follows a phased approach. The initial *Technology and Market Assessment* phase (Phase 1) included a literature review and interview survey to identify key peak thermal load reduction and peak load management strategies. The research team identified seven leading strategies and summarized their regulatory, modeling, and market landscape, along with their benefits, barriers, and data gaps for each strategy. The following list summarize these strategies.

Thermal Load Reduction

- Strategy 1: Account for Building Envelope Thermal Bridging
- Strategy 2: Introduce a Building Thermal Envelope Backstop
- Strategy 3: Increase Air Tightness Requirements
- Strategy 4: Advance Envelope Thermal Performance Requirements

Peak Load Management

- Strategy 5: Ambient Thermal Energy Source TES
- Strategy 6: Primary Thermal Energy Source TES
- Strategy 7: Small Scale Packaged TES

The Phase 1 *Technology and Market Assessment Report: Peak Thermal Load Reduction and Management Strategies* provides additional information about these seven strategies and includes a comprehensive policy overview.

Phase 2, documented in this report, builds on Phase 1 findings by using building energy modeling to quantify the energy and cost savings of two selected strategies. The research team focused on *Strategy 6: Primary TES* which in this context refers to "sensible TES," where thermal energy is stored in hot or cold water and used directly in a hydronic system that uses a liquid or vapor to heat or cool a building. This approach contrasts with "latent TES," which stores thermal energy in phase change materials and releases it during a phase change transition, such as in ice storage systems.

The research team prioritized *Strategy 6: Primary TES* over *Strategy 5: Ambient TES* as it had a better opportunity to contribute to novel research. Ambient TES is defined as stored water at a neutral temperature, such that the heating or cooling plants can draw thermal energy from the tank by raising or lowering the temperature of the water to meet the exact building needs. Ambient TES is actively being researched by other research teams in California for 2028 Title 24 code enhancement opportunities.

The team also examined *Strategy 2: Envelope Backstop*, a thermal load reduction measure with strong potential for inclusion in future Title 24 cycles. The research team used building energy modeling software and an excel-based calculator to analyze TES energy and cost savings for both strategies across three tiers of envelope performance in two climate zones.

Purpose

Phase 2 of this study examines how peak thermal load reduction strategies and load shifting with chilled water (CHW) and heating hot water (HHW) TES can reduce building peak electric demand, annual energy use, and annual energy cost. The analysis builds on Phase 1 outcomes, which prioritized TES strategies for large nonresidential building HVAC systems and explores how these systems can play a greater role in decarbonizing electricity generation and shifting building loads to off-peak times. As the electric grid evolves rapidly and the demand for fossil-free heating solutions in nonresidential buildings grows, TES presents even more opportunities to support California's decarbonization goals than previously recognized.

Objectives

Phase 2 of this study quantifies energy and cost savings of peak thermal load management and reduction strategies and identifies opportunities to integrate these strategies into Title 24.

The research team established the following research objectives for Phase 2:

- Quantify the peak electric demand and energy cost savings of TES.
- Identify energy cost-effective peak thermal load management or reduction strategies that could be adopted into Title 24.
- Identify Title 24 compliance software enhancements to increase the accuracy of building envelopes and TES systems.
- Identify considerations and recommendations related to TES system Title 24 performance compliance credit.

To address the research objectives, the research team developed the following research questions:

- What energy, cost, and peak demand savings result from using TES with hydronic space conditioning systems in California?
- How does the building thermal load profile impact TES peak electric demand and energy cost savings?
- How do different envelope performance levels that meet or exceed Title 24 requirements affect TES energy and energy cost savings?
- What design practices are important considerations to sizing hydronic heating and cooling plants and TES?
- Is it possible to reduce the hydronic heating and cooling plant size when utilizing TES?

METHODS

The Phase 2 methodology applies building energy modeling and fundamental heat transfer principles to evaluate the potential benefits of TES systems in select non-residential building prototypes (U.S. DOE n.d. A). The analysis leverages existing prototype building energy models and draws on the research team's expertise in evaluating large TES systems to investigate their potential benefits.

Phase 2 examines TES potential in non-residential new construction buildings. The analysis uses 2025 Long-Term System Cost factors (LSC), specifically the non-residential electricity LSC factors, to compare energy savings and evaluate the long-term impact of energy costs in each evaluated climate zone.

To complete the TES modeling analysis, the research team followed these steps:

1. **Generated building thermal loads:**
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3. **Analyzed results**

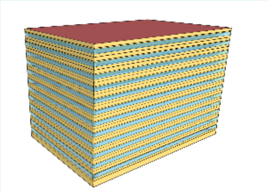
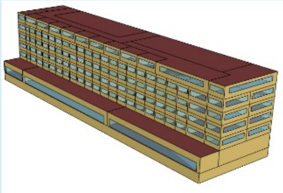
LOAD GENERATION

PROTOTYPE SELECTION

The research team evaluated the building prototypes developed by the California Energy Commission (CEC) and the U.S. Department of Energy (DOE), where both sets of building prototypes are built on the same energy modeling engine EnergyPlus, and selected two prototypes with distinct thermal load scales and prevalence to assess how TES can benefit different building types and operations (CEC n.d.; U.S. DOE B n.d.). The selection process focused on large buildings with CHW and HHW system for space conditioning, as these are most likely to integrate TES.

Initially, the research team considered hospital, large hotel, and large office prototypes. However, to align with the dominant existing building stock and projected new construction trends in California, the research team refined the selection to Large Hotel and Large Office prototypes. As a result, the research team selected and used the Large Office prototype from the 2025 Title 24 CASE process and the Large Hotel prototype from the DOE. The CEC 2022 prototype library only has a small hotel prototype, so the research team used the DOE large hotel prototype to provide the massing and key assumptions. Table 2 provides prototype details. Across both models thermal envelope performance and weather data were updated to match the Title 24 compliance assumptions for a new construction building.

TABLE 2. SUMMARY OF PROTOTYPE ELEMENTS

Model Element		Large Office Prototype	Large Hotel Prototype
Building Massing			
Prototype Source		CEC [1]	DOE [2]
Prototype Software and Engine Used		CBECC 2025.04.RV (EnergyPlus 9.4)	EnergyPlus 22.1
Architecture	Thermal Construction	2022 Title 24 Part 6 ACM	
	Air Leakage Rates		
System Use	Space Use Types	2022 Title 24 Part 6 ACM	DOE, ASHRAE 90.1 2022
	Internal Gain Values		
	Internal Gain Schedules		
HVAC System Efficiencies	Fan System	2022 Title 24 Part 6 ACM	DOE, ASHRAE 90.1 2022
Weather Data		2025 Title 24 Compliance Weather Data	
LSC Version		2025 Title 24 Non-Residential Electricity LSC	
Conditioned Floor Area (ft^2)		498,598	122,119
Number of Stories		13 1 below ground, 13 conditioned floors	7 1 below ground basement, 7 conditioned floors

[1] Source: CEC 2024
[2] Source: U.S. DOE 2024

ITERATION IDENTIFICATION

During Phase 1, the research team identified that a key strategy for reducing a building's peak thermal load is to minimize the overall thermal demand by optimizing the envelope through improved insulation, air sealing, thermal bridging mitigation, and refined envelope accounting. Therefore, when analyzing TES, the research team sought to understand how TES performs in buildings with varying envelope performance. To explore this, the research team identified three envelope iterations for evaluation:

1. **A mandatory minimum envelope** that builders often select by installing other high-efficiency measures and trading off envelope performance under the Title 24 performance pathway.
2. **A prescriptive envelope**, which builders follow if complying with the Title 24 prescriptive pathway.

3. **An enhanced envelope** that is a high-performance envelope and includes measures such as improved insulation, air sealing, and fenestration.

Each envelope iteration is outlined in the following *Envelope* section.

Another critical factor to evaluate was building location, or climate zone. The research team selected Climate Zone 10 (CZ10), representing cities such as Riverside, California, a cooling-dominated climate with a notable winter heating load, and Climate Zone 12 (CZ12), representing cities such as Sacramento, California, which have a more balanced profile with comparable heating and cooling demands. The research team ran each set of model iterations in CZ10 and CZ12.

Prototype Refinement

Internal Gains

During Phase 1, the research team identified a modeling accuracy gap in the Title 24 compliance software, specifically in the internal gains, receptacle load, and assumptions for non-residential space types. Recent research by Pacific Northwest National Laboratory (PNNL) found that the average office building's internal gains are 0.66 W/sf (PNNL 2024). In contrast, the Title 24, Part 6 ACM sets internal gains and receptacle loads for non-residential office areas at 1.5 W/sf.

Although PNNL's value was developed using a different methodology than the space type assumptions in the Title 24, Part 6 ACM, research, most notably ASHRAE RP 1742 in 2018, shows that ACM office internal gains exceed field collected data. ASHRAE RP 1742 found that in office buildings, by counting equipment to estimate plug loads ranged from a load factor of 0.34 W/sf in offices with mostly laptops to 1.53 W/sf in offices with heavy desktops and multiple screens (Sarfraz and Bach 2017). Based on these findings, the research team adjusted the Large Office prototype's internal gains to align with the PNNL value of 0.66 W/sf.

The research team did not modify the internal gains for the Large Hotel prototype, leaving them as defined by the DOE. For this analysis internal gains appeared relatively consistent or higher than internal gains for equivalent space types in Title 24, so they were left unchanged. A comparison chart of the internal gains is included in Appendix A, section Internal Gain Assumptions.

Envelope

The research team developed three envelope performance scenarios to represent:

1. **Mandatory:** The lowest insulation levels defined by the mandatory minimum criteria,
2. **Prescriptive:** The prescriptive requirements, and
3. **Enhanced:** A set of enhanced envelope performance requirements informed by the literature review and interviews in this project.

For both building prototypes, the research team maintained the same construction assembly makeup for roof, walls, and glazing, as both buildings exceed 100,000 square feet.

Each envelope iteration accounted for two major factors affecting building model assumptions: Thermal bridging heat losses between assemblies (e.g., where the wall meets the roof), and Envelope infiltration.

The following table outlines the key elements of each envelope iteration—mandatory, prescriptive, and enhanced—for both prototypes. Additional details on air leakage calculations may be found in *Appendix A. Methodology Tables*.

Table 3. Prototype Envelope Inputs and Characteristics

Enclosure Component Type	Mandatory	Prescriptive	Enhanced
Envelope Construction Type	Other Roof (Insulation entirely above deck) Metal Framed Walls		
Roof U-factor / R-Value	0.075 / R-13.3	0.034 / R-29.4	0.025 / R-40
Fenestration U-Value	0.47	0.34	0.30
Fenestration SHGC	0.70	0.22	0.22
Wall U-factor / R-Value	0.151 / R-6.6	0.055 / R-18.2	0.043 / R-23.3
Air Leakage (CFM/sf of Exterior Wall Area)	0.3696	0.2352	0.1344

The research team incorporated linear thermal bridging at key connection points, including the window frame edge and wall, exterior wall and ground, exterior wall and roof, and interior floor and exterior wall. These considerations resulted in the thermal transmittance values shown in Table 4. Additional details on the thermal bridging approach are available in *Appendix A. Methodology Tables*.

The following table compares the heat transmission (or UA[2], in Btu/h°F) of each envelope package under two conditions:

1. Using the standard model assumptions that exclude thermal bridging effects, and
2. Incorporating thermal bridging effects.

Table 4. Prototype Envelope Heat Transmittance

	Total Envelope Heat Transmittance, UA [1]		
	Mandatory	Prescriptive	Exceeds
Large Office (w/o Thermal Bridging)	45,164	26,128	23,305
Large Office (w/ Thermal Bridging)	48,149	29,114	26,291
Large Hotel (w/o Thermal Bridging)	14,281	7,811	6,844
Large Hotel (w/ Thermal Bridging)	15,601	9,130	8,136

[1] Source: ANSI/ASHRAE/IES Standard 90.1-2022, Table A10.1 Thermal Bridging Psi-Factors & Chi-Factors for Thermal Bridges, addition information in *Appendix A. Methodology Tables*.

The impact of thermal bridging ranges from 6% to 20%, with greater effects observed in higher-performance envelope packages. This occurs because the thermal bridging derating UA remains constant but has greater influence as overall envelope performance improves.

Baseline Results

The following chart presents the CZ12 model baselines after refining the prototypes. In the Large Office, heating and cooling account for 36% of the building's energy use, totaling 7.3

[2] UA is the sum of U-factor times envelope area.

kBtu/sf with the prescriptive envelope. In the Large Hotel, heating and cooling make up for 22% of the total energy use, or 11.3 kBtu/sf, with the prescriptive envelope due to higher energy demands for cooking and service hot water.

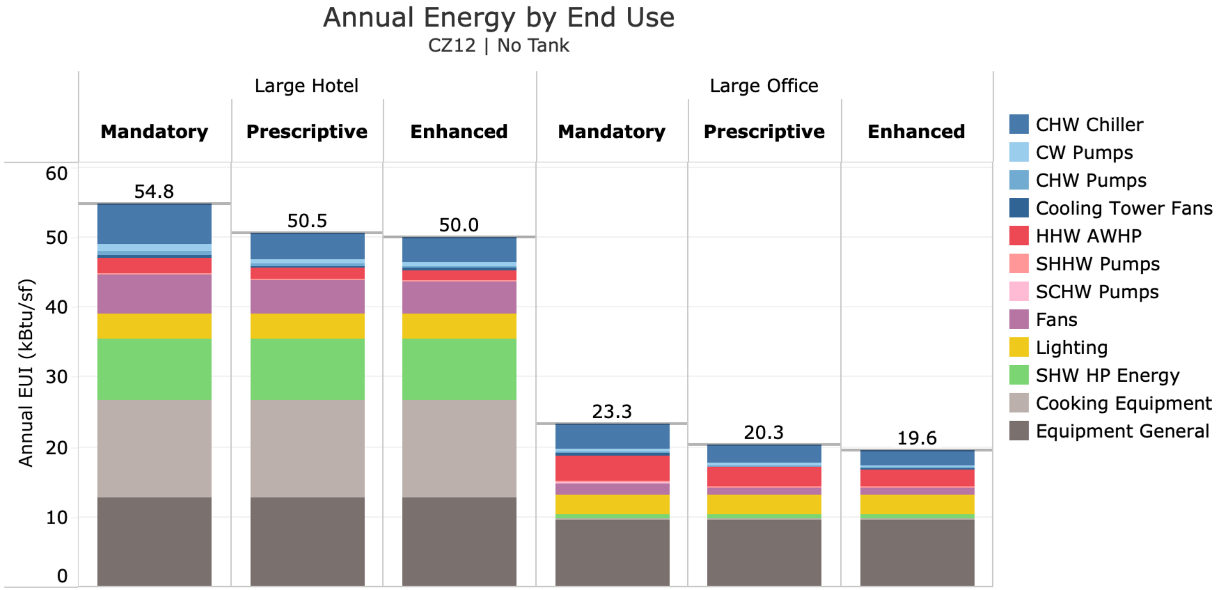


Figure 1. Energy Use Intensity for Each Building Prototype Envelope Configuration in CZ12

CZ10 shows similar results to the energy use patterns in CZ12. In the Large Office, heating and cooling account for 33% of the building's energy use, totaling 6.2 kBtu/sf with the prescriptive envelope. In the Large Hotel, heating and cooling make up for 23% of the total energy use, or 11.5 kBtu/sf, with the prescriptive envelope due to higher energy demands for cooking and service hot water. Located in Southern California, CZ10 has fewer heating hours but more cooling hours.

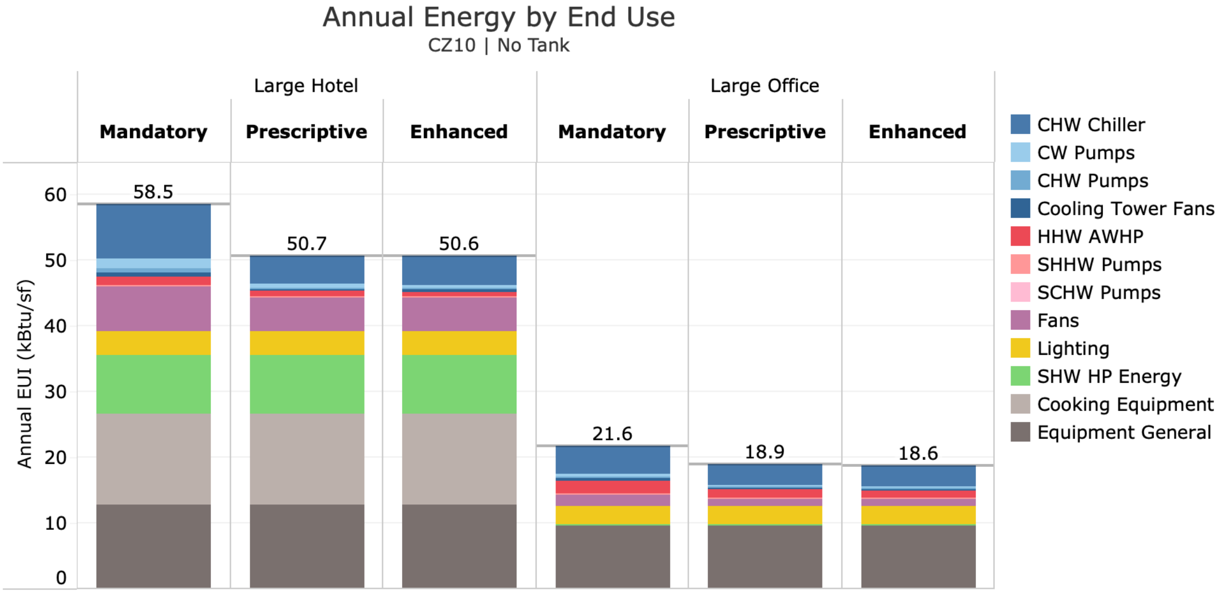


Figure 2. Energy Use Intensity for Each Building Prototype Envelope Configuration in CZ10

TES Energy and LSC Savings Generation

TES Model

Glumac led the development of the TES model and HVAC sizing for each iteration. The model, an Excel-based calculator designed to quantify the energy impact and LSC of TES in buildings. Leveraging hourly calculations, the model accommodates any CHW and HHW load profile. For this study, the research team generated 12 hourly load profiles from prototype models, representing various building types, envelope performance levels, and climate zones with high potential for TES. For each building iteration, the model calculated the CHW and HHW plant energy consumption with and without TES.

Long-Term System Cost (LSC)

LSC is the CEC-projected present value of costs to California's energy system over a 30-year period, representing the hourly cost of marginal generation, transmission and distribution, fuel, capacity, losses, and cap-and-trade-based carbon dioxide (CO_2) emissions (Energy Code Ace n.d.). As the successor to time dependent value (TDV), LSC factors were introduced for the 2025 Title 24. This study uses non-residential electricity LSC factors, with a unit of 30 year net present value (NPV) $/kWh (LSC $) to compare energy savings and evaluate the long-term impact of energy costs.

Regulated Energy

In Title 24 compliance, building energy end uses fall under "regulated energy," end uses that are subject to meeting Title 24 efficiency requirements, and non-regulated energy, end uses that are always treated as compliance neutral . Regulated energy, also known as compliance total energy, includes space conditioning, domestic and service water heating, and indoor lighting energy uses. This excludes all exterior lighting, process based energy uses such as cooking and laundry and receptacle (plug load) energy usage. In Title 24, regulated energy is the same set of energy end uses as those included in the "Total LSC Energy," which represents the total energy cost of regulated energy end uses (CEC 2023). Throughout this report the research team refers to regulated energy savings and regulated energy LSC, as those are the key values relevant to Title 24 compliance.

TES Model Inputs and Assumptions

Prototype Outputs

- Weather conditions, including dry-bulb, wet-bulb, humidity ratio.
- The loop demand comes from the EnergyPlus output "Plant Supply Side Cooling/Heating Demand Rate," and is sourced from the baseline model results outlined in the Load Generation section.

Calculated Values

- The secondary loop flow is calculated based on hourly loop demand and design delta T.
- The secondary pump power is determined by using pump affinity law with a modified power exponent for variable-speed operation.

Additional Assumptions

- A single TES system is used for both heating and cooling storage, changing between heating hot water and chilled water storage based on season.

HVAC System Design

Table 5 outlines the key design parameters for each system plant. The office and hotel plants were identical.

Table 5. Key HVAC System Design Parameters

	Chilled Water Plant	Heating Hot Water Plant
Simple description	Water Cooled Chillers and Cooling Towers	Air to Water Heat Pumps
Pumping Arrangement & Controls	Primary: Constant Speed Secondary: Variable Speed	Primary: Constant Speed Secondary: Variable Speed
Primary Pump Power (W/gpm)	8	8
Secondary Pump Power (W/gpm)	22	20
Leaving Design Water Temperature (F)	44	130
Assumed loop delta T (F)	20	20
Rated Full Load Efficiency (COP)	6.28	2.77
Cooling Tower gpm/hp	42.1	NA
Condenser Pump Power (W/gpm)	12	NA

The following sections describe the cooling and heating plants. Additional TES plant parameters can be found in *Appendix B. Additional TES Model Methodology Details*.

Chilled Water Plant

The research team modeled the chilled water plant in a primary-secondary loop configuration with water-cooled chillers. The secondary loop uses variable-flow with variable-speed pumps, and each chiller has a dedicated constant-flow primary pump. The research team varied the number of chillers in the system for each model.

The research team modeled the condenser water loop with open cooling towers and dedicated constant-flow primary pumps for each chiller, assuming the number of cooling towers equals to the number of chillers. Figure 4 provides an example of the CHW plant with two chillers and no TES.

