Project Report

Technology and Market Assessment: Peak Thermal Load Reduction and Management Strategies

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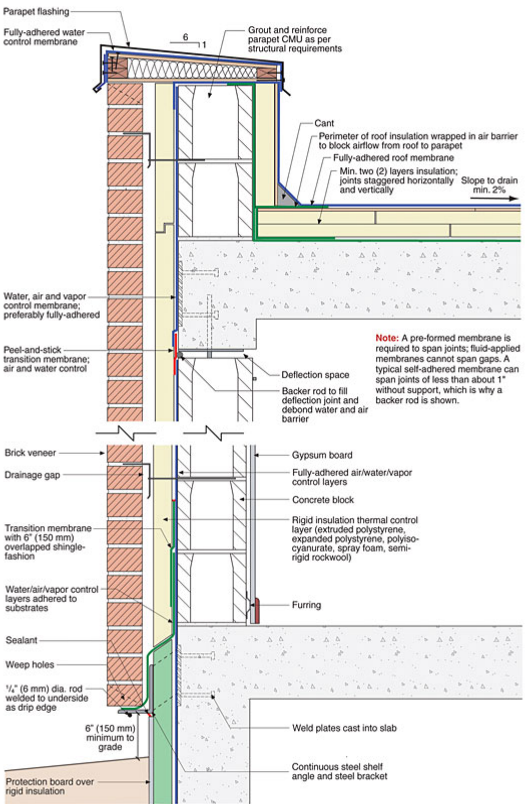

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Credits

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Executive Summary

Introduction

This research project was designed to introduce strategies that reduce and manage building peak electric demand to those involved with the development and implementation of California's Title 24, Part 6, Building Energy Efficiency Standards ("Title 24"). A key challenge and barrier in the transition to a fully decarbonized non-residential building stock in California is managing coincident peak electric demand during daily (morning and afternoon-evening peaks) and seasonal (summer cooling and winter heating) periods. One pathway to address this is at the building side, focusing on building thermal loads,[1] or HVAC energy consumption, specifically reducing or shifting thermal loads to align with building or grid renewable generation. While thermal load reduction and peak thermal load management are generally accepted as desirable practices, the specific strategies are not fully understood. This study aims to address that gap by identifying and assessing high-performance envelope strategies that reduce peak thermal load, and thermal energy storage (TES) technologies that manage and shift thermal load. This research effort is broken out into two phases, this report covers Phase 1 and outlines specific Title 24 enhancement and research recommendations that will feed into Phase 2 and aid in the further development of codes and standards that enable peak electric demand management.

Project Description

The Code Readiness Project Team (research team) was comprised of Pacific Gas and Electric Company, 2050 Partners, and A2 Efficiency. This project aimed to identify a range of code and standard enhancement recommendations that promote thermal load reduction and support peak thermal load management. In support of this objective, the research team conducted Phase 1, 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. This report documents the work conducted under Phase 1 and concludes by specifying building code and standard enhancements that would support a decarbonized and resilient built environment in California.

Phase 2 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. Phase 2 findings can be found in a report titled *Energy Modeling Analysis: Peak Thermal Load Management Strategies.*

Methods

The research team first conducted a market, literature, and data review of strategies to reduce and/or manage peak thermal loads across the categories of thermal envelope, heat recovery ventilation, internal gain reduction, HVAC controls, and TES. The team reviewed data from online scientific journals, reports from national laboratories, national and state codes and standards, and manufacturer materials to evaluate each strategy. Findings from the data review included an evaluation of each strategy's capabilities, limitations, costs, current market placement, and barriers to modeling, calculation, and market adoption.

[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.

The team then developed interview guides for three categories of subject matter experts (SME): envelope designers and specialists, thermal storage and controls technology specialists, and code and market stakeholders. They identified SMEs across these categories and conducted hour-long interviews with 21 SMEs.

Key Findings

The seven peak thermal load reduction and management strategies are outlined in the tables below along with their primary barriers and existing data gaps.