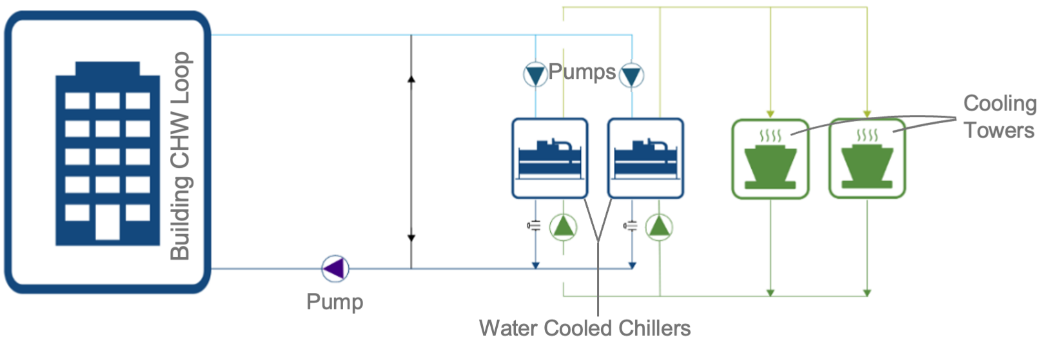


Figure 3. CHW Loop Setup without TES

In this model, the TES storage temperature matches the CHW supply temperature of 44°F. For TES-equipped models, the research team minimized the primary equipment capacities as much as possible while still meeting all space loads.

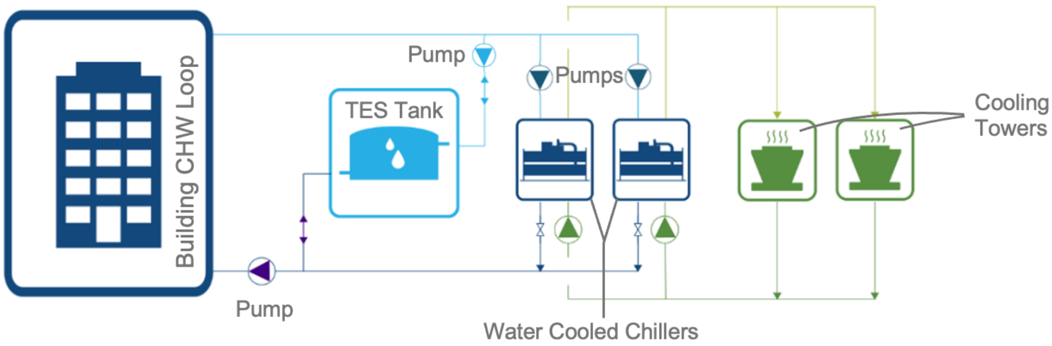


FIGURE 4. CHW LOOP SETUP WITH TES

Heating Hot Water Plant

The base heating hot water plant uses a primary-secondary loop configuration, with air-to-water heat pumps (AWHP) supplying the entire load. The secondary loop operates with variable-flow with variable-speed pumps, while each AWHP has a dedicated constant-flow primary pump. The number of AWHPs in the system can be adjusted for each model. Figure 6 shows an example of the HHW plant with two AWHPs and no TES.

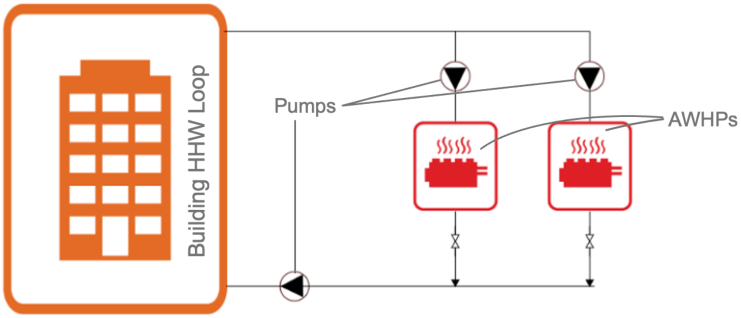


FIGURE 5. HHW LOOP SETUP WITHOUT TES

Like the chilled water loop, the HHW loop model with TES maintains a supply temperature of 130°F for TES storage. In models with TES, primary equipment capacities are minimized while still meeting all space loads.

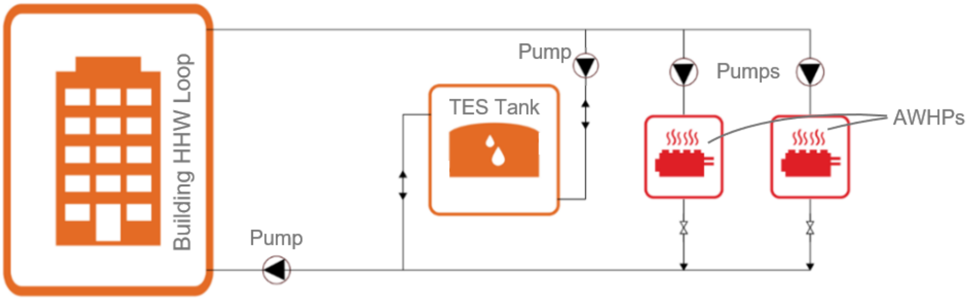


FIGURE 6. HHW LOOP SETUP WITH TES

This system works by having the TES tank serve as a source of HHW in discharge mode, with heat flowing from the tank or the heat pumps, and the flow of water reversing through the tank when the TES tank is recharged and acts as a thermal load.

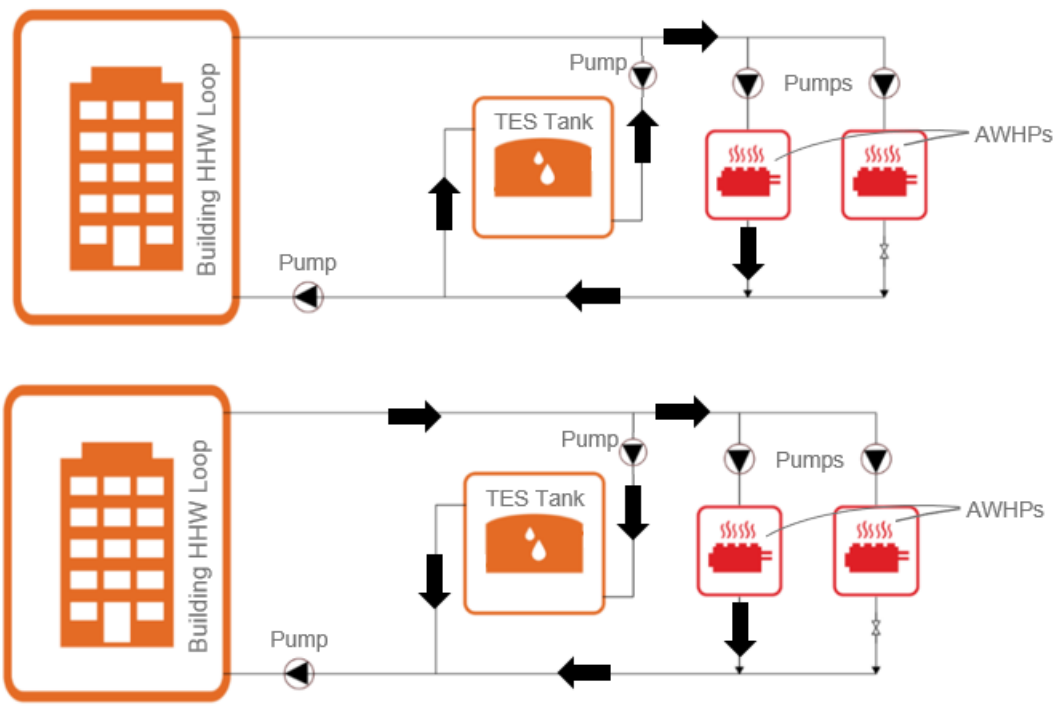


Figure 7: HHW Loop Operating in TES Charging (upper diagram) and Discharging (lower diagram)

TES Sizing Approach

The literature review and technical interviews revealed there is no one standardized approach for sizing TES systems. Some designers evaluate peak thermal loads, while others note they are primarily constrained by site limitations and available space. Initially, the research team considered sizing the TES to serve 100% of the building's demand during the peak 1-3 hours aligning with peak LSC. However, this approach resulted in oversized storage tanks that were impractical for building designers and operators due to space and cost constraints.

Instead, the research team assessed each prototype and selected a storage size that was feasible in terms of both square footage and volume, making it appropriate for real-world applications. To determine the appropriate range, the research team reviewed available drawings of TES installations in nonresidential and multifamily buildings over 100,000 square feet. This analysis identified a tank size-to-floor area ratio between 0.75% and 2%. Table 6 outlines the selected storage tank sizes and tank size to floor area ratio.

Throughout this report, "TES tank" means the array of TES tanks that serve the system.

Table 6. TES Tank Size Summary

Component	Large Office Prototype	Large Hotel Prototype
Total Floor Area (sf)	498,598	122,119
Number of Floors	13	7

Component	Large Office Prototype	Large Hotel Prototype
Area Per Floor	38,354	17,445
Prototypical Tank	5,000 gallons, 10'x10'x8.5', 256 ft^2 each	
Total Tank Capacity (Gallons)	75,000	45,000
Tank Total Occupied Floor Area (square feet)	3,840	2,304
Percent TES Floor Area of Total Building Floor Area	0.77%	1.89%

Figure 8 shows an elevation section view of a tank room with a typical 5,000-gallon tank, required clearances, and a scale figure for reference.

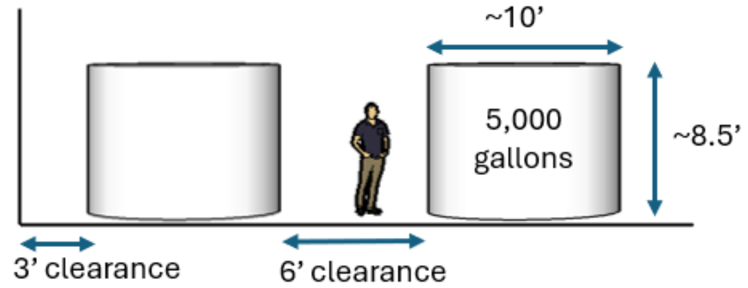


FIGURE 8. ELEVATION SECTION VIEW OF TANK

Figure 9 illustrates a "five-by-three" layout of the tank room for the Large Office prototype. A similar layout would apply to the large hotel but with a three-by-three configuration.

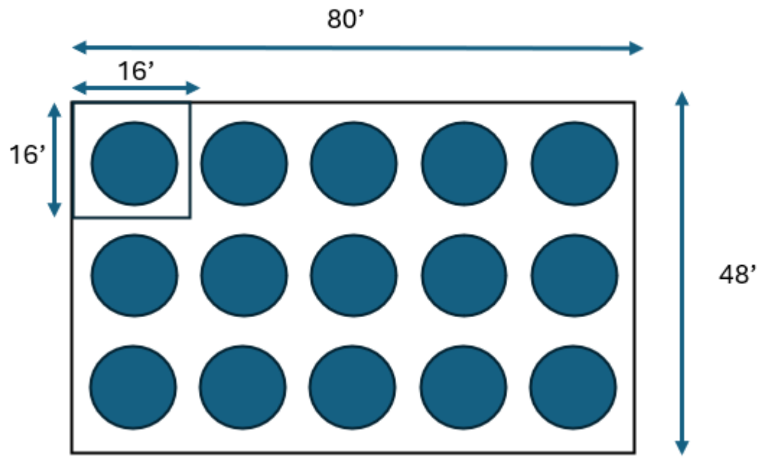


FIGURE 9. LARGE OFFICE TANK LAYOUT

For this analysis, the research team assumed the tanks used 100% water to simplify calculations. Additionally, the research team assumed the tanks to be perfectly insulated to isolate the benefits of thermal load shifting and the potential magnitude of those benefits at this stage of research.

TES Control

TES controls have three key attributes: mode, duration, flow rate, each varying by season and daily operation.

TES Modes

The three distinct control modes are charging, discharging, and off modes.

- **In charging mode,** the heating or cooling plant serves the immediate space conditioning needs and then fills or "charges" the TES tank with hot or cold water with any additional available plant capacity.
- **In discharging mode**, the system utilizes the TES tank as a first source of hot or cold water, where the tank supplies or "discharges" hot or cold water to the hydronic loop. In cases where the TES does not meet the building's load, the system utilizes the heating or cooling plant as needed to meet space conditioning needs. In this way, the system offsets as much mechanical space conditioning energy as possible with stored energy to reduce peak electric demand (kW) when the grid is experiencing high demand (e.g. summer late afternoons and winter early mornings).
- **In off mode**, the TES tank is not utilized, and the heating or cooling plant serves the space conditioning needs.

Figure 10 shows the percentiles and average LSC $/kWh factors for CZ12 throughout the year. To minimize building LSC energy costs, the ideal TES charging period occurs during low LSC factors, roughly between 6:30 a.m. and 4:30 p.m., while the optimal discharging period aligns with high factors, approximately between 4:30 p.m. to 6:30 a.m.

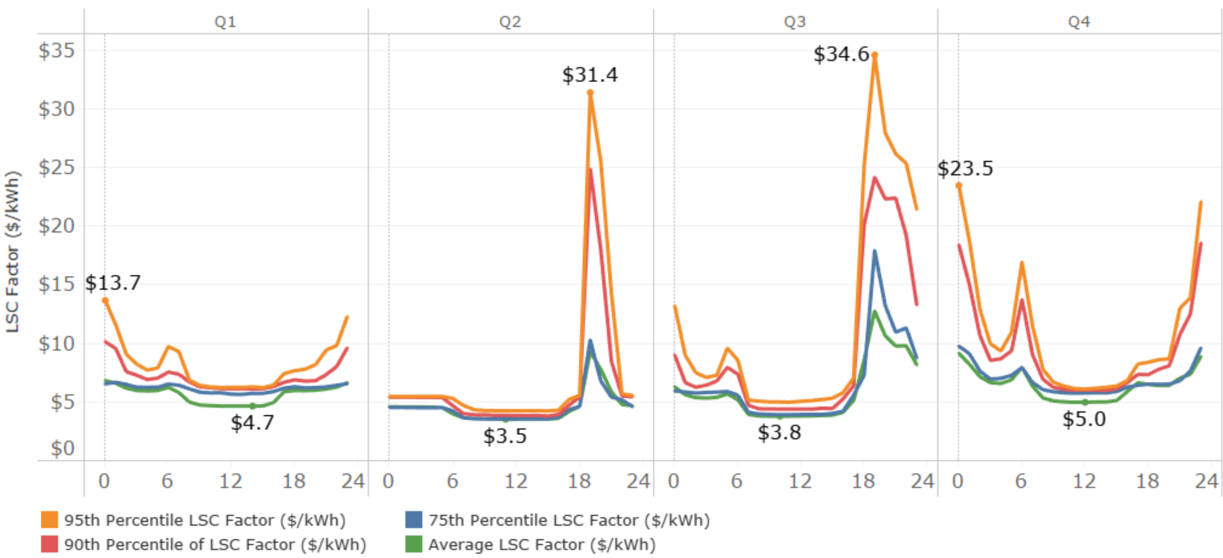


FIGURE 10. 2025 TITLE 24 NON-RESIDENTIAL ELECTRICITY LSC FACTORS, CZ12

TES Charge and Discharge Duration

The duration of each TES control mode is a key factor in system performance. The ideal charge and discharge durations depend on the type of building and its space heating and cooling load profiles.

For large office buildings, the 24-hour space heating load profile features a significant and abrupt heating demand in the early morning, commonly known as the "morning warmup" period. During this time, the building activates mechanical ventilation and adjusts setpoint temperatures to compensate for colder outdoor air temperatures and limited internal gains before occupants arrive.

To determine the optimal duration for each mode, the team overlaid the average 24-hour space conditioning loads with the average 24-hour LSC rate for the corresponding climate zone and heating or cooling season, identifying periods of overlap.

Figure 11 highlights the heating discharge mode in green, from 4 AM to 10 AM. The charging period, when space conditioning loads are minimal and LSC factors are lowest, is highlighted in orange from 10 AM to 4 PM.

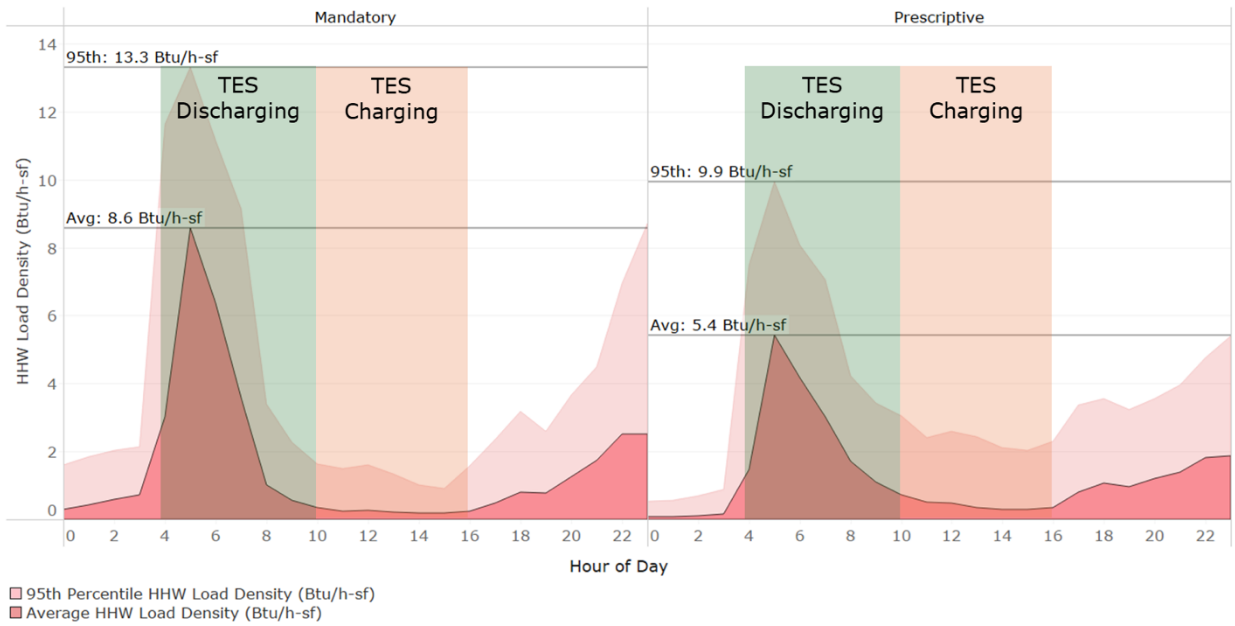


FIGURE 11. LARGE OFFICE CLIMATE ZONE 12 – QUARTER 1 & 4 - AVERAGE 24 HOUR HHW LOAD PER SQUARE FOOT

A large hotel's 24-hour space heating load profile features prolonged heating demand throughout the night and early morning. This occurs because the building maintains setpoint temperatures and mechanical ventilation overnight while experiencing lower internal gains and colder outside air temperatures. To address this, the research team selected a longer discharge period, from 12 a.m. to 9 a.m., to capture all nighttime thermal loads when LSC factors are higher.

For charging, the research team chose a midday period similar to the large office from 10 a.m. to 5 p.m. This timing aligns with lower LSC factors, reduced operation, and warmer outdoor air temperatures, which improve AWHP performance and capacity.

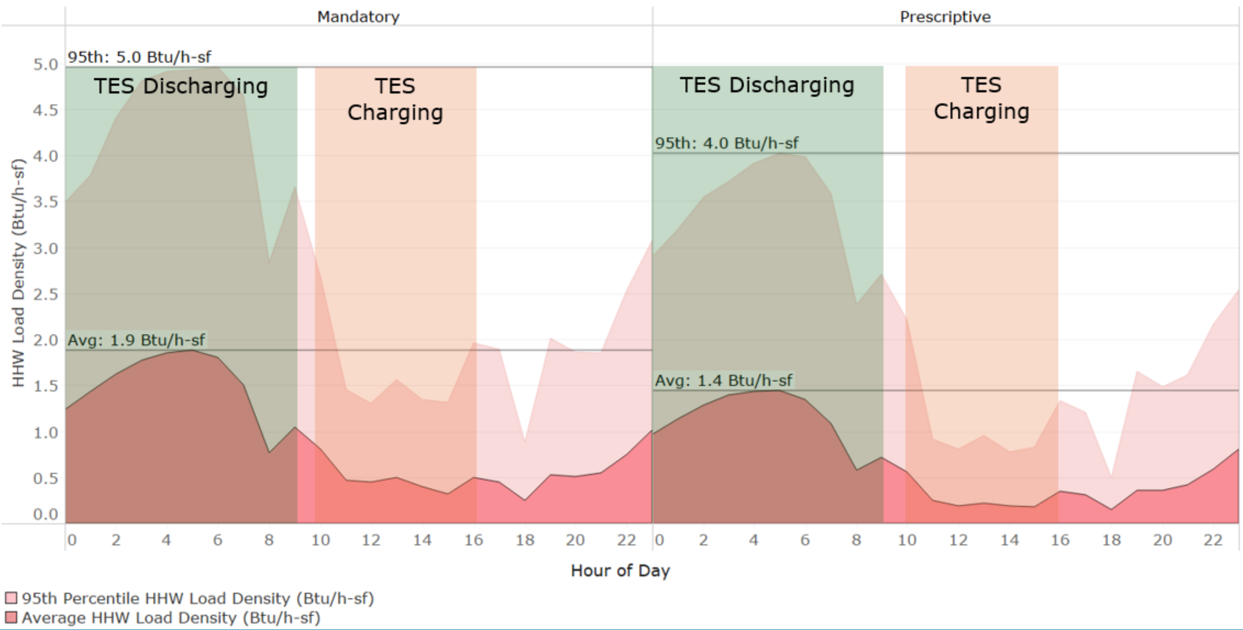


FIGURE 12. LARGE HOTEL CZ12 – QUARTER 1 & 4 AVERAGE 24-HOUR HHW LOAD PER SQUARE FOOT

The large office's 24-hour space cooling load peaks midday when the building maintains its setpoint temperature, operates ventilation during high internal heat gains, and experiences higher outdoor air temperatures and solar gains. However, by late afternoon, most cooling load contributors decrease due to setback temperatures, reduced internal gains, and moderate outdoor air conditions. As a result, cooling demand drops just as the LSC rate climbs, creating a non-ideal coincidence.

To optimize efficiency, the research team set the cooling charge period from 3 a.m. to 10 a.m., when cooling loads are minimal and outdoor air temperatures are lower, improving CHW plant performance. Chilled water is discharged from 5 p.m. to 12 a.m. to manage any remaining afternoon load when LSC factors are high.

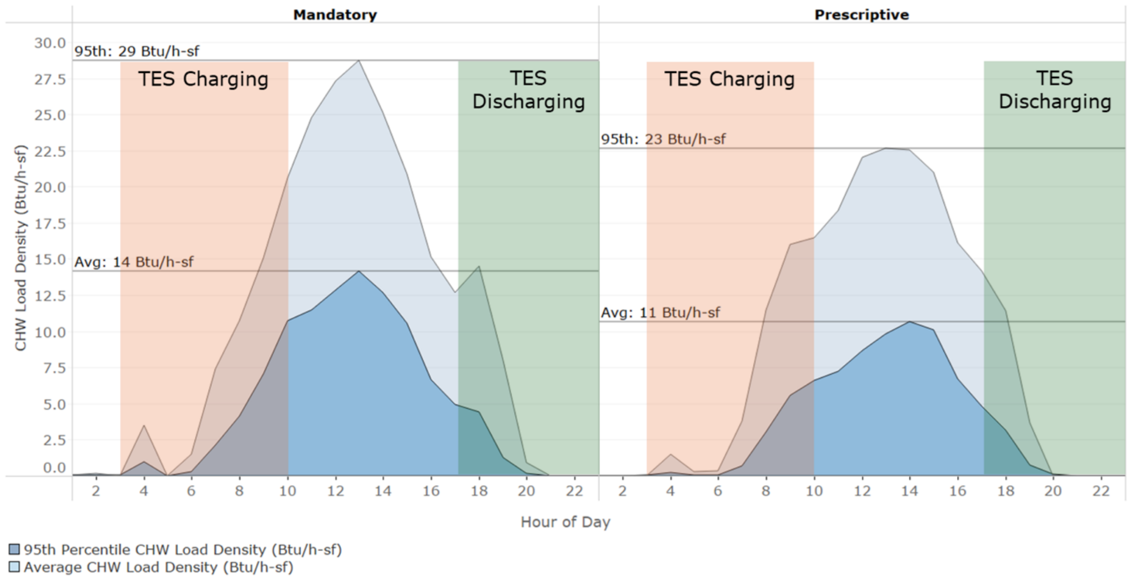


FIGURE 13. LARGE OFFICE CZ12 – QUARTER 2 & 3 AVERAGE 24-HOUR CHW LOAD DENSITY

In contrast, the Large Hotel's cooling load shape aligns well with a TES system. Cooling demand remains steady throughout the day due to varying occupancy levels and the continuous operation of common areas, and peaks in the late afternoon as guest room occupancy increases. To optimize CHW plant efficiency, the research team set the CHW TES charging period from 2 a.m. to 10 a.m., when operation is lower and outdoor air temperatures are cooler. The CHW TES discharges from 4 p.m. to 12 a.m. to align with high afternoon LSC factors.

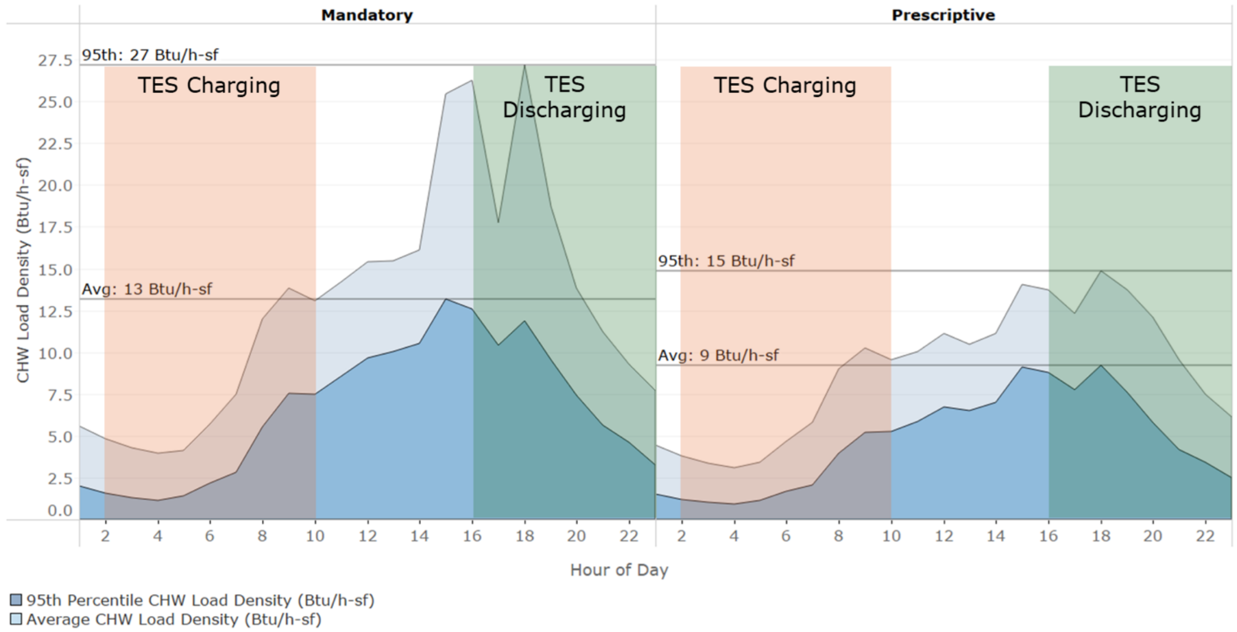


FIGURE 14. LARGE HOTEL CZ12 – QUARTER 2 & 3 AVERAGE 24-HOUR CHW LOAD DENSITY

TES Flow Rate

TES flow rate determines how quickly water flows in and out of the system, affecting the charging and discharging speed per hour. This rate depends on the piping and distribution layout set by the designer. In this analysis, the maximum TES charging and discharging flow rate does not exceed the primary flow rate of an individual component used for space conditioning. However, it is further limited by the capacity (ton-hours) of the selected tank size.

TES Frequency

Since TES introduces a layer of control complexity beyond the typical knowledge base of many building operators, this study adopts a consistent daily charge and discharge cycle as a conversative first step in estimating TES savings potential. While optimizing mode durations and variable flow factors could increase savings, these adjustments also add complexity for building operators.

Given the large spatial footprint of TES, the research team modeled a system that serves both heating and cooling, maximizing tank cost-effectiveness. The TES operates in heating mode for six months (Quarters 1 and 4) and in cooling mode for the remaining six months. While separate TES tanks for heating and cooling could provide some additional savings, the observed benefits were minimal due to lack of substantial winter cooling and summer heating in the prototype models. Moreover, the dedicated tank arrays would potentially double the required floor space and increase costs while offering only marginal savings.

HVAC Sizing Method

The study evaluated electric energy savings, peak demand reduction, and potential first cost savings associated with reducing the HVAC system size. The research team sized the CHW and HHW plants, to meet the annual peak load while minimizing unmet load hours for each building scenario based on the annual thermal load profile. This method prioritized simplicity and differed from a detailed design approach, which would account for design-day profiles and operational risk factors to ensure reliable capacity—ultimately leading to larger equipment.

Table 7. Large Office Iteration HVAC Sizes

	Large Office, CZ12				Large Office, CZ10			
	No TES		TES		No TES		TES	
	Heating Plant	Chilled Water Plant	Heating Plant	Chilled Water Plant	Heating Plant	Chilled Water Plant	Heating Plant	Chilled Water Plant
Mandatory	4x 3,000 kBtu/h	2x 850 tons	3x 2,800 kBtu/h	2x 850 tons	3x 3,500 kBtu/h	2x 700 tons	2x 2,650 kBtu/h	2x 700 tons
Prescriptive	3x 3,000 kBtu/h	2x 650 tons	3x 1,600 kBtu/h	2x 650 tons	3x 2,400 kBtu/h	2x 700 tons	2x 1,600 kBtu/h	2x 700 tons
Enhanced	3x 3,000 kBtu/h	2x 600 tons	3x 1,600 kBtu/h	2x 600 tons	2x 3,000 kBtu/h	2x 600 tons	2x 1,500 kBtu/h	2x 600 tons

Table 8. Large Hotel Iteration HVAC Sizes

	Large Hotel, CZ12				Large Hotel, CZ10			
	No TES		TES		No TES		TES	
	Heating Plant	Chilled Water Plant	Heating Plant	Chilled Water Plant	Heating Plant	Chilled Water Plant	Heating Plant	Chilled Water Plant
Mandatory	2x 650 kBtu/h	2x 250 tons	2x 550 kBtu/h	2x 200 tons	2x 550 kBtu/h	2x 300 tons	2x 350 kBtu/h	2x 300 tons
Prescriptive	2x 500 kBtu/h	2x 150 tons	2x 400 kBtu/h	2x 100 tons	2x 425 kBtu/h	2x 85 tons	2x 325 kBtu/h	2x 85 tons
Enhanced	2x 450 kBtu/h	2x 120 tons	2x 375 kBtu/h	2x 100 tons	2x 400 kBtu/h	2x 80 tons	2x 300 kBtu/h	2x 80 tons

RESULTS

KEY FINDINGS

The research team evaluated the Large Office and Large Hotel prototypes in two representative California climate zones using a seasonal TES configuration. In this setup, the tank stores CHW during summer months and HHW during winter. Key findings include:

1. **Energy and Cost Savings:** TES provided measurable energy and cost savings across both building protypes in CZ10 and CZ12, using the prescriptive envelope:
   a. Regulated annual energy savings ranged from 1.5% to 4.2%.
   b. Regulated energy LSC savings ranged from 4.1% to 9.8%.
   c. Average morning peak heating demand savings ranged from 0.14 to 0.69 W/sf.
   d. Average afternoon peak cooling demand savings ranged from 0.13 to 0.42 W/sf.
2. **Significant Energy Savings from HHW TES:** While CHW TES is widely used in California, the findings from the HHW TES analysis suggest this technology provides an opportunity to reduce peak heating demand and downsize electric heating equipment and would likely lower peak and annual operational energy costs.
3. **Need for Flexible Configurations of Controls:** TES systems are traditionally controlled on a fixed schedule based on the building's rate structure during commissioning. However, rates and peak periods are evolving with increased grid solar generation and electric batteries. As TOU rates evolve TES controls will need the capability to be easily re-commissioned, and potentially to actively respond to real-time building and utility signals, to optimize HVAC plant and TES assets. Research should be done to standardize TES control capabilities and strategies for building operators and designers when selecting and evaluate advanced integrated TES controls.
4. **An Envelope Backstop would Complement TES:** The Title 24 performance compliance pathway permits various envelope trade-offs. Introducing TES into compliance software without safeguards could lead to high-efficiency HVAC systems with TES being used to offset lower envelope performance. The research team recommends implementing an envelope backstop for non-residential buildings to prevent excessive trade-offs.

TES ENERGY COST SAVINGS

The research team analyzed three TES configurations to assess potential energy cost savings using 2025 LSC factors:

1. CHW TES during six summer months, May through October. In this scenario no TES is utilized in the winter months.
2. HHW TES during six winter months, November through April. In this scenario no TES is utilized in the summer months.
3. Seasonal TES, where the same tank is used for HHW TES in the six winter months (Nov-April) and for CHW TES in the six summer months (May-Oct).

Figure 15 illustrates 30-year LSC savings for the seasonal TES and the individual contributions of CHW and HHW TES system for each prototype and climate zone.

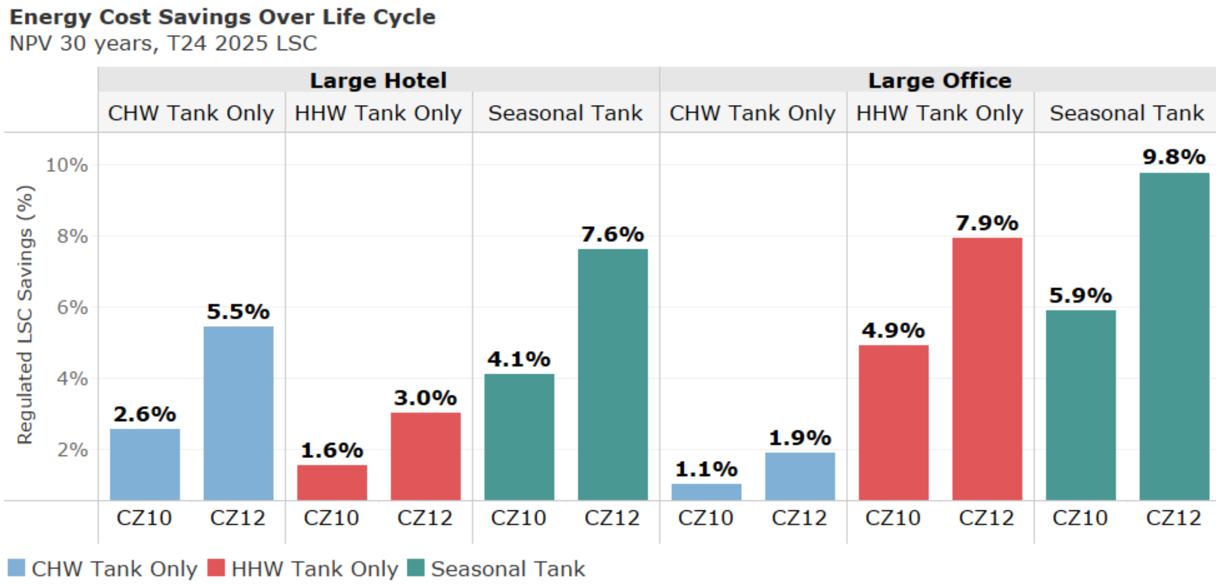


FIGURE 15. LSC ENERGY COST SAVINGS

Table 9 presents the regulated energy and LSC savings in table format. The seasonal TES lowered the regulated LSC energy costs by 4.1-7.6% for the Large Hotel, and 5.9-9.8% for the Large Office.

TABLE 9. SEASONAL TES ENERGY AND LSC SAVINGS FOR LARGE HOTEL AND LARGE OFFICE (PRESCRIPTIVE ENVELOPE)

	Large Hotel		Large Office	
	CZ10	CZ12	CZ10	CZ12
Regulated Energy without TES (kWh)	862,107	856,308	1,348,982	1,555,832
Regulated Energy with TES (kWh)	847,639	820,431	1,328,676	1,494,627
Regulated Energy Savings (kWh)	14,468	35,877	20,306	61,205
Regulated Energy Savings (%)	1.7%	4.2%	1.5%	3.9%
Regulated LSC Cost without TES (LSC $)	$5,048,587	$5,157,498	$6,680,393	$8,065,092
Regulated LSC Cost with TES (LSC $)	$4,840,919	$4,764,035	$6,285,887	$7,276,997
Regulated LSC Cost Savings (LSC $)	$207,667	$393,463	$394,506	$788,095
Regulated LSC Cost Savings (%)	4.1%	7.6%	5.9%	9.8%

The following paragraphs explore the load shapes with TES for each prototype and identify elements that impacted energy and LSC savings.

Figure 16 shows that the Large Office HHW TES achieves the highest LSC savings due to the sharp rise in winter morning energy costs. In contrast, the Large Office CHW TES provides modest energy savings. Figure 16 shows that thermal loads and HVAC electrical demands decrease rapidly after 6 p.m., when energy costs peak, which limits potential LSC cost savings.

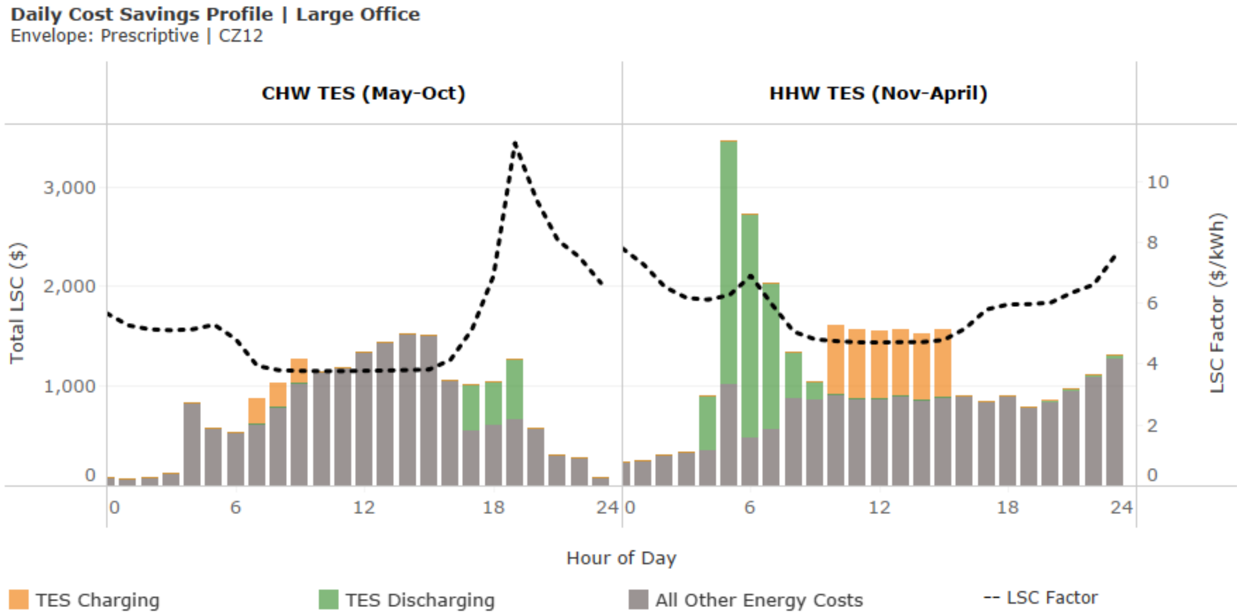


FIGURE 16. AVERAGE DAILY LSC: LARGE OFFICE, CZ12 (PRESCRIPTIVE ENVELOPE)

The Large Hotel prototype achieved greater energy cost savings overall compared to the Large Office due to its steady thermal load profiles for both heating and cooling, allowing TES to be effectively deployed during high-cost hours. Figure 17 shows the consistent thermal loads and extended evening cooling demand, enabling CHW TES to significantly reduce peak loads.

The Large Office HHW TES achieved significant savings because the peak heating event was brief each morning, allowing TES to frequently cover the entire heating load. In contrast, the Large Hotel required sustained heating throughout the morning, requiring both the TES and the heating system.

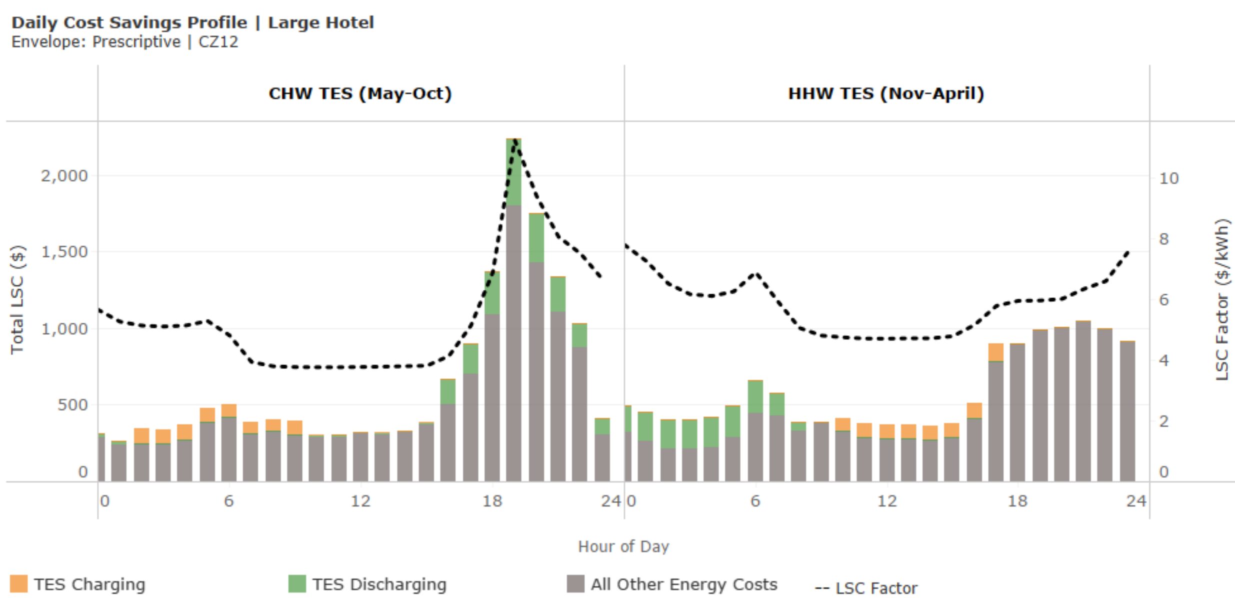


FIGURE 17. AVERAGE DAILY LSC: LARGE HOTEL, CZ12 (PRESCRIPTIVE)

TES Peak Electrical Demand Benefits

Beyond cost savings, this research focused on evaluating TES effectiveness in reducing peak electric demand during high TOU rates. The research team used 2025 LSC values as indicators of future peak TOU rates. Overall, TES shifted HVAC power demand—raising demand during charging and lowering it during discharging periods.

Figure 18 illustrates the average daily power demand savings (W/sf) from TES in the Large Office during summer and winter in CZ10 and CZ12. In summer, CHW TES lowered the afternoon peak by 0.13-0.20 W/sf on average, while morning charging increased demand by 0.04-0.13 W/sf. In winter, HHW TES reduced the morning peak by 0.46-0.69 W/sf on average, while midday charging increased demand by 0.17-0.25 W/sf.