Peak Thermal Load Reduction Strategies

	1. Account for Building Envelope Thermal Bridging	2. Introduce a Building Thermal Envelope Backstop	3. Increase Air Tightness Requirements	4. Advanced Envelope Thermal Performance Requirements
Description	Increase the accuracy of Title 24 compliance rulesets to account for thermal bridging	Introduce an envelope backstop to reduce envelope tradeoffs under the Title 24 performance pathway	Introduce additional air tightness Title 24 prescriptive requirements for non-residential buildings	Increase Title 24 prescriptive envelope requirements, in particular for non-residential buildings
Key Benefit	• Better estimation of thermal envelope loads • Support HVAC right-sizing	• Ensure all buildings achieve a higher-performance envelope	• Manage moisture • Reduce thermal losses • Reduce HVAC size	• Improve overall insulation levels and occupant comfort
Primary Barrier	• Detailing and accounting complexity	• Impact on building design and market	• Lack of comprehensive best practices • Market reluctance • Testing challenges	• Existing cost-effectiveness framework
Data Gaps	• Field demonstrations • Comprehensive cost-effectiveness analysis	• Data on effectiveness of envelope backstop implementation	• Comprehensive cost-effectiveness analysis for non-residential buildings	• Field performance data on the benefits of non-residential envelope improvements

Peak Thermal Load Management Strategies

	5. Ambient Thermal Energy Source TES	6. Primary Thermal Energy Source TES	7. Small Scale Packaged TES
Description	Support use of ambient TES with air to water heat pump HVAC technologies.	Support use of primary CHW and HW TES with air to water heat pump HVAC technologies.	Support use of PCM TES in a small scale application
Key Benefit	• Improve equipment efficiency • Reduce peak electric demand	• Reduce peak electric demand	• Smaller footprint • Reduce peak electric demand
Primary Barriers	• Large footprint	• Lack of standardized sizing and integration • Complexity	• High cost • Lack of industry-wide standards

	5. Ambient Thermal Energy Source TES	6. Primary Thermal Energy Source TES	7. Small Scale Packaged TES
	• Lack of sizing standardization and support • Complexity	• Large footprint	• Market reluctance
Data Gaps	• Thermal load profiles • Field demonstrations • Advanced control sequence strategies • Cost-effectiveness analysis	• Thermal load profiles • Field demonstrations • Cost-effectiveness analysis	• Field demonstrations

Conclusions

The first four load reduction strategies outlined in this report have proven successful in codes or stretch codes throughout the U.S. Many of the jurisdictions that have adopted these approaches plan to increase the stringency in the future. The final three strategies, or technologies, supporting peak electric demand management, are not yet well demonstrated or widely adopted. While there is great potential for TES to reduce the cost and size of heat pumps, further research is required to better understand the peak energy and cost saving potential for TES applications of all sizes.

Code and Standard Enhancement Recommendations

Based on this assessment, the research team identified the following recommendations for further investigation and consideration in future code cycles:

- **Implement an envelope backstop for performance compliance of non-residential and multifamily buildings in Title 24**.
- **Require air leakage testing requirement for multifamily and nonresidential buildings in Title 24**, similar to efforts by ASHRAE 90.1-2022. Recommend a phased approach over multiple years or code cycles similar to efforts in Washington State, requiring projects test without achieving a limit, followed by a full requirement to test and pass a limit.
- **Improve envelope calculation accuracy of thermal bridging between assemblies** in Title 24 compliance software rules for predicting heating and cooling needs. This could be through specific user inputs for thermal linear and point intersections or through simplified rules for default assumptions.
- **Account for thermal bridging in compliance models and ACM:** Update nonresidential building energy modeling rulesets for Title 24, Part 6 in the Alternate Compliance Manual to include thermal bridging intersection accounting and set default assumptions about thermal loss factors. Default accounting will improve the accuracy of the compliance models of seasonally heating and cooling needs.
- **Advance the envelope thermal performance cost-effectiveness calculation**, by considering the holistic first-cost benefits of HVAC equipment rightsizing and cost-tradeoffs.
- **Update the internal gains assumptions for non-residential space types in Title 24** compliance software and ruleset to be representative of modern building uses and resources used by the DOE or similar scale agencies.