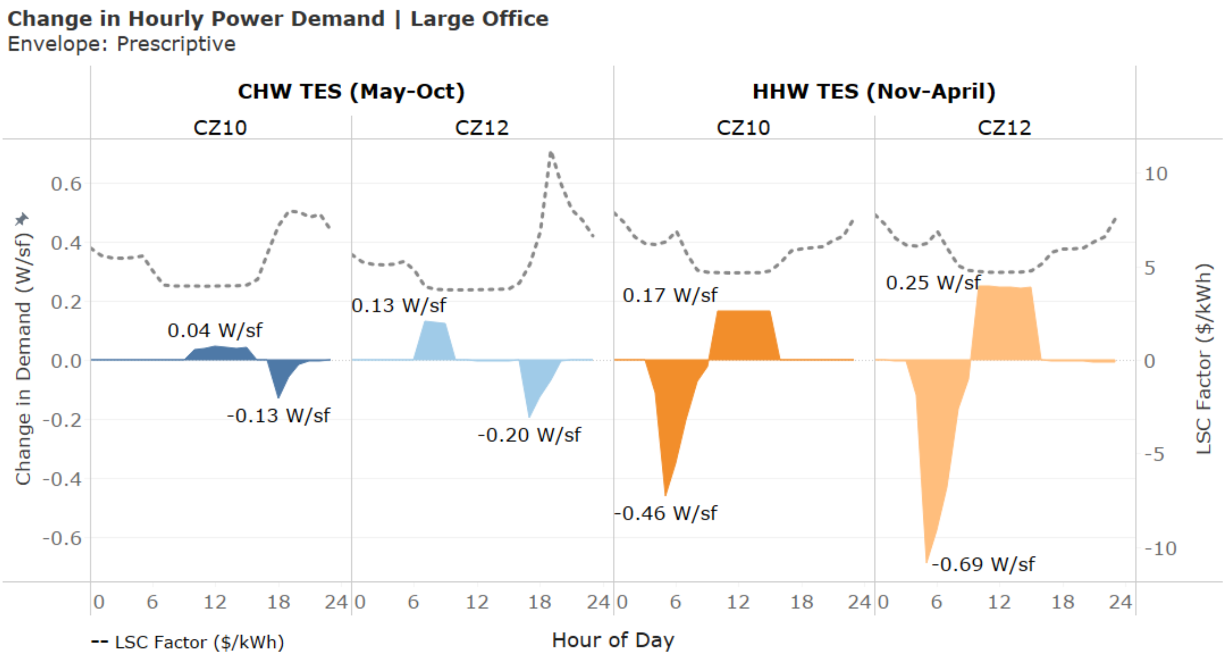


Figure 18. Change in Average Hourly Power Demand (W/sf): Large Office, CZ12 & CZ10 (Prescriptive)

Figure 19 shows the extended peak power demand savings in the Large Hotel, with HHW and CHW TES savings reversed compared to Large Office. In summer, CHW TES lowered the afternoon peak by 0.32-0.42 W/sf on average, while morning charging increased demand by 0.19-0.27 W/sf. In winter, HHW TES discharge reduced the morning peak by 0.14-0.24 W/sf on average, while midday charging raised demand by 0.07-0.14 W/sf.

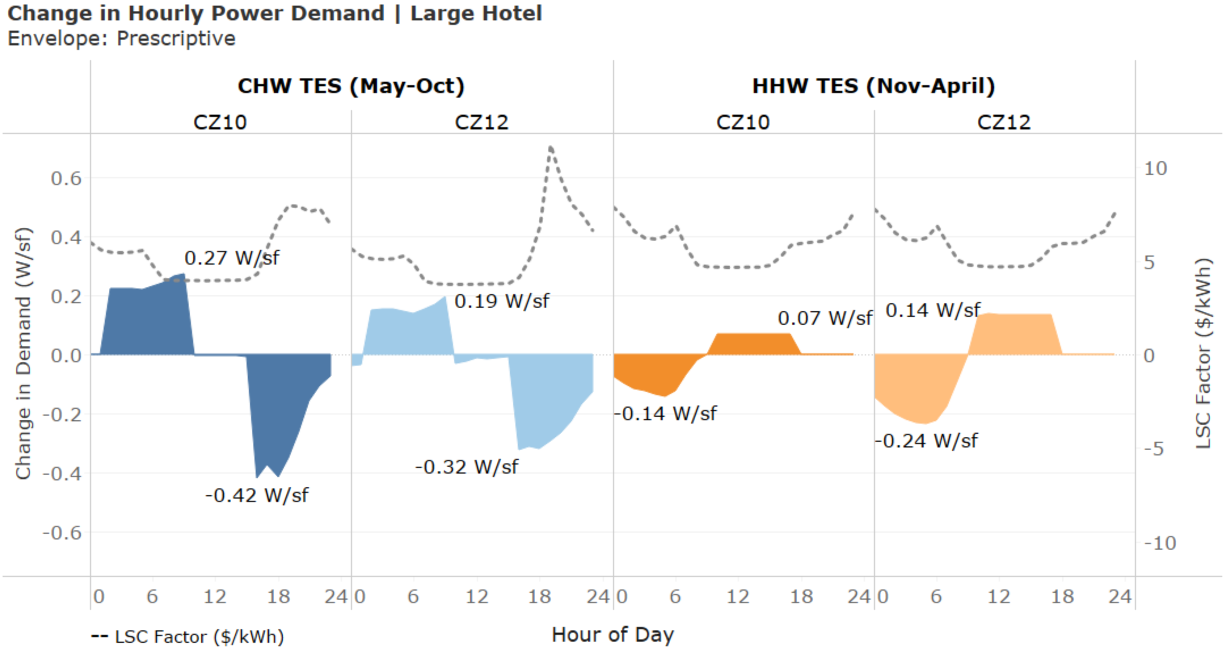


FIGURE 19. AVERAGE DAILY PEAK DEMAND SAVINGS: LARGE HOTEL, CZ12 & CZ10 (PRESCRIPTIVE)

To put peak demand savings into context, the team analyzed the whole-building demand profile reductions. In the Large Office, adding TES shifted the peak electric demand to midday, aligning with on-site or grid renewable generation. The analysis shows that HHW TES delivered the most significant whole-building demand savings.

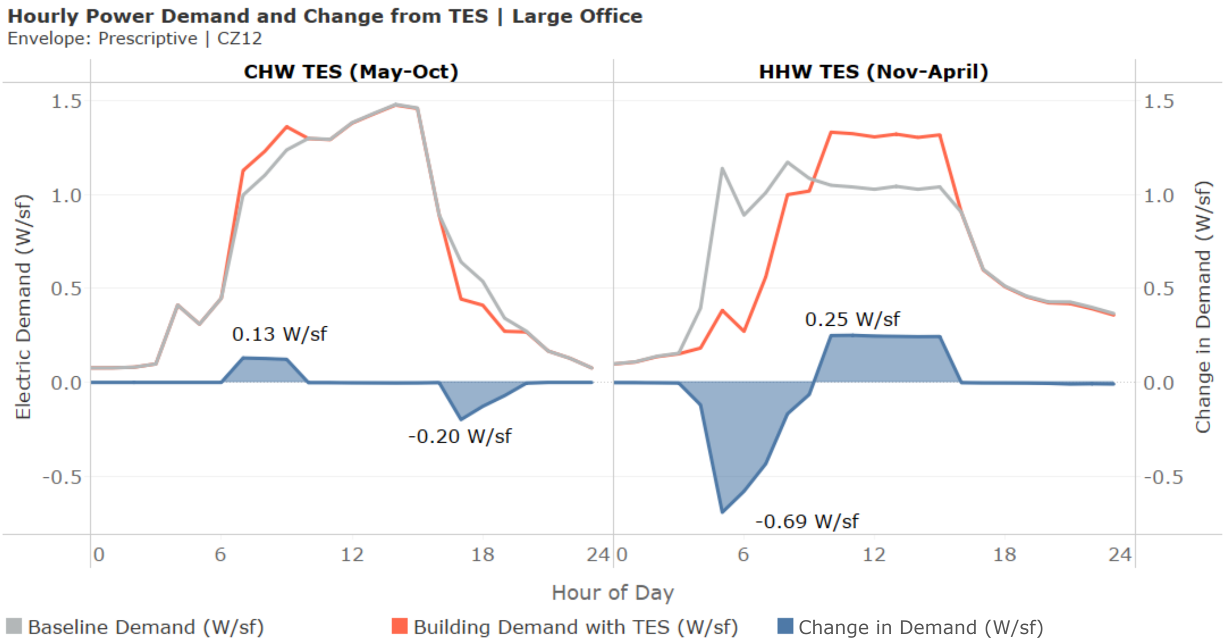


FIGURE 20. AVERAGE DAILY POWER DEMAND: LARGE OFFICE, CZ12, (PRESCRIPTIVE)

Figure 21 shows the Large Hotel's whole-building peak demand differs in shape and scale due to the larger base system loads, including service hot water and cooking equipment. For this prototype, the CHW TES reduced peak demand, cutting 0.32 W/sf from the total building load in the afternoon when the grid is less clean. The HHW TES provided a reduction of 0.24 W/sf in the winter morning peak electric demand.

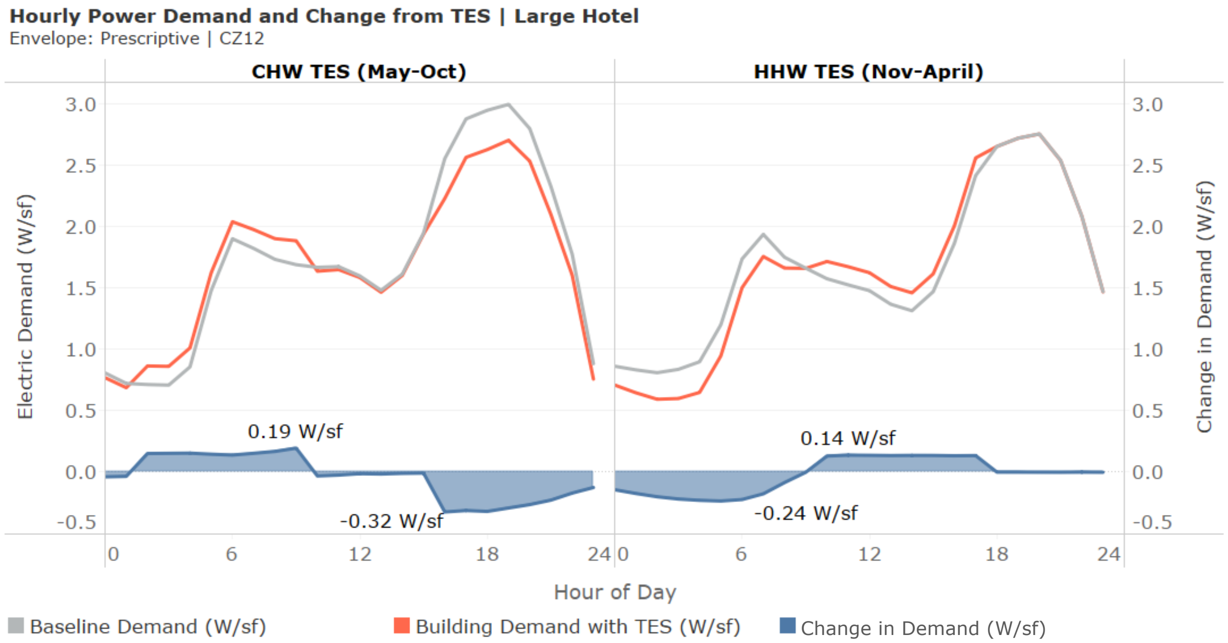


FIGURE 21. AVERAGE DAILY POWER DEMAND: LARGE HOTEL, CZ12, (PRESCRIPTIVE)

TES Peak Thermal Load Reduction

TES can be configured to also reduce or shift thermal demands, both seasonally and at peak instances. Seasonally, TES can reduce high thermal loads, avoiding a need to operate equipment at full capacity and potentially during more favorable outdoor air conditions when equipment can operate more efficiently. At peak instance, depending on the control strategy and load shape of a building, TES can be used to downsize a HHW or CHW plant, potentially saving on first costs.

Seasonal Peak Load Reduction

In this analysis, the research team optimized TES operation periods to minimize peak electric pricing during summer and winter and the resulting demand shifts are shown in the following charts and tables. Figure 22 illustrates the Large Hotel average HHW thermal load, with supplemental HHW plant usage in red, TES-served load in orange, and the TES charging load in pink for each month. The TES effectively shifted the load, particularly November through February, reducing HHW plant operation during early morning winter peak LSC hours.

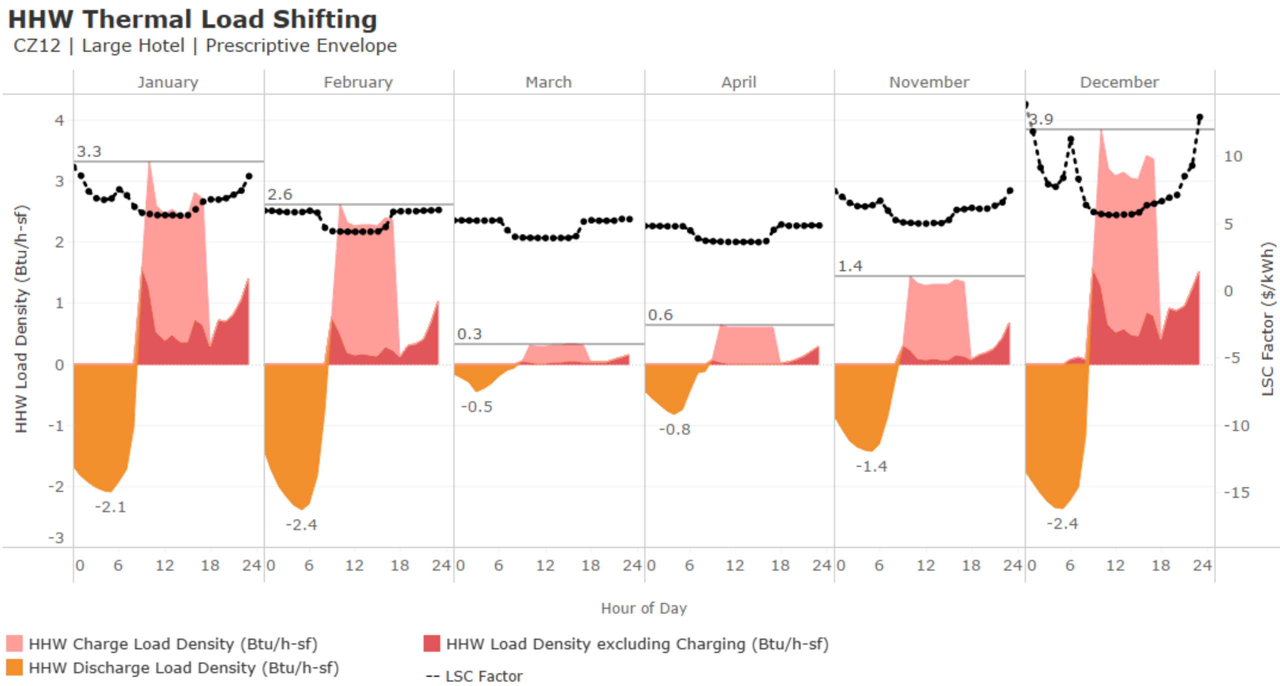


FIGURE 22. HHW TES THERMAL LOAD PER MONTH: LARGE HOTEL, CZ12 (PRESCRIPTIVE)

The CHW TES results for the Large Hotel are shown below. Figure 23 shows average CHW thermal load, with supplemental CHW plant usage in light blue, TES-served load in orange, and the TES charging load in dark blue for each month.

The analysis shows that in the afternoon, when LSC costs peak, the CHW plant load is fully reduced during the shoulder seasons and partially reduced in the summer months.

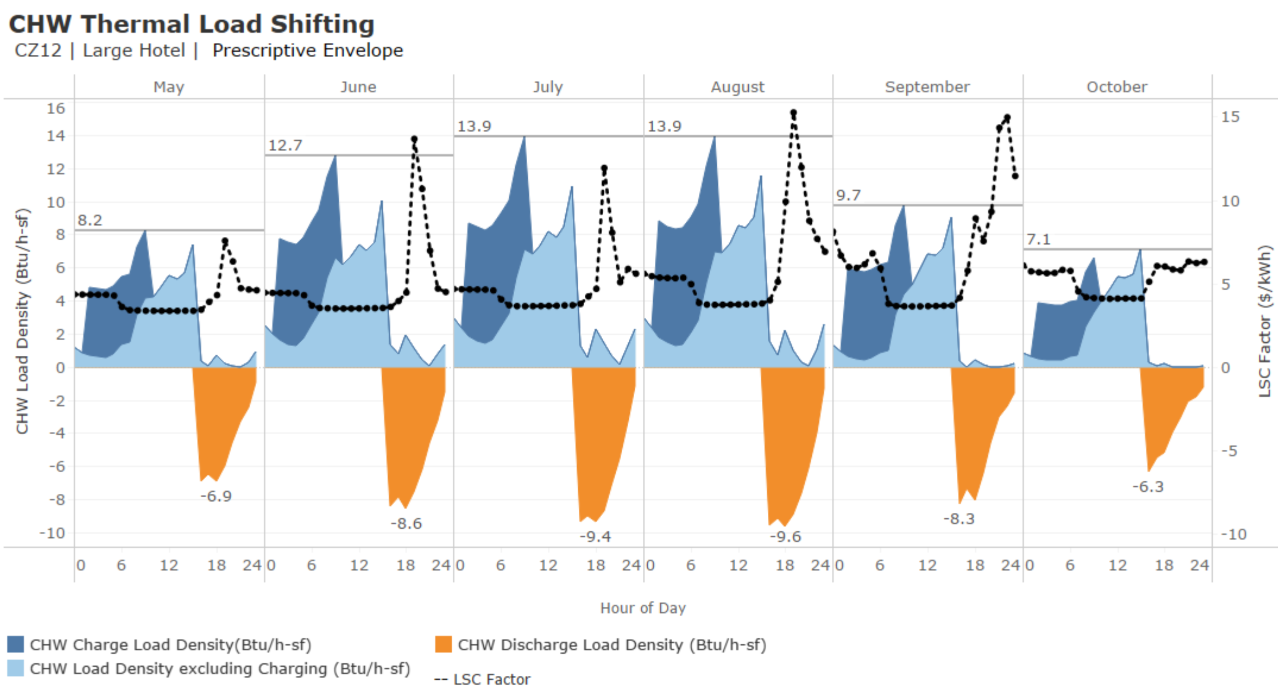


FIGURE 23. CHW TES DAILY SHIFT PER SUMMER MONTH FOR THE LARGE HOTEL, CZ12 (PRESCRIPTIVE)

Table 10 presents the Large Hotel's' monthly peak electric demand (kW), energy use (kWh), and LSC energy costs for two scenarios, no TES, and with seasonal TES. The table highlights sizable savings in kW, kWh, and LSC costs at different points throughout the year: the CHW TES reduced the peak building demand by 39-59 kW May through October. The analysis shows a reduction in building energy use in all months, with lower savings in the shoulder months. Seasonal TES led to sizable LSC cost savings in all months, aside from March and April.

Table 10. Seasonal TES Peak demand, Energy, and LSC Savings, Large Hotel CZ12 (Prescriptive)

Large Hotel CZ12	Building Peak (kW)			Building Energy (kWh)			Building LSC ($)		
	No Tank	Seasonal Tank	Savings	No Tank	Seasonal Tank	Savings	No Tank	Seasonal Tank	Savings
Jan	382	382	0	150,617	147,441	3,176	$1,024,387	$986,503	$37,884
Feb	345	345	0	136,980	133,304	3,676	$742,820	$714,160	$28,660
Mar	355	355	0	148,217	148,061	156	$699,596	$697,897	$1,698
Apr	353	354	-1	142,874	142,161	713	$617,590	$612,844	$4,746
May	407	358	49	153,964	149,719	4,245	$686,283	$659,185	$27,098
Jun	450	398	52	155,292	151,750	3,542	$859,955	$817,679	$42,275
Jul	428	369	59	161,935	158,509	3,426	$862,382	$823,830	$38,552
Aug	407	356	51	162,097	158,977	3,120	$1,080,830	$1,026,906	$53,923
Sep	406	356	50	149,658	146,344	3,314	$1,059,844	$1,010,752	$49,092
Oct	376	337	39	150,243	146,367	3,876	$829,641	$802,325	$27,316
Nov	350	350	0	144,050	142,291	1,759	$861,647	$844,331	$17,315
Dec	406	402	4	155,185	150,311	4,874	$1,194,137	$1,129,234	$64,903
SUM	-	-	-	1,811,112	1,775,235	35,877	$10,519,112	$10,125,646	$393,462

Peak Thermal Load Reduction

Figure 24 shows the thermal load per square foot at the Large Office with and without HHW TES. The Y-axis represents thermal load density (Btu/sf), while the X-axis plots each load instance at 5 °F outdoor air temperature (dry bulb) bins. The peak thermal load value per temperature bin is identified on the chart.

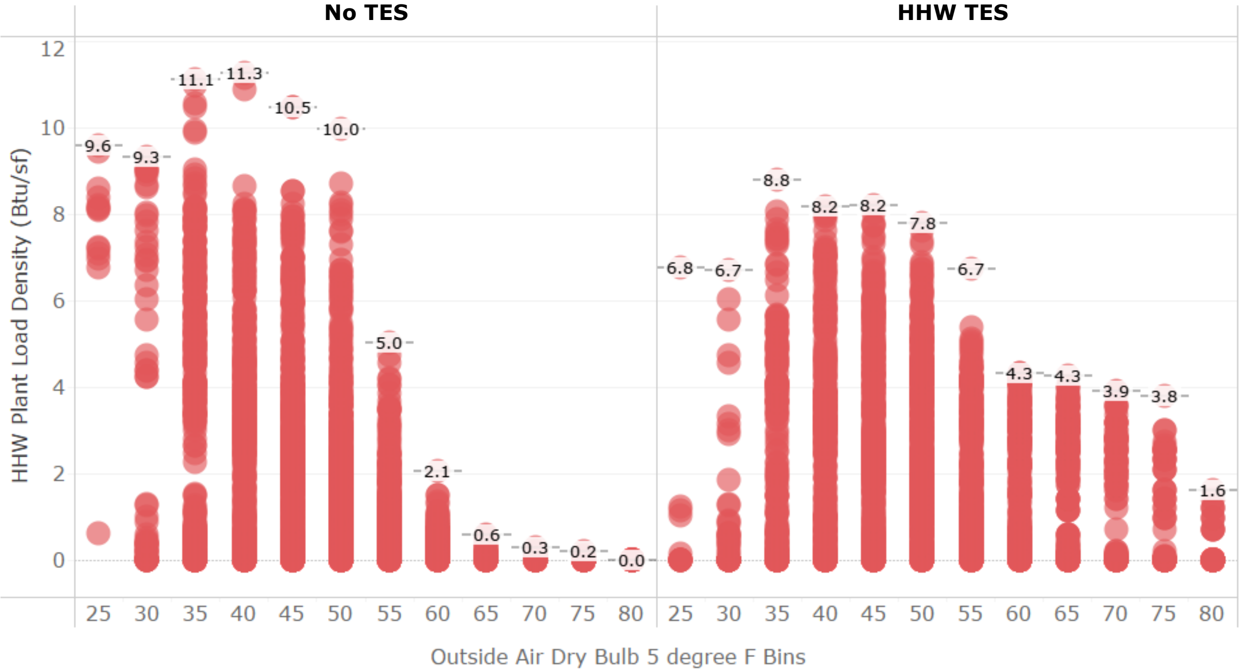


FIGURE 24. HHW PEAK THERMAL DEMAND REDUCTION VS OUTDOOR AIR DRY BULB, LARGE OFFICE, CZ12

The HHW TES schedule sets charging during warmer mid-day hours, which shifts some HHW plant, or AWHP, operation to warmer outdoor air temperatures. At the 25°F temperature bin, the HHW TES reduced the peak thermal load by approximately 29%, from 9.6 Btu/h-sf to 6.8 Btu/h-sf. At the 35 degrees Fahrenheit bin, there are some instances of the HHW TES operating in charging mode, e.g. at the 10am hour of the day. Therefore, the thermal load reduction of the HHW plant is reduced by only 21%, from 11.1 Btu/h-sf to 8.8 Btu/h-sf.

These results provide a promising opportunity to reduce the size of the AWHP central heating plant but require added consideration to the equipment's specific capacity availability at different outdoor air temperatures and the charging mode's control flexibility.

The same analysis was conducted for the Large Hotel in the same CZ12, shown in Figure 25. At the Large Hotel, the morning peak heating event lasts four to six hours, requiring an extended heating period and TES discharge period compared to the Large Office. As a result, the Large Hotel has more occurrences of simultaneous space heating loads and charging mode operation.

At the 25 degrees Fahrenheit temperature bin, the HHW TES reduced the thermal load by approximately 100%, from 4.7 Btu/h-sf to 0 Btu/h-sf, as shown in Figure 25. However, at the 35 degrees Fahrenheit temperature bin the HHW TES increases peak thermal loads by 144%, from 3.9 Btu/h-sf to 9.5 Btu/h-sf. The 24-hour thermal load shape of the Large Hotel HHW TES plant illustrates the importance of charge mode flexibility.

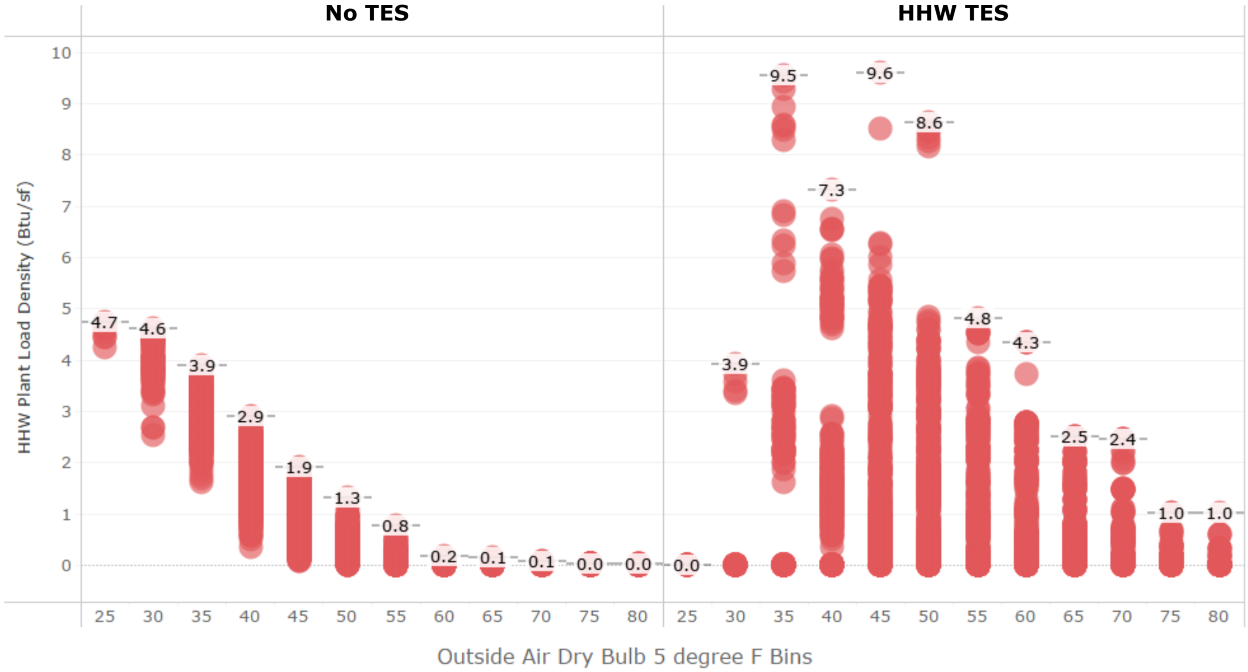


FIGURE 25. HHW PEAK THERMAL DEMAND REDUCTION VS OUTDOOR AIR DRY BULB, LARGE HOTEL, CZ12

IMPACT OF ENVELOPE ON PEAK THERMAL LOAD

This study also examined how envelope performance affects peak thermal load reduction. The research team compared a mandatory minimum envelope to a prescriptively compliant envelope. The analysis showed a significantly higher peak and average heating and cooling loads for both prototypes. Peak thermal loads were 25-34% higher for heating and 26-80% higher for cooling compared to the prescriptive envelope. Figure 26 and Figure 27 illustrate these findings, highlighting the 95th percentile and average thermal loads for heating and cooling.

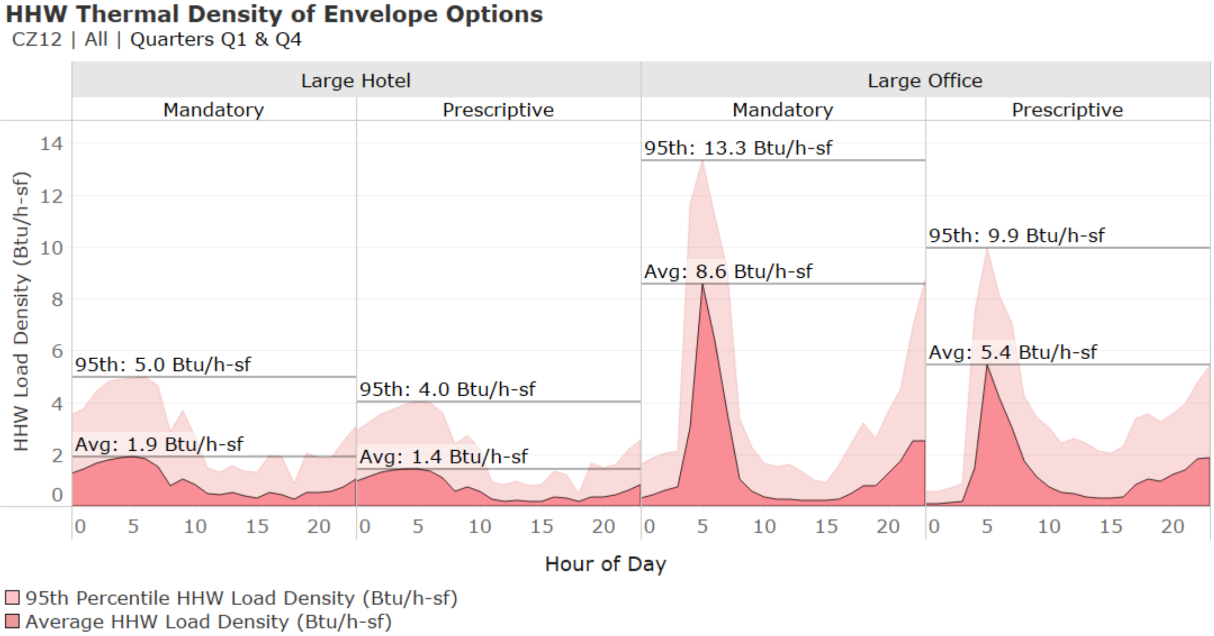


FIGURE 26. HHW THERMAL LOAD DENSITY OF PRESCRIPTIVE AND MANDATORY ENVELOPE, CZ12

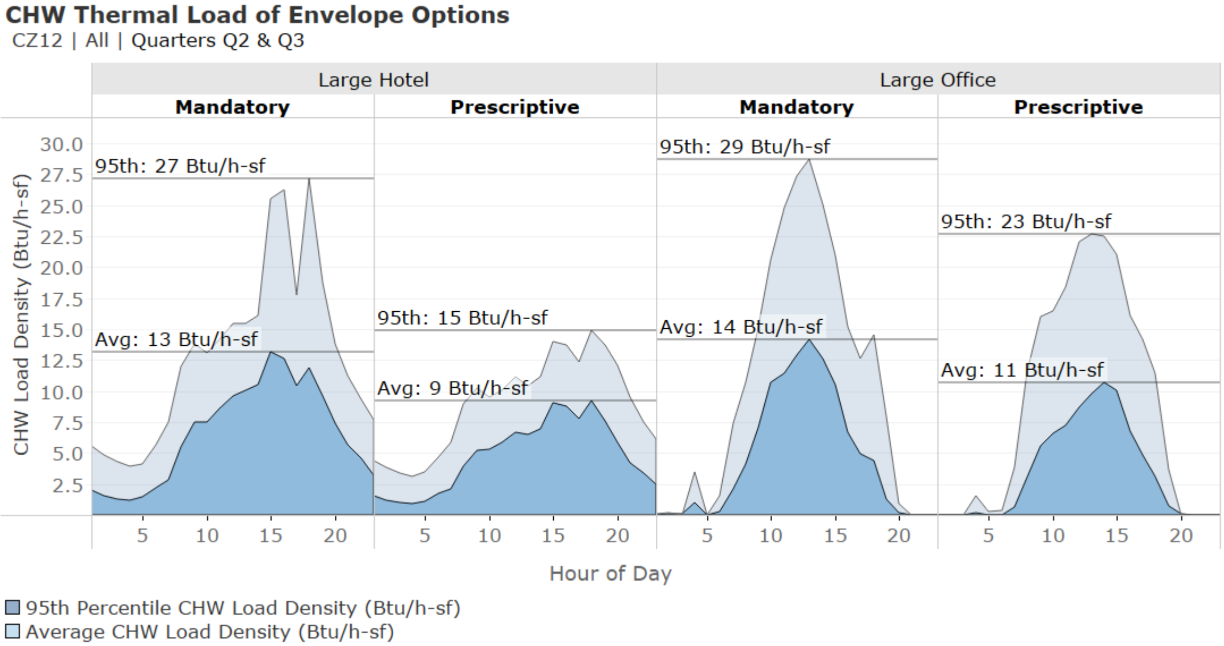


FIGURE 27. CHW THERMAL LOAD DENSITY OF PRESCRIPTIVE AND MANDATORY ENVELOPE, CZ12

The research team analyzed envelope performance scenarios without and with TES to determine their combined impact on energy cost and code compliance. Each scenario evaluated the building regulated energy cost in terms of LSC per floor area (LSC/sf). The team used the prescriptive envelope configuration without TES as the baseline for required energy use under code. Figure 28 and Figure 29 show the findings for the Large Hotel and Large Office in CZ12.

In the Large Hotel, TES provided similar percent savings for each envelope iteration: 12.5% LSC savings for the poorest envelope performance (mandatory minimum envelope), 13% for the standard prescriptive envelope, and 11.5% savings for the enhanced envelope.

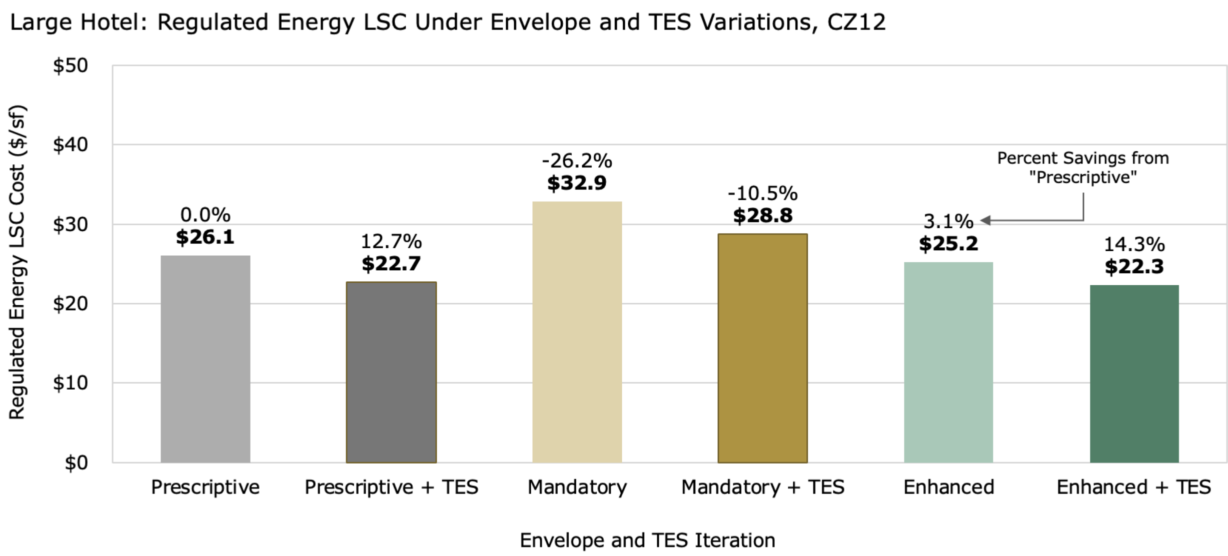


FIGURE 28. ENVELOPE EFFICIENCY WITH AND WITHOUT THERMAL ENERGY STORAGE BENEFITS, LARGE HOTEL CZ12

The Large Office showed similar trends to the Large Hotel, with TES providing similar percent savings for each envelope iteration: 8.3% LSC savings for the mandatory minimum envelope, 10.4% for the standard prescriptive envelope, and 9.8% savings for the enhanced envelope.

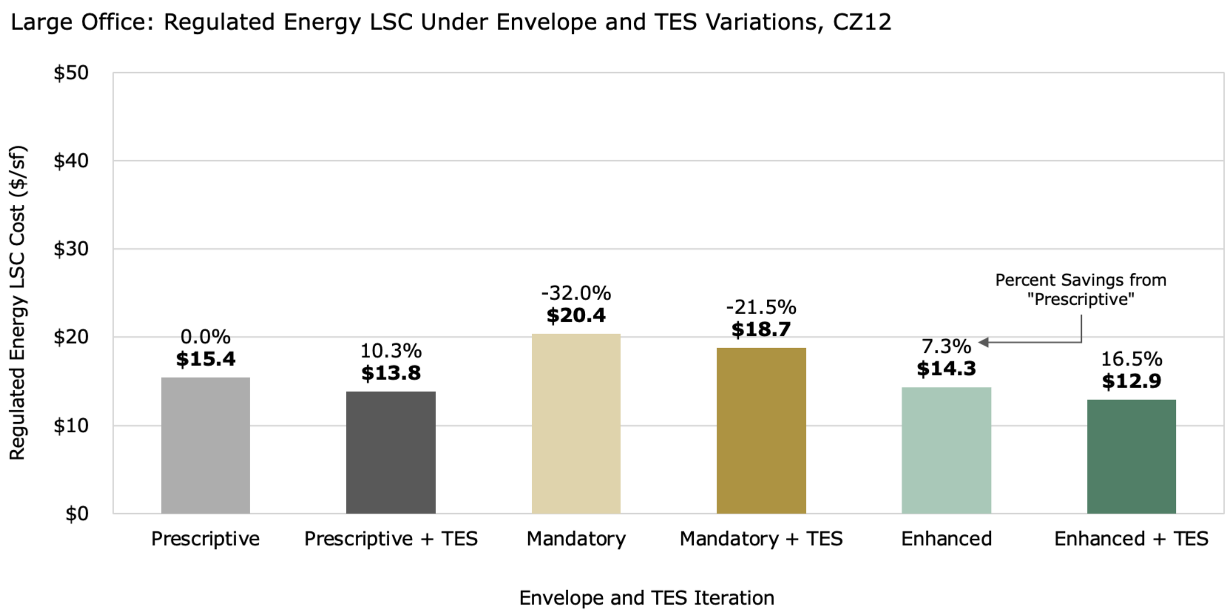


FIGURE 29. ENVELOPE EFFICIENCY WITH AND WITHOUT THERMAL ENERGY STORAGE BENEFITS, LARGE OFFICE CZ12

The following tables outline the annual energy usage and energy savings with no TES and a seasonal TES for each envelope iteration. Seasonal TES delivered annual energy savings under each scenario, more so in CZ12, which experiences higher heating degree days.

Table 11. Envelope Savings Summary, Large Office CZ12 & CZ10

Large Office		Mandatory		Prescriptive		Enhanced	
		No TES	Seasonal TES	No TES	Seasonal TES	No TES	Seasonal TES
CZ12	Building Annual Energy (kWh)	3,417,463	3,363,631	2,979,553	2,918,348	2,875,026	2,823,000
	Regulated Annual Energy (kWh)	1,993,742	1,939,911	1,555,832	1,494,627	1,451,305	1,399,279
	Regulated Annual Energy Savings (%)	-	2.7%	-	3.9%	-	3.6%
CZ10	Building Annual Energy (kWh)	3,163,801	3,132,134	2,772,703	2,752,397	2,727,101	2,709,132
	Regulated Annual Energy (kWh)	1,740,080	1,708,414	1,348,982	1,328,676	1,303,381	1,285,411
	Regulated Annual Energy Savings (%)	-	1.8%	-	1.5%	-	1.4%

Table 12. Envelope Savings Summary, Large Hotel CZ12 and CZ10

Large Hotel		Mandatory		Prescriptive		Enhanced	
		No TES	Seasonal TES	No TES	Seasonal TES	No TES	Seasonal TES
CZ12	Building Annual Energy (kWh)	1,965,977	1,915,804	1,811,112	1,775,235	1,793,398	1,766,204
	Regulated Annual Energy (kWh)	1,011,173	961,000	856,308	820,431	838,594	811,400
	Regulated Annual Energy Savings (%)	-	5.0%	-	4.2%	-	3.2%
CZ10	Building Annual Energy (kWh)	2,098,385	2,052,536	1,816,911	1,802,443	1,813,730	1,800,731
	Regulated Annual Energy (kWh)	1,143,581	1,097,732	862,107	847,639	858,926	845,927
	Regulated Annual Energy Savings (%)	-	4.0%	-	1.7%	-	1.5%

DISCUSSION

Throughout this research project, that team identified several key insights related to the sensitivity of TES controls, the benefits of combining multiple HVAC demand reduction measures, the potential for downsizing HVAC systems with TES, and the advantages TES offers for existing buildings.

TES CONTROLS SENSITIVITY

Further research should examine existing TES control strategies and establish clearer control selection guidance and standardization.

At the onset of this research, the research team found no standardized resources and few guides for TES control selection options. The research team selected a schedule-based approach, informed by the thermal load profile and the LSC factors. Even with this fairly simple control strategy, the team observed how a one-hour shift in charge or discharge could have a noticeable impact on energy, peak demand, and cost savings. While the selected TES control strategies may have optimized results for these prototype buildings, actual buildings will likely have different thermal loads and energy cost rates available today, rather than the forecast factors used in this study (LSC factors), resulting in different optimal charge and discharge duration.

Typically, chilled water and ice TES systems operate based on utility TOU charges, structured around off-peak and on-peak periods with a seasonal summer and winter variations. Since utility TOU rate structure periods have remained largely unchanged over time in terms of the focus summer peak demand, existing chilled water and ice TES systems have not required major control reconfigurations. However, as winter TOU rates evolve, TES controls should be re-commissioned frequently or enhanced with advanced systems that can actively respond to real-time building utility rates, onsite renewable generation, and weather forecasts. Research should be done to standardize TES control strategy selection and evaluate advanced integrated TES controls.

MULTI-MEASURE DEMAND REDUCTION FOR HVAC LOADS

Field research should evaluate how combining TES with other energy efficiency measures can optimize load shifting potential and TES cost effectiveness.

While this configuration of TES as a technology proved to achieve improvements in operational energy costs and peak electric demand reduction, the impact cost effectiveness could be increased through incorporating additional efficiency measures. From past research efforts by the Code Readiness team, efficiency HVAC strategies were identified to reduce peak demand while also improving energy efficiency (Weitze 2023). Strategies included active ventilation controls based on CO_2 or occupancy sensors, heat or energy recovery ventilation (HRV or ERV) with bypass control, and thermostat setbacks. The prototype HVAC systems in this study did not incorporate these energy efficiency measures. However, implementing these measures alongside TES would likely extend benefits, enhancing the system's ability to reduce peak demand and costs.

HVAC Sizing with TES

The industry needs further research and design resources on hydronic space conditioning system with TES sizing strategies.

HHW TES has historically been overlooked because natural gas boilers, the previous primary heating source, operate on flat utility rates. As building owners transition to all-electric AWHP systems, they must consider TOU rates and peak demand charges in addition to high equipment costs. HHW TES has the potential to reduce the AWHP plant size, however, it depends on building thermal load shape and the selected TES control strategy. The research team ultimately recommends the development of industry resources and standards for sizing hydronic space conditioning systems with TES.

Compared with traditional natural gas-sourced HHW plants, AWHP plants are expensive, space-intensive, and restricted to typically small rooftop and outdoor areas. Incorporating HHW TES in the Large Office allowed up to a 30% average thermal load reduction across envelope iterations and climate zones, which would likely allow for HHW plant downsizing. In the Large Hotel, the research team determined it would be unlikely to downsize the HHW plant. The difference in ability to downsize the HVAC stems from variations in daily load shapes and subsequent TES control duration.

The Large Office experienced a short, abrupt morning warm-up spike, allowing for a higher hourly discharge rate. The Large Hotel required sustained overnight heating, necessitating a lower hourly discharge rate to maintain consistency over nine hours. As a result, the Large Hotel experienced more coincident space heating and charging loads especially during colder outside air temperatures which limit HHW plant reduction.

Further downsizing the Large Hotel HHW plant may be possible by utilizing a dual discharge cycle per day or flexible charging controls that activate based on both time of day scheduling and a minimum outside air temperature criteria could mitigate coincident space heating and charging loads.

The research team recommends the development of TES design industry resources and standards, including:

- Minimum qualifications for building energy modeling professionals, given the importance of 24-hour load shapes in determining downsizing potential.
- Guidance on generating 24-hour load shape scenarios to ensure adequate capacity, considering:
    - Weather iterations
    - Occupied hours iterations (HVAC space temperature setpoint and ventilation)
    - Operational overrides that disable energy efficient technologies
    - Internal gains iterations
- Typical piping arrangements and pumping controls for flow rate limitations.
- Sequencing strategies between TES tanks and central mechanical plants.

TES Potential for Existing Buildings

As the industry works towards decarbonization, interviewed professionals note that retrofitting existing buildings for electrified space heating presents challenges, including limited roof space and insufficient electrical infrastructure. Many buildings must rely on partial electrification, retaining combustion-based heating plants to supplement all-electric heating equipment, such as AWHPs.

In cases where partial electrification is necessary, TES can reduce reliance on combustion equipment. AWHPs can charge HHW TES tanks during daytime hours when heating loads and LSC factors are low, and outdoor air temperatures are higher—boosting capacity and efficiency. During the peak morning and overnight heating events, the system can prioritize heating TES tanks, followed by AWHPs, and finally combustion heating only when necessary. This sequence minimizes combustion heating plant output.

Performance Path Compliance Considerations

The performance path currently allows envelope trade-offs that favor active systems over passive systems. Passive systems such as high-performance envelopes aid resiliency: under power outage and extreme weather event, a building with a high-performance envelope can maintain a comfortable indoor temperature for much longer than one without. One approach to prevent excessive reliance on active systems, is the introduction of an envelope backstop, which limits envelope trade-offs in compliance calculations to a certain limit, enforcing a certain quality of the building envelope.

Another strategy to address this issue is limiting the credit given to systems exceeding prescriptive requirements—a concept similar to a backstop but referred to as a "front-stop." ASHRAE Standard 90.1 performance compliance paths cap the credit for solar PV capacity, ensuring buildings meet a passive and active efficiency threshold. Title 24 restricts battery storage credit in the performance compliance pathway by only allowing it in the source energy assessments, not in the energy cost assessments.

This study's findings indicate significant TES savings, which could allow excessive design flexibility in the performance pathway. The research team recommends further investigation into a TES front-stop to encourage envelope efficiency. One example is the 2025 Oregon Energy Efficiency Specialty Code, which is based on ASHRAE Standard 90.1-2022 and includes a credit limit on TES contribution, allowing TES to account for only 60% of the total energy credits.

Conclusions and Recommendations

Key Findings

Need for TES Controls Advancement

The 2025 LSC factors indicate that carbon emissions and energy costs in California are lowest midday during sunny, hot days when solar PV offsets energy demand and highest during summer evenings and winter mornings. Historically, CHW and ice TES has been used to shift electrical loads from peak to off-peak hours, charging the TES at low electricity prices in the evening, and discharging during high prices during the afternoon. However, increased solar generation and grid electric batteries are pushing grid peak demands and prices beyond 6 p.m. on hot summer days, creating a controls challenge where peak thermal capacity and peak electric costs no longer align. Similarly, with the increase of electrification in space heating and hot water, winter morning peaks are now an anticipated grid and cost peak period.

As TOU rates evolve TES controls will need the capability to be easily re-commissioned, and potentially enhanced to actively respond to real-time building and grid utility signals, to deploy TES at the optimal time. Research should be done to standardize TES control capabilities and strategies for building operators and designers when selecting and evaluate advanced integrated TES controls.

Sizable Energy Savings from HHW TES

While CHW TES is widely used in California, the findings from the HHW TES analysis suggest this technology provides an opportunity to reduce peak heating demand and downsize electric heating equipment and lower a buildings annual operational energy cost.

TES Performance Compliance Considerations

The Title 24 performance compliance pathway permits various envelope trade-offs with other energy systems such as HVAC and lighting. This study's findings indicate sizable TES savings, which could allow excessive design flexibility in the performance pathway. Introducing TES into compliance software without safeguards on the extent of energy cost savings could lead to unintended scenarios of lower performance building envelopes. The research team recommends further investigation into an envelope backstop and TES front-stop to encourage performance compliance that prioritizes energy efficiency.

Research Questions

This section presents conclusions for key research questions, offering insights to enhance statewide energy codes and standards while serving as a reference for future studies on TES systems.

What energy, cost, and peak electric demand savings result from using TES with hydronic space conditioning systems in California?

The project analyses resulted in the following savings summary:

TABLE 13. TES SAVINGS SUMMARY

	Large Hotel Seasonal TES Prescriptive Envelope		Large Office Seasonal TES Prescriptive Envelope	
	CZ10	CZ12	CZ10	CZ12
Annual Regulated Energy Savings (kWh)	14,468	35,877	20,306	61,205
Annual Regulated Energy Savings (%)	1.7%	4.2%	1.5%	3.9%
Regulated Energy LSC Savings ($)	$207,667	$393,463	$394,506	$788,095
Regulated Energy LSC Savings (%)	4.1%	7.6%	5.9%	9.8%
Winter Morning Peak Electric Demand Savings (W/sf)	0.14	0.24	0.46	0.69
Summer Afternoon Peak Electric Demand Savings (W/sf)	0.42	0.32	0.13	0.20

How does the building thermal load profile impact TES peak electric demand and energy cost savings?

The Large Hotel, which had consistent thermal loads throughout the day, experienced greater percentage energy cost savings from TES than the Large Office, see Table 13. The Large Office operates primarily during daytime hours, with thermal loads dropping after 5pm. This pronounced thermal load demand limited the ability and need to shift load from peak to off-peak hours. These findings suggest that buildings with longer operation and significant thermal needs during peak TOU rates will likely see higher operational cost savings potential due to TES.

The Large Office did see higher winter morning peak electric demand savings compared to the Large Hotel, because the Office had a very high early morning warm-up thermal demand. Buildings with pronounced thermal loads may be able to use TES to shave off significant electric demand peaks and have a higher potential to downsize the HVAC plant to a smaller peak heating or cooling load.

How do different envelope performance levels that meet or exceed Title 24 requirements affect TES energy and cost savings?

TES consistently delivered cost savings across all envelope performance levels, building types, and climate zones studied in this analysis. However, as envelope performance improved from the mandatory minimum to the enhanced configuration, TES benefits declined due to reduced energy use. This trend aligns with expectations, as TES primarily shifts energy use rather than improving efficiency. The following table outlines the key energy and cost savings of each prototype in CZ12:

TABLE 14. ENVELOPE SAVINGS SUMMARY, CZ12

Envelope Type:		Mandatory		Prescriptive		Enhanced	
		No TES	Seasonal TES	No TES	Seasonal TES	No TES	Seasonal TES
Large Office	Regulated Energy LSC/sf ($/sf)	$32.9	$28.8	$26.1	$22.7	$25.2	$22.3
	Regulated Annual Energy (kWh)	1,993,742	1,939,911	1,555,832	1,494,627	1,451,305	1,399,279
	Regulated Annual Energy Savings (%)	-	2.7%	-	3.9%	-	3.6%
Large Hotel	Regulated Energy LSC/sf ($/sf)	$20.4	$18.7	$15.4	$13.8	$14.3	$12.9
	Regulated Annual Energy (kWh)	1,011,173	961,000	856,308	820,431	838,594	811,400
	Regulated Annual Energy Savings (%)	-	5.0%	-	4.2%	-	3.2%

What design practices are important considerations to sizing hydronic heating and cooling plants and TES?

Literature reviews, interviews, and TES analyses revealed the following key parameters that should be considered in a hydronic heating and cooling plant(s) and TES:

1. Accuracy in defining building occupancy and thermal load shape
2. TES control strategies that consider utility rates, on-site renewables, and outdoor ambient temperatures
3. TES capacity for charging and discharging, determining what limits exist on the system flow rate for CHW and HHW
4. Building space constraints that consider required area of TES physical systems

Is it possible to reduce the hydronic heating and cooling plant size when utilizing TES?

This study's analysis shows that TES can reduce peak thermal plant size in certain buildings, primarily in heating applications. However, its effectiveness depends on TES configuration—whether it serves as primary or secondary storage—and discharge controls. When prioritizing HHW plant reduction, control the TES to discharge at peak thermal load conditions rather than peak electric demand costs.

RECOMMENDATIONS

TITLE 24

To accelerate TES adoption in California, the research team recommends the following updates to Title 24:

6. **Incorporate HHW TES into compliance software and ACM:** Add a compliance option for HHW TES to nonresidential buildings for hydronic hot water heating loops to enable basic control strategies and functionalities similar to those defined for CHW TES.
7. **Update internal gains assumptions in ACM:** Update internal gains assumptions for nonresidential buildings by space types based on modern sources of heat gains for equipment, improving the accuracy of the average assumptions used for compliance.
8. **Establish an envelope backstop to complement TES:** The current Title 24 nonresidential performance compliance pathway for energy efficiency allows for a wide range of envelope trade-offs. With the introduction of accurate TES to compliance software there is a risk of increasing the ability to trade-off a high-performance envelope with high-efficiency HVAC systems with TES. The research team recommends the development of an envelope backstop that limits envelope trade-offs to mitigate this concern.
9. **Set limits on excessive energy trade-offs from TES:** Consider a prescriptive compliance credit limit to apply to thermal and electrical shifting technologies like TES to limit excessive energy trade-offs between building systems.
10. **Expand TES compliance options:** The current Title 24 compliance software allows for CHW thermal storage. Expand upon this configuration, allowing for other technologies such as ice storage and phase-change materials, to provide more compliance options.

FUTURE RESEARCH

TES proved energy and LSC cost savings under the developed control scenarios for the selected large building prototypes in CZ10 and CZ12. While the savings are promising, further research is needed to scale TES adoption and refine cost-effectiveness in various applications. The research team recommends the following areas for further investigation:

7. **Define minimum TES configuration and control requirements** to optimize charge and discharge scheduling across multiple utility rate structures currently available compared to the long-term forecast rates of LSC.
8. **Conduct cost-effectiveness analyses:** Identify the smallest TES system size that remains cost-effective for large nonresidential buildings. Large in this context should be defined as building size or plant capacity to enable cost effectiveness in projects and a minimum TES size.
9. **Conduct field studies** on TES control strategies and maintenance to better understand operational costs and challenges.
10. **Identify standardized TES attribute terminology,** such as TES charging and discharging functionalities, to streamline use and education of those terms.

11. **Develop design guidelines** for incorporating HHW and CHW TES plant equipment sizing at peak demand. Specifically, guidance and methods for considering HHW where peak load assessment is typically done for a steady state condition only.
12. **Explore whole-building thermal performance targets** beyond the prescriptive envelope criteria. Building on Phase 1 findings, evaluate how energy codes could adopt flexible whole-envelope performance metrics or efficiency compliance credits.

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APPENDICES

Appendices are divided into items included in this report and separate appendices which are attached in a separate document available upon request from the Code Readiness program. Titles for all appendices are included below:

Included Appendices

Appendix A. Methodology Tables

Appendix B. Additional TES Model Methodology Details

Appendix C. Additional TES Analysis

APPENDIX A. METHODOLOGY TABLES

As summarized in the methods, three packages of envelope assemblies were assessed; one based on the mandatory minimum Title 24 allows assuming efficiency can be made up in other ways, one based on the prescriptive requirements, and one based on an enhanced level of performance informed by the literature review and interviews of industry professionals in California as part of this study.

This appendix documents the thermal bridging calculations and infiltration air leakage assumptions used for each envelope configuration.

THERMAL BRIDGING ASSUMPTIONS

Historically, the thermal resistance of building enclosures has most commonly been quantified by thermal transmittance (U-value) and area of specific enclosure assemblies. In recent energy codes, methodologies and standards have been provided for more specific thermal bridges.

A thermal bridge can be defined as a specific part of the building enclosure where the thermal resistance is weakened such as framing that interrupts an insulation material. A more specific form is called a linear thermal bridge that occurs at the interfaces or intersection of different building assemblies or components characterized by linear feet of length along a building surface.

For this analysis, a specific prototypical building energy model's massing was used to estimate the new annual space heating and space cooling loads of an envelope package when incorporating the additional weakening of thermal resistance by accounting for linear thermal bridging.

The following table lists the Linear Thermal Bridge by component and the ASHRAE Standard 90.1-2022 listed default Chi value (Ψ) associated with that unique enclosure component.

TABLE. THERMAL BRIDGING PSI VALUES

Enclosure Component Type	Psi value (Ψ)	Length Description
Roof Parapet	0.14	One Instance of Perimeter of Building Footprint
Window-Wall Transition	0.112	Perimeter of each window
Interior Floor Transitions	0.049	Perimeter of Building Footprint reflecting the remaining number of floors

The window frame area was obtained from thermal bridging calculations developed by PNNL for both prototype buildings, assuming a standard size window for each building and the associated frame area[3].

For these prototypical energy models, the window-wall transition component type accounted for the majority of reduced thermal resistance, totaling 80% of the derated resistance value.

[3] Table B.2. Thermal Bridging Parameters for Window-to-Wall Intersections
https://www.energycodes.gov/sites/default/files/2024-02/Standard_90.1-2022_Final_Determination_TSD.pdf

Air Leakage Assumptions

The air leakage was adjusted for each of the three envelope scenarios developed by selecting a higher stringency option presented in the Title 24 compliance software CBECC. In the software, air barrier options include:

- No Air Barrier
- Air Barrier – not verified
- Air Barrier – verified by visual inspection
- Air Barrier – verified by air leakage testing

The options selected for each configuration are shown in the table below. The research team used the same air leakage rates for both Large Office and Large Hotel prototype models.

Table. Air Leakage Rate Summary

	Envelope Type		
	Mandatory	**Prescriptive**	**Exceeds**
Air Leakage Setting	No Air Barrier	Air Barrier – not verified	Air Barrier – verified by air leakage testing
Air Leakage (CFM/sf of Exterior Wall Area)	0.3696	0.2352	0.1344

Internal Gain Assumptions

The following is a comparison of the equipment internal heat gain between the ASHRAE 90.1-2022 large hotel space types and the equivalent space types for Title 24, Part 6 (U.S. DOE 2024; CEC 2023).

Zone Name	Floor Area per Zone (sf)	Multiplier	Total Floor Area (sf)	ASHRAE 90.1-2022 Equipment Internal Heat Gain (W/sf)	Title 24, Part 6 Equipment Internal Heat Gain (W/sf)
ROOM_1_FLR_3	420	4	1,680	0.63	0.50
ROOM_2_FLR_3	420	4	1,680	0.63	0.50
ROOM_3_MULT19_FLR_3	264	76	20,059	0.98	0.50
ROOM_4_MULT19_FLR_3	264	76	20,067	0.98	0.50
ROOM_5_FLR_3	420	4	1,680	0.63	0.50
ROOM_6_FLR_3	420	4	1,680	0.63	0.50
ROOM_1_FLR_6	420	1	420	0.63	0.50
ROOM_2_FLR_6	420	1	420	0.63	0.50
ROOM_3_MULT9_FLR_6	264	9	2,376	0.98	0.50
BASEMENT	21,300	1	21,300	0.50	0.20
RETAIL_1_FLR_1	722	1	722	1.00	1.00
RETAIL_2_FLR_1	836	1	836	1.00	1.00

Zone Name	Floor Area per Zone (sf)	Multiplier	Total Floor Area (sf)	ASHRAE 90.1-2022	Title 24, Part 6
				Equipment Internal Heat Gain (W/sf)	Equipment Internal Heat Gain (W/sf)
MECH_FLR_1	1,768	1	1,768	0.50	3.00
STORAGE_FLR_1	1,020	1	1,020	0.25	0.20
LAUNDRY_FLR_1	840	1	840	55.51	3.00
CAFE_FLR_1	2,033	1	2,033	0.50	0.50
LOBBY_FLR_1	14,081	1	14,081	0.75	0.50
CORRIDOR_FLR_3	4,191	4	16,766	0.00	0.20
BANQUET_FLR_6	3,570	1	3,570	6.30	1.00
DINING_FLR_6	3,570	1	3,570	6.30	0.50
KITCHEN_FLR_6	1,112	1	1,112	272.80	7.76
CORRIDOR_FLR_6	4,436	1	4,436	0.00	0.20

Appendix B. Additional TES Model Methodology Details

The following sections outline additional TES model parameters and calculation details.

Supplemental TES Operation Details

TES Operation

TES is available in a simulation if a TES capacity is entered in the model inputs and if the current hour's month is set to Enabled in the Monthly Schedule. The TES tank is assumed to be fully charged at the beginning of the simulation. TES operation is similar for both the chilled water (CHW) and heating hot water (HHW) plants; primary equipment here refers to water-cooled chillers for CHW and AWHPs for HHW.

CHW Plant

Temperatures		
CHW design temperature	44.0	deg F
CHW design deltaT	20.0	delta-F
CW design temperature	85.0	deg F
CW design deltaT	15.0	delta-F
CW tower setpoint control	WB Reset	-
Chillers		
Chiller Quantity	2	Qty
Chiller Rated Capacity	750	Tons
Chiller Rated Capacity	9,000	kbtu/hr
Chiller Primary CHW Flow	900	gpm
Chiller Primary CW Flow	1418	gpm
TES Capacity		
TES Storage Capacity	1,042	Ton-hrs
TES Storage Capacity	12,500	kbtu
TES Storage Volume	75,000	Gallons
TES Charge/Discharge		
Hours for Max Discharge Rate	4.0	
Max Discharge Rate (Tons)	260	Tons
Max Discharge Rate (kbtu/hr)	3,125	kbtu/hr
Max Discharge flow	313	gpm
Hours for Max Charge Rate	4.0	
Max Charge Rate (Tons)	260	Tons
Max Charge Rate (kbtu/hr)	3,125	kbtu/hr
Max Charge flow	313	gpm
Charge Controls	Even	NOTE
Pumps (* = VSD)		
SCHWP* Power (total)	46.5	kW

Monthly TES Schedule

Month	Status
1	Off
2	Off
3	Off
4	Off
5	Enabled
6	Enabled
7	Enabled
8	Enabled
9	Enabled
10	Enabled
11	Off
12	Off

"Even" charging should only be used if there is a single contiguous charge period.

Figure. CHW TES Inputs in Calculator Workbook

TES operating mode is purely based on a schedule where the operating mode for each hour of the day is defined as an input to the model. The available operating modes are:

- Discharge: TES will operate at the maximum allowed discharge, primary equipment meets leftover load

- Charge: TES will charge based on either a Fast or Even control strategy (see below) using left over capacity from the primary equipment after loop demands have been met by the primary equipment
- Off: TES is disabled and will neither charge nor discharge.

The hourly TES capacity is defined in the model as the amount of capacity in the TES at the beginning of the hour before the TES has been charged or discharged. This is used to define the hourly available capacity in discharge mode and amount of capacity "missing" from the TES at each hour during charge mode.

The Discharge and Charge operating modes are described below. In the simulation, all charging or discharging is reported as the "TES Discharge Rate". A positive value represents the energy rate that the TES is discharging to meet load, while a negative value represents the hourly energy rate to charge the TES tank from the primary equipment.

DISCHARGE MODE

When the TES Operating Mode is set to discharge, the TES will first meet the load, followed by the primary equipment picking up any remaining load. The maximum amount that the TES can discharge per hour is limited to the smaller of:

- The maximum discharge rate is based on model inputs. This is defined as the total capacity of the TES divided by the "Hours for Max Discharge Rate" input. As an example, setting the hours for max discharge value = 1 means that the entire capacity of the TES could be discharged in a single hour.
- The available capacity in the TES tank at the beginning of the simulation hour
- The CHW or HHW loop demand

CHARGE MODE

When the TES Operating Mode is set to charge, the primary equipment will first meet any building loads prior to charging the TES tanks. If there is no building load present, the primary equipment can still be enabled to operate to charge the TES tanks. There are two (2) available methods of charging the TES tank, Fast or Even.

FAST CHARGING

For "Fast" charging, the primary equipment will charge the tanks as fast as possible. The maximum rate that the primary equipment can charge the TES tanks is limited to the smaller of:

- The maximum charge rate is based on model inputs. This is defined as the total capacity of the TES divided by the "Hours for Max Charge Rate" input. This input acts similar to the max discharge hours described above.
- The "missing" capacity of the TES tank at the beginning of the simulation hour. This represents how much capacity it would take to charge the tank to full capacity at each hour.
- The total available capacity of the primary equipment (as adjusted for current hour operating conditions).

Even Charging

For "Even" charging, the charging of the tank will be spread out evenly over the charge window (defined by the hourly TES operating schedule inputs). First, the amount of "missing" capacity in the TES tank at the first hour in the charge window is determined. This value is then divided by the total number of hours in the charging window so that charging is even across the window and the TES tank will only reach 100% capacity at the end of the charge window.

Important note: this charging method should only be used if there is a single contiguous charge window, as the maximum rate of charge in each window is divided by the total number of charge hours in each 24-hour period. If there are multiple charge windows in a 24-hour period, the TES system will not reach full charge at the end of any of the individual charge windows.

The maximum rate that the primary equipment can charge the TES tank is the same as the rate defined in the "Fast" charging option, with an additional limit of the "maximum even charging rate". Re-summarized, the Even charging option constrains the maximum charge rate of the TES to the smaller of:

- The maximum charge rate is based on model inputs.
- The "missing" capacity of the TES tank at the beginning of the simulation hour.
- The total available capacity of the chillers (as adjusted for current hour operating conditions)
- The "Load to bring TES to full at beginning of charge window" divided by the number of hours in the charge window. This is the "maximum even charging rate".

TES Flow

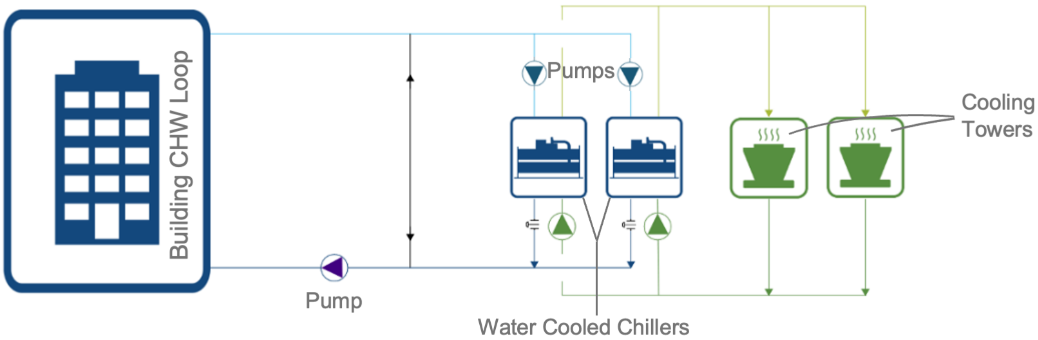
Finally, the amount of flow leaving or entering the TES is dependent based on the operating mode:

- In Discharge mode, the flow is the lesser of the maximum discharge flow (model input) or the CHW loop secondary flow (based on hourly load).
- In Charge mode, the flow is the lesser of the maximum charge flow (model input) or sum of the primary flow for the available primary equipment.

Pump power for the TES is calculated similar to the CHW secondary pumps using the hourly flow rate vs design flow and an affinity curve with a modified exponent.

Chilled Water Plant

The chilled water plant is modeled in a primary-secondary loop configuration with water-cooled chillers. The secondary loop is variable-flow with variable-speed pumps, and each chiller has a dedicated constant-flow primary pump. The number of chillers in the system can be varied for each model. The condenser water loop is modeled with open cooling towers and dedicated constant-flow primary pumps for each chiller; the number of cooling towers is assumed equal to the number of chillers. An example of the CHW plant with two chillers is shown in the figure below. This section details other assumptions and calculations made for the CHW TES configuration.



CHILLER CAPACITY

Target chilled water (CHW) supply temperature is kept constant at 44°F for all iterations. Target condenser water (CW) supply temperature is either:

- Fixed at design CW temperature (as defined by Title 24 & climate zone), or
- Tracks OAWB based at a constant 15F approach temperature and a minimum tower LWT of 70F.

The rated capacity of each chiller for the plant is sized uniquely for each of the 12 provided load trends to minimize unmet load hours. Available chiller capacity to serve the loop load at any given hour is adjusted using an hourly multiplier based on:

- Leaving evaporator water temperature (CHWST)
- Entering condenser water temperature (CWST)

CHILLER POWER

The number of chillers operating each hour is determined based on the minimum number of chillers required to meet the load observed by the chillers. If more than one chiller is required to operate, the load will be shared evenly between all chillers operating. The power requirements for a single chiller are first calculated and then multiplied by the number of chillers operating to get the total plant power.

Hourly chiller power is based on the following:

- The rated COP (load / power) is converted to a rated EIR (power / capacity). The rated COP is based on the minimum efficiency for water-cooled centrifugal chillers per Title 24-2025.
- The rated EIR is first adjusted for the hourly operating CHW and CW temperatures.
- The rated EIR is next adjusted for the current part load ratio (PLR) and compressor lift.
- If the chiller is operating above its minimum operating point but below its Minimum Unloading Ratio, the chiller is falsely loaded using hot gas bypass (HGBP). This is disabled if the minimum operating point and minimum loading ratio are set equal.
- If the chiller is operating below its minimum operating point, then it is assumed to cycle. The cycling ratio represents the fraction of the hour that the chiller is operating (cycled on).
- Individual chiller power = available capacity * adjusted EIR * cycling ratio
- Total chiller power is calculated for an individual chiller then multiplied by the number of chillers operating.

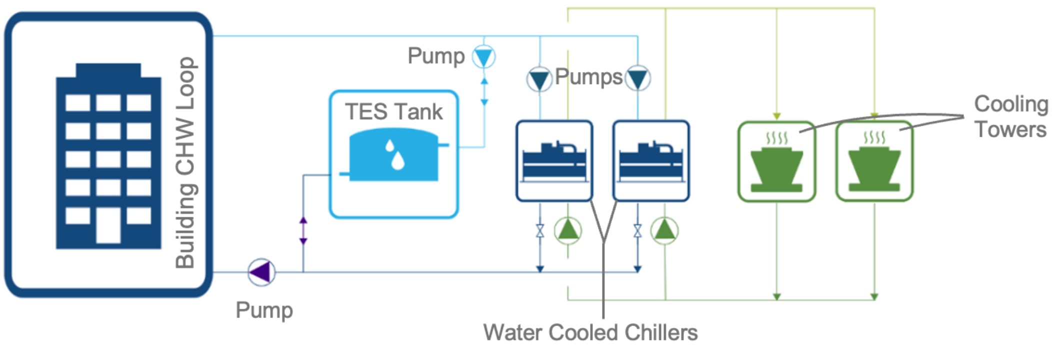
Flow through each chiller evaporator and condenser is constant, so total chiller pump power is calculated by multiplying the CHW and CW primary pump powers with the number of chillers operating.

Cooling Towers

Hourly cooling tower power is calculated using a simple and constant EIR, representing the fan power consumed per load on the tower. As cooling tower energy is a small portion of central plant consumption, a more complex or iterative tower model is not required for this analysis. However, separate tower equipment models were used to validate that a reasonably sized cooling tower could provide the target condenser water temperatures assumed in the simulation.

Chilled Water TES

The addition of a TES to this CHW loop model assumes that the CHW supply temperature of 44°F is also used for the TES storage temperature. For models with TES, primary equipment capacities are reduced as much as possible while still meeting all space loads.

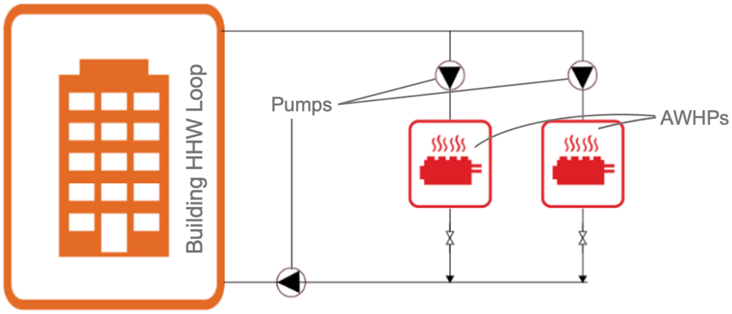


"Total chiller capacity available to charge TES" is the number of chillers in the design multiplied by the hourly available chiller capacity of each hour, MINUS the current hour CHW loop demand (this assumes that the chillers must first meet the loop demand during charging mode before charging the TES tank). The amount of load passed to the chillers is based on the TES operating modes.

- TES discharge: any remaining loop demand that the TES is unable (or not allowed) to meet.
- TES charge: sum of the loop demand and amount used to charge tanks (limits described above)
- TES off: all loop demand

Heating Hot Water Plant

The base heating hot water plant is modeled in a primary-secondary loop configuration with AWHPs meeting the entire load. The secondary loop is variable-flow with variable-speed pumps and each AWHP has a dedicated constant-flow primary pump. The number of AWHPs in the system can be varied for each model. An example of the HHW plant with two AWHPs is shown in the figure below.



AWHP Capacity

Target heating hot water (HHW) supply temperature is kept constant at 130°F for all iterations. AWHP performance at low ambient conditions is adjusted for outdoor coil frost formation and heat pump defrost operation using empirical formulas originally developed for DOE-2 and currently utilized by EnergyPlus. Defrost is required when an ambient dry-bulb is below 41F and is modeled as a timed reverse-cycle operation.

The rated capacity of both AWHPs for the plant is sized uniquely for each of the 12 provided load trends to minimize unmet load hours. Available AWHP capacity to serve the loop load at any given hour is adjusted using an hourly multiplier based on the following:

- Ambient dry bulb temperature
- Ambient humidity ratio (defrost mode only)
- Leaving hot water temperature

AWHP Power

The number of AWHPs operating each hour is determined based on the minimum number of AWHPs required to meet the load passed to the AWHPs. If more than one AWHP is required to operate, the load will be shared evenly between all AWHPs operating. The power requirements for a single AWHP are first calculated and then multiplied by the number of AWHPs operating to get the total plant power.

Hourly AWHP power is based on the following:

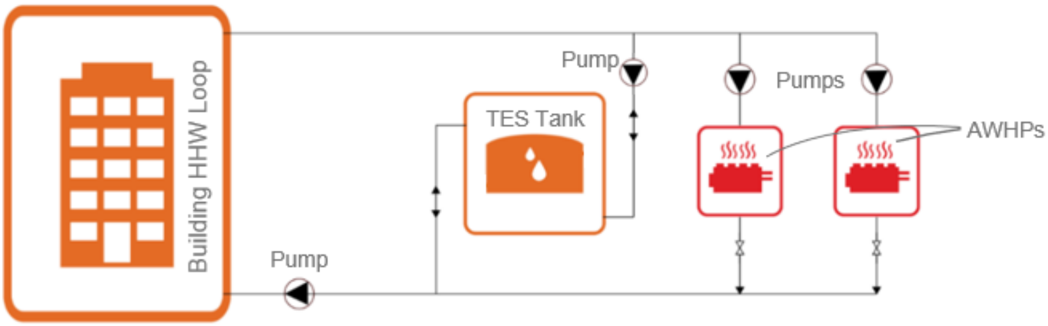
- The rated COP (load / power) is converted to a rated EIR (power / capacity). Rated COP is modeled as the minimum efficiency required per Title 24-2025
- The rated EIR is first adjusted for the hourly operating HHW loop temperatures and ambient conditions.
- The rated EIR is next adjusted for the current part load ratio (PLR)
- If the AWHP is operating above its minimum operating point but below its Minimum Unloading Ratio, the AWHP is false loaded using hot gas bypass (HGBP). This is disabled if the minimum operating point and minimum loading ratio are set equal.
- If the AWHP is operating below its minimum operating point, then it is assumed to cycle. The cycling ratio represents the fraction of the hour that the AWHP is operating (cycled on).
- Individual AWHP heating power = available capacity * adjusted EIR * cycling ratio
- Individual AWHP defrost power (if in defrost mode) = (rated capacity / 1.017) * cycling ratio * defrost time fraction
    - The defrost time fraction is the percentage of the hour spent in defrost mode, which is set to 0.05 for all simulations in this study.

- Total AWHP plant power = (Individual AWHP heating power + Individual AWHP defrost power) * number of AWHPs operating

Flow through each AWHP is constant, so total AWHP pump power is calculated by multiplying the HHW primary pump power with the number of AWHPs operating.

Heating Hot Water TES

Like the chilled water loop, the addition of a TES to this HHW loop model assumes that the HHW supply temperature of 130°F is also maintained for the TES storage temperature. For models with TES, primary equipment capacities are reduced as much as possible while still meeting all space loads.



"Total AWHP capacity available to charge TES" is the number of AWHPs in the design multiplied by the hourly available AWHP capacity of each hour, MINUS the current hour HHW loop demand (this assumes that the AWHPs must first meet the loop demand during charging mode before charging the TES tank). The amount of load passed to the AWHPs is based on the TES operating modes.

- TES discharge: any remaining loop demand that the TES is unable (or not allowed) to meet.
- TES charge: sum of the loop demand and amount used to charge tanks (limits described above)
- TES off: all loop demand

Appendix C. Additional TES Analysis Results

Analysis results for additional climate zones and building types for HHW TES and CHW TES are included below.

Large Office: CZ12 Prescriptive

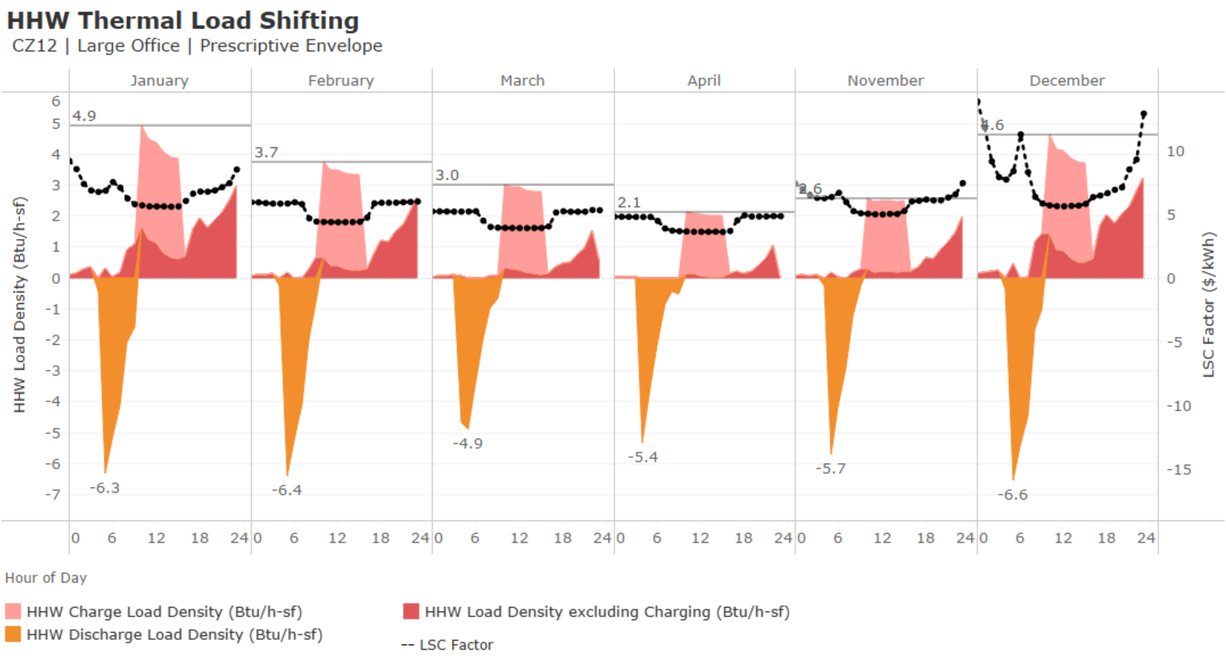


Figure. Average Monthly Winter HHW TES Thermal Load Shift, Large Office, CZ12 (Prescriptive)

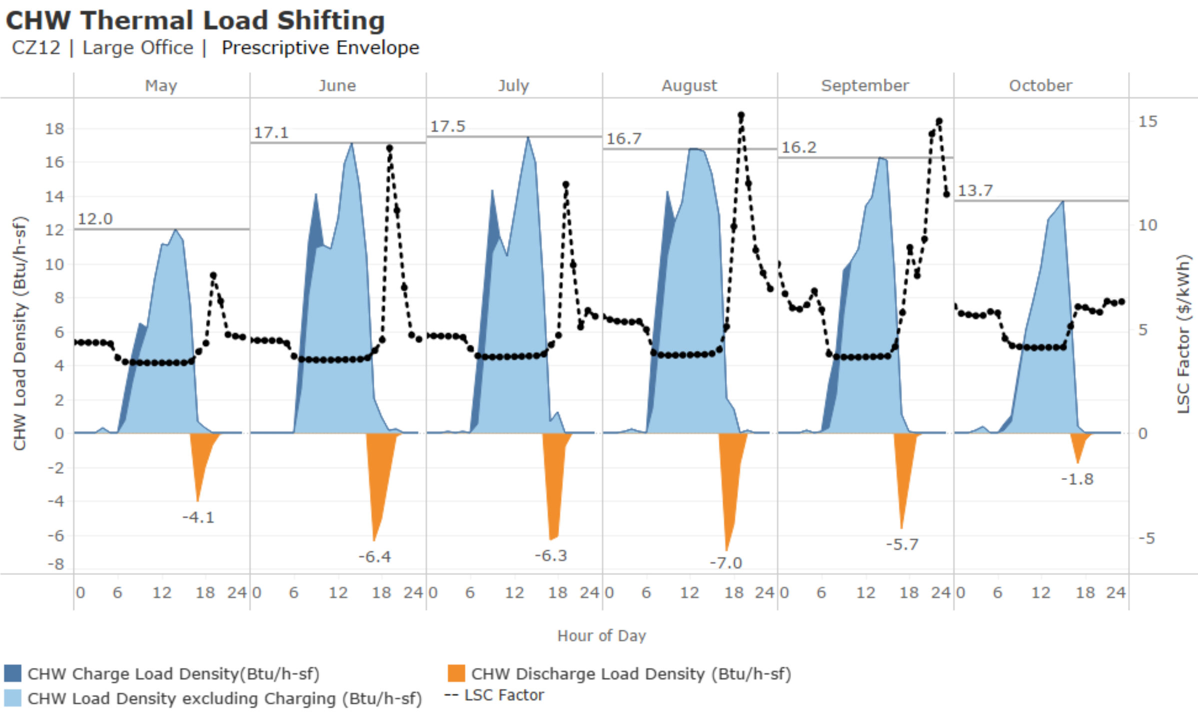


Figure. Average Monthly Summer CHW TES Thermal Load Shift, Large Office, CZ12 (Prescriptive)

Table. Seasonal TES Monthly Energy, Peak Demand, & LSC, Large Office, CZ12 (Prescriptive)

Large Office CZ12	Building Peak (kW)			Building Energy (kWh)			Building LSC ($)		
	No Tank	Seasonal Tank	Savings	No Tank	Seasonal Tank	Savings	No Tank	Seasonal Tank	Savings
Jan	1,327	1,144	183	276,989	263,455	13,534	$1,775,057	$1,635,690	$139,367
Feb	1,406	1,070	336	232,551	219,630	12,921	$1,181,923	$1,075,351	$106,572
Mar	1,027	1,112	-85	234,694	229,791	4,903	$1,026,966	$975,892	$51,074
Apr	1,132	1,171	-39	234,010	231,241	2,769	$915,522	$885,238	$30,284
May	1,301	1,295	6	227,401	228,160	-759	$851,832	$843,168	$8,664
Jun	1,313	1,363	-50	260,317	258,487	1,830	$1,088,828	$1,046,270	$42,558
Jul	1,341	1,334	7	262,058	261,377	681	$1,082,874	$1,059,638	$23,236
Aug	1,306	1,361	-55	261,407	260,162	1,245	$1,251,787	$1,191,159	$60,628
Sep	1,369	1,362	7	242,710	242,709	1	$1,126,288	$1,109,686	$16,602
Oct	1,487	1,478	9	235,382	235,600	-218	$1,092,328	$1,088,953	$3,375
Nov	1,338	1,112	226	219,814	212,223	7,591	$1,243,899	$1,167,196	$76,703
Dec	1,459	1,119	340	292,218	275,511	16,707	$2,052,293	$1,823,263	$229,030
SUM	-	-	-	2,979,551	2,918,346	61,205	$14,689,597	$13,901,504	$788,093

Large Office: CZ10, Prescriptive

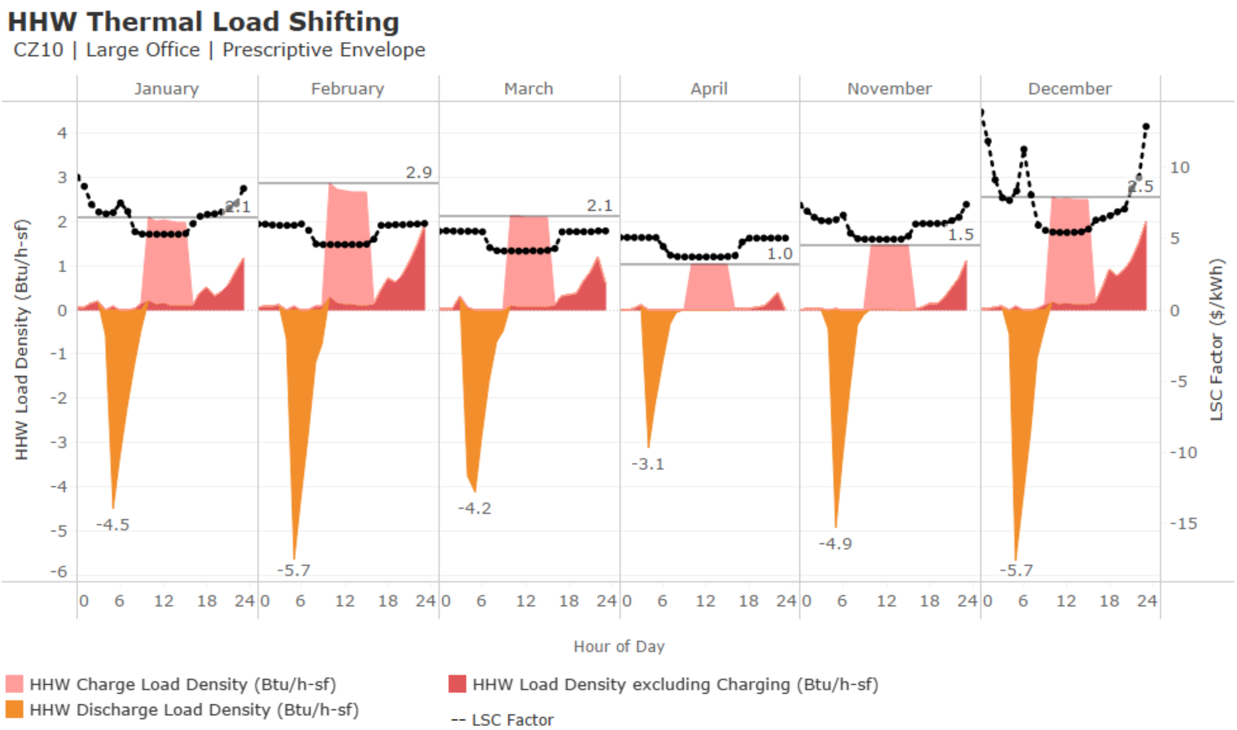


Figure. Average Monthly Winter HHW TES Thermal Load SHIFT: Large Office, CZ10 (Prescriptive)

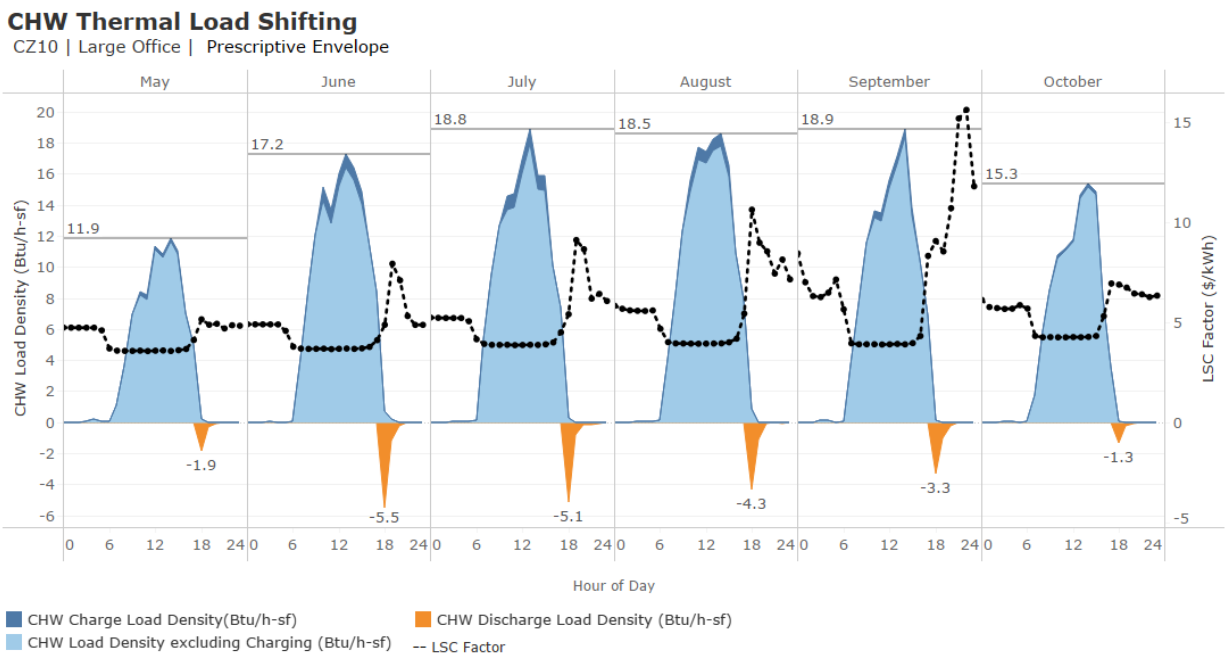


Figure. Average Monthly Summer CHW TES Thermal Load Shift, Large Office, CZ10 (Prescriptive)

Table. Seasonal TES Monthly Energy , Peak Demand & LSC, Large Office, CZ10 (Prescriptive)

Large Office CZ10	Building Peak (kW)			Building Energy (kWh)			Building LSC ($)		
	No Tank	Seasonal Tank	Savings	No Tank	Seasonal Tank	Savings	No Tank	Seasonal Tank	Savings
Jan	1,043	1,155	-112	218,500	215,270	3,230	$1,294,315	$1,239,705	$54,610
Feb	1,082	1,101	-19	207,146	201,709	5,437	$1,049,724	$995,405	$54,319
Mar	1,006	1,118	-112	231,431	227,139	4,292	$1,040,811	$996,846	$43,965
Apr	1,153	1,160	-7	224,567	223,960	607	$889,953	$875,961	$13,992
May	1,168	1,166	2	212,903	214,820	-1,917	$824,216	$827,694	-$3,478
Jun	1,286	1,284	2	252,012	251,961	51	$1,018,690	$1,006,000	$12,690
Jul	1,235	1,281	-46	258,202	259,423	-1,221	$1,102,385	$1,092,934	$9,451
Aug	1,282	1,299	-17	253,597	252,666	931	$1,180,521	$1,151,198	$29,323
Sep	1,212	1,231	-19	241,156	240,723	433	$1,203,192	$1,183,803	$19,389
Oct	1,216	1,213	3	231,639	232,246	-607	$1,103,860	$1,102,132	$1,728
Nov	1,046	1,098	-52	204,006	201,592	2,414	$1,110,317	$1,071,816	$38,501
Dec	1,147	1,212	-65	237,543	230,888	6,655	$1,559,361	$1,439,342	$120,019
SUM	-	-	-	2,772,702	2,752,397	20,305	$13,377,345	$12,982,836	$394,509

LARGE HOTEL: CZ10, PRESCRIPTIVE

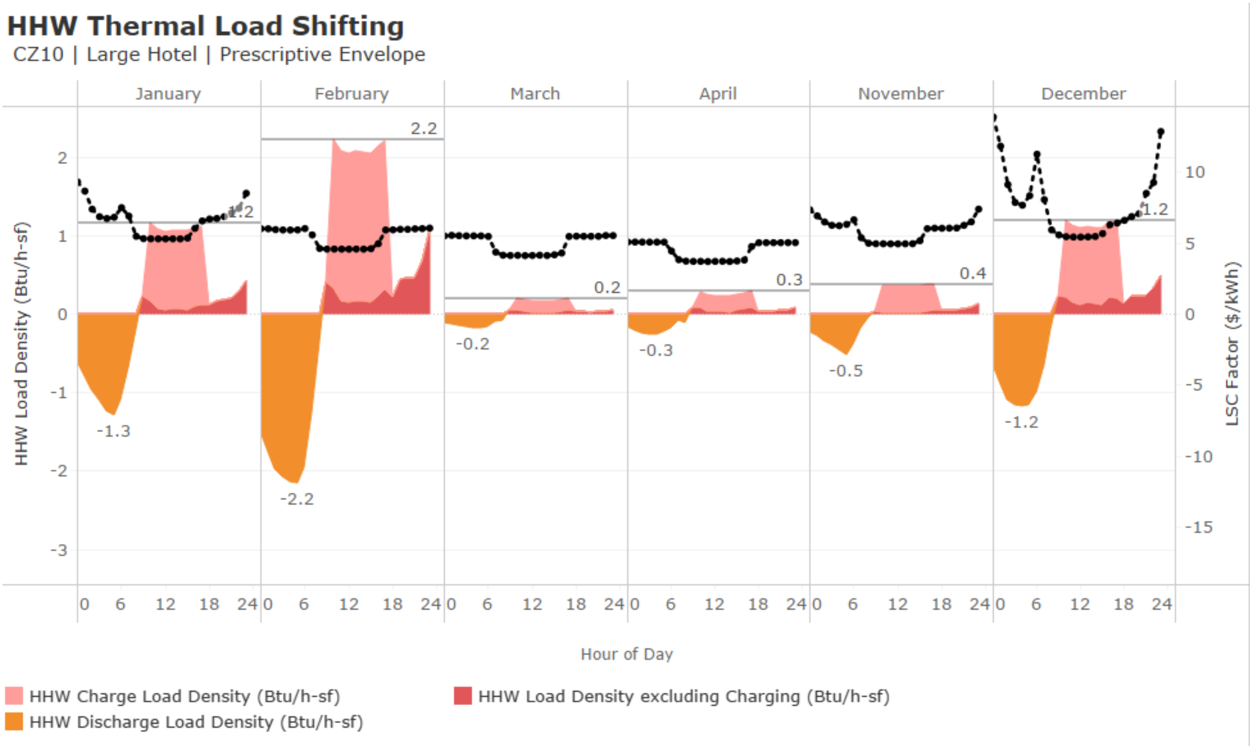


FIGURE. AVERAGE MONTHLY WINTER HHW TES THERMAL LOAD SHIFT: LARGE HOTEL, CZ10 (PRESCRIPTIVE)

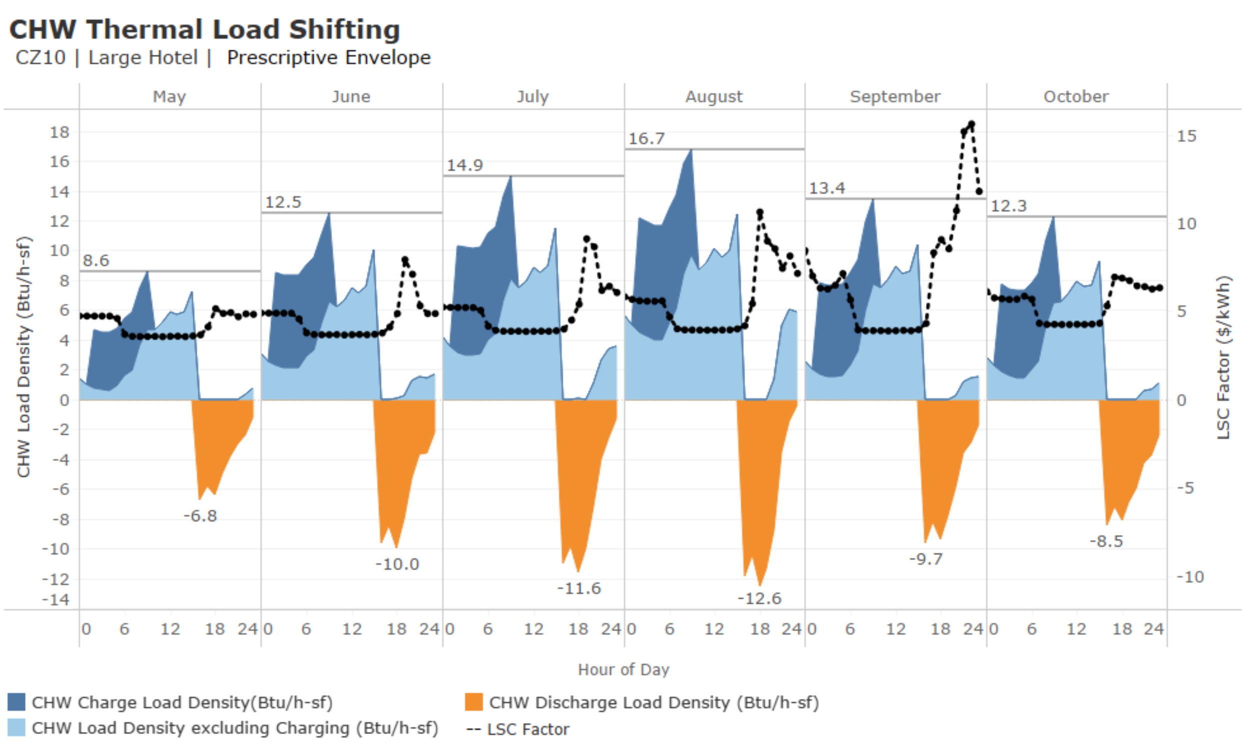


FIGURE. AVERAGE MONTHLY SUMMER CHW TES THERMAL LOAD SHIFT, LARGE HOTEL, CZ10 (PRESCRIPTIVE)

TABLE. SEASONAL TES MONTHLY ENERGY , PEAK DEMAND, & LSC, LARGE HOTEL, CZ10 (PRESCRIPTIVE)

Large Hotel CZ10	Building Peak (kW)			Building Energy (kWh)			Building LSC ($)		
	No Tank	Seasonal Tank	Savings	No Tank	Seasonal Tank	Savings	No Tank	Seasonal Tank	Savings
Jan	346	346	0	147,066	145,777	1,289	$965,106	$949,657	15,449
Feb	373	377	-4	137,979	133,667	4,312	$757,869	$726,624	31,245
Mar	370	370	0	148,023	147,929	94	$731,420	$730,472	948
Apr	370	370	0	143,288	143,040	248	$636,611	$634,803	1,808
May	380	332	48	151,116	149,478	1,638	$656,395	$646,102	10,293
Jun	418	392	26	154,529	153,136	1,393	$756,744	$739,469	17,275
Jul	417	376	41	164,422	163,574	848	$856,862	$838,735	18,127
Aug	418	388	30	170,201	169,786	415	$1,024,800	$995,826	28,974
Sep	417	374	43	154,292	153,189	1,103	$1,132,709	$1,096,060	36,649
Oct	388	332	56	155,533	154,413	1,120	$889,017	$871,054	17,963
Nov	354	354	0	143,121	142,786	335	$838,340	$833,488	4,852
Dec	347	347	0	147,341	145,669	1,672	$1,103,997	$1,079,912	24,085
SUM	-	-	-	1,816,911	1,802,444	14,467	$10,349,870	$10,142,202	$207,668

BUILDING COMPARISON: HOTEL VS. OFFICE CZ10 HHW TES

Here we compare the hotel vs. office HHW TES thermal load and LSC costs in CZ10. The dotted line represents the scenario without TES.

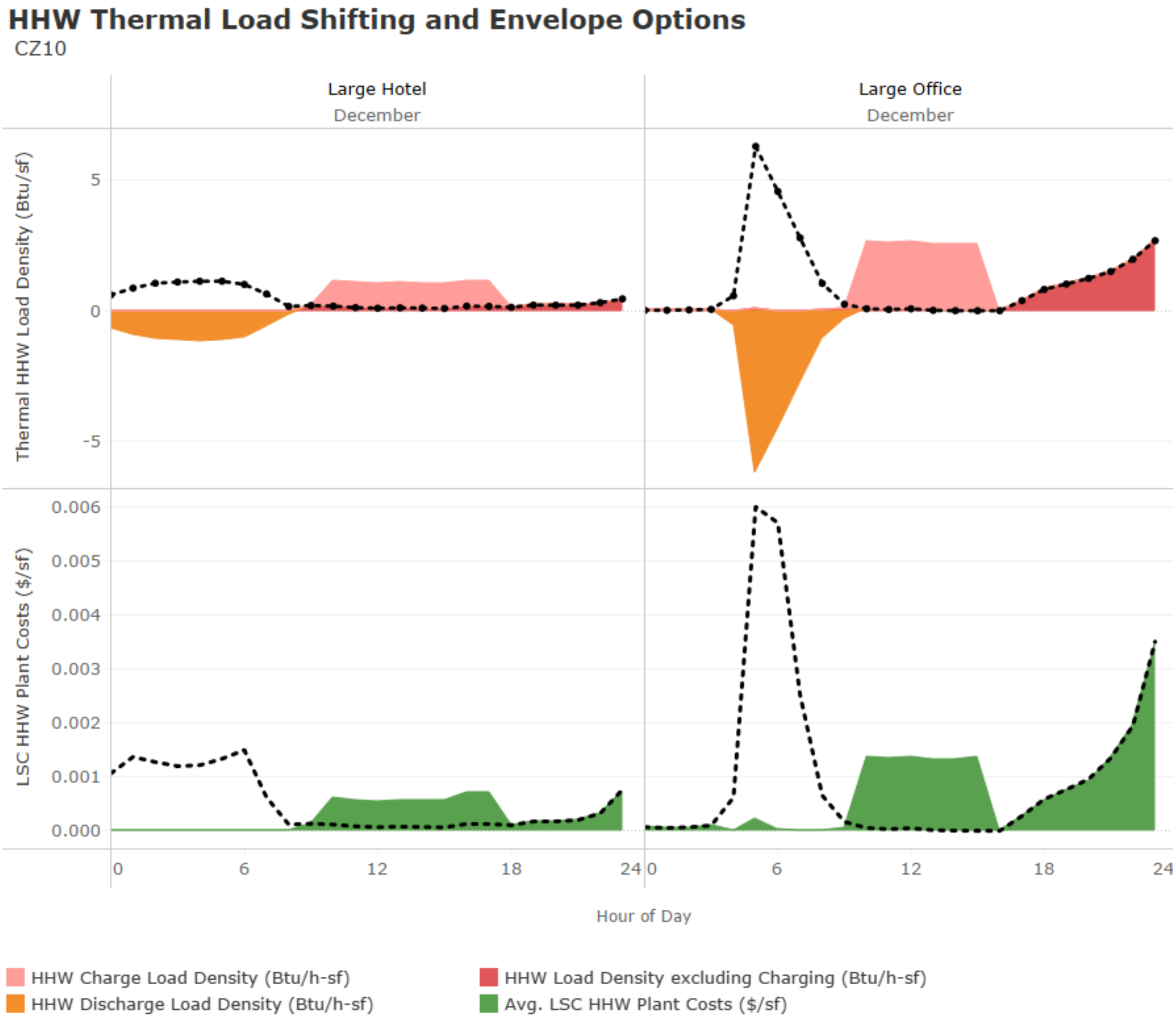


FIGURE. COMPARISON OF HHW LOAD DENSITY AND LSC PLANT COSTS, LARGE HOTEL AND OFFICE, CZ10 (PRESCRIPTIVE)

TABLE. HHW ANNUAL ENERGY AND PEAK DEMAND, LARGE HOTEL AND LARGE OFFICE, CZ10 (PRESCRIPTIVE)

	Large Hotel		Large Office	
	CZ10		CZ10	
	Prescriptive		Prescriptive	
	No Tank	HHW Tank Only	No Tank	HHW Tank Only
Building Energy (kWh)	1,816,911	1,808,828	2,772,703	2,749,533
Regulated Energy (kWh)	862,107	854,024	1,348,982	1,325,812
Winter Peak (Regulated) (kW)	202	203	1,098	764

	Large Hotel		Large Office	
	CZ10		CZ10	
	Prescriptive		Prescriptive	
	No Tank	HHW Tank Only	No Tank	HHW Tank Only
Summer Peak (Regulated) (kW)	252	252	838	838
Regulated Energy Costs ($)	$3,115,009	$3,036,004	$6,680,393	$6,352,241
(% $ LSC) HHW Plant Savings	0%	41%	0%	26%
Regulated Energy LSC Cost Savings (%)	0%	2%	0%	5%

Building Comparison: Hotel vs. Office CZ12 CHW TES

Here we compare the hotel vs. office CHW TES thermal load and LSC costs in CZ12. The dotted line represents the scenario without TES.

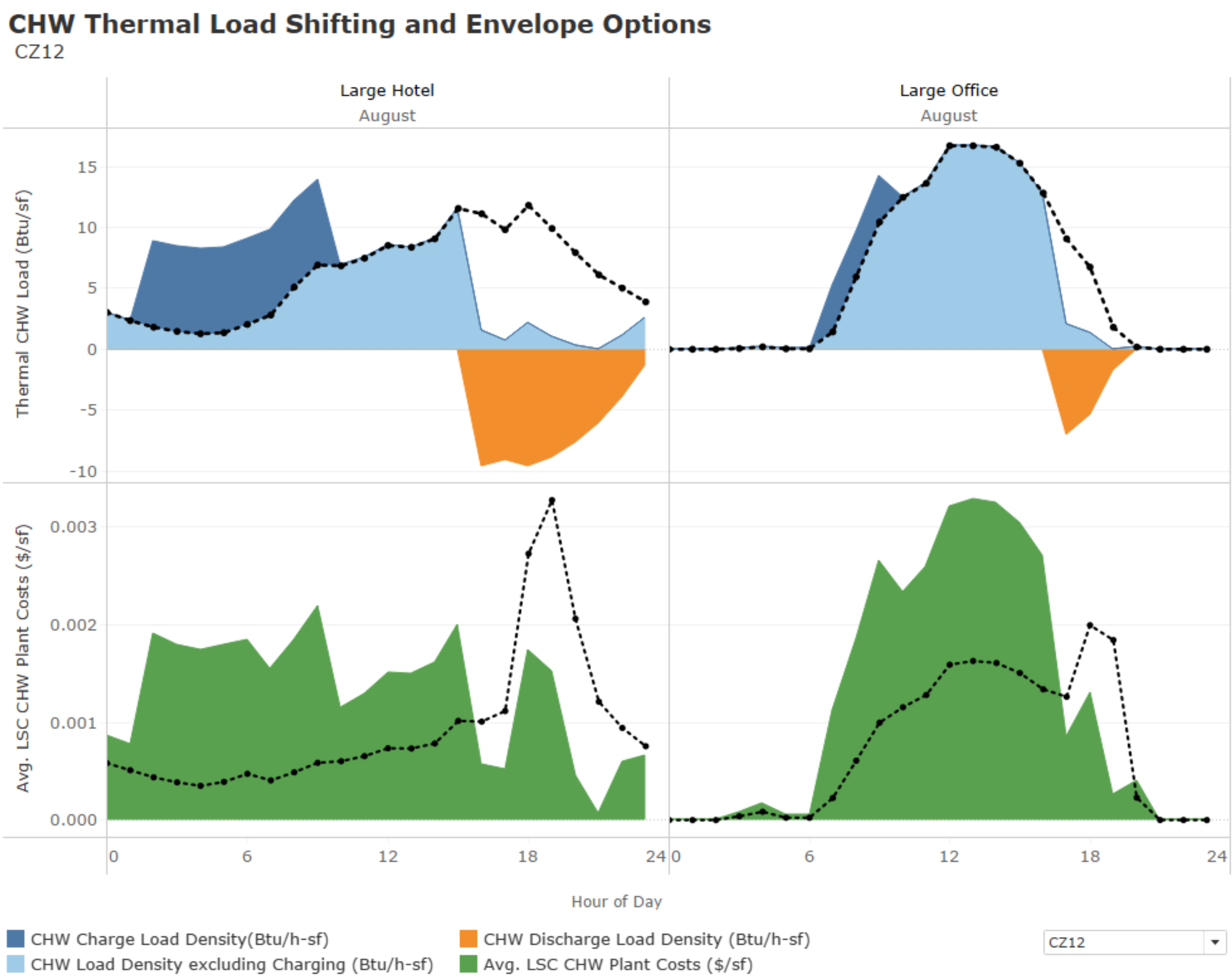


Figure. Comparison of CHW Load Density and LSC Plant Costs, Large Hotel and Office, CZ12 (Prescriptive)

Table. CHW Annual Energy and Peak Demand, Large Hotel and Large Office, CZ12

	Large Hotel		Large Office	
	CZ12		CZ12	
	Prescriptive		Prescriptive	
	No Tank	CHW Tank Only	No Tank	CHW Tank Only
Building Energy (kWh)	1,811,112	1,780,856	2,979,553	2,976,823
Regulated Energy (kWh)	856,308	826,052	1,555,832	1,553,102
Winter Peak (Regulated) (kW)	234	234	1,409	1,408
Summer Peak (Regulated) (kW)	278	224	1,039	1,029
Regulated Energy Costs (LSC-2025) ($30/yrs)	$3,182,608	$2,889,597	$7,692,957	$7,533,001
(% $ LSC) CHW Plant Savings	0%	29%	0%	8%
Energy Cost Savings (% Regulated LSC) (T24 2025)	0%	5%	0%	2%