Additional Opportunities

The research team found the below to be potential opportunities for additional research, collaboration, and progress towards the optimization of thermal load management in existing nonresidential buildings.

- **Develop resources, guidelines, or case studies on today's TES sizing best practices** including guidance for HW TES plant sizing to consider peak-day profiles rather than a peak hour.
- **Create a new requirement to the prescriptive pathway of Title 24 part 6 for additional efficiency credits** such as those used in ASHRAE 90.1, IECC, and WSEC; to promote the adoption of high-performance envelope strategies and TES configurations. Such code structures have been found to identify climate specific solutions which can inform future mandatory code change requirements.

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Acronyms and Abbreviations

Term or Acronym	Definition
ACM	Alternative Calculation Method Reference Manual
AMY	Actual Meteorological Year
AWHP	Air to Water Heat Pump
Btu/h	British Thermal Unit per hour
CBECC	California Building Energy Code Compliance, a software tool used to demonstrate compliance with energy codes
CEC	California Energy Commission
CFM	Cubic Feet per Minute – a unit of air flow
COP	Coefficient of Performance
CZ	Climate Zone
F	Degrees Fahrenheit
h/hr	Hour
HRV	(Sensible) Heat Recovery Ventilator
HVAC	Heating, Ventilation, Air Conditioning
IECC	International Energy Conservation Code
IT	Information Technology
kBtu	Kilo-British Thermal Unit
kW, kWh	Kilowatt, Kilowatt-hour
LSC	Long-term System Cost
OA, OAT, OADB	Outdoor Air, Outdoor Air Temperature, Outdoor Air Dry-bulb Temperature
RAT	Return Air Temperature
SAT	Supply Air Temperature
sf	Square Feet
TES	Thermal Energy Storage
Title 24	Title 24, Part 6 Building Energy Efficiency Standards
VRF	Variable Refrigerant Flow
W	Watts, a unit of power
W/CFM	Watts per Cubic Feet per Minute, a unit of fan power
yr	Year

INTRODUCTION

This research project supports the development and implementation of California's Building Energy Efficiency Standards Title 24, Part 6 (Title 24) by identifying and evaluating strategies that reduce and manage building peak electric demand. A key challenge and barrier in the transition to a fully decarbonized non-residential building stock in California is managing coincident peak electric demand during daily (morning and afternoon-evening peaks) and seasonal (summer cooling and winter heating) periods. One pathway to address this is at the building side, focusing on building thermal loads,[2] or HVAC energy consumption, specifically reducing or shifting thermal loads to align with building or grid renewable generation.

While thermal load reduction and peak thermal load management are generally accepted as desirable practices, the specific strategies are not fully understood. This study aims to address that gap by identifying and assessing high-performance envelope strategies that reduce peak thermal load, and thermal energy storage (TES) technologies that manage and shift thermal load. This research effort is broken out into two phases, this report covers Phase 1 and will outline specific Title 24 enhancement and research recommendations that will feed into Phase 2 and aid in the further development of codes and standards that enable 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

PROJECT BACKGROUND

A key challenge and barrier in the transition to a fully decarbonized non-residential building stock in California is managing peak electric demand on daily (morning and afternoon-evening peaks) and seasonal (summer cooling and winter heating peaks) periods. Those involved with the development and implementation Title 24 must consider forward-looking enhancements to address the anticipated growth of coincident peak electric demand on the grid due to the rise of all-electric heating ventilation and air conditioning (HVAC) and other systems, particularly considering the electrification of the existing building stock. With this

[2] 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.

current shift taking place in HVAC from gas heating to electric heating in particular there is an opportunity to re-consider efficiency strategies which can reduce thermal gains as well as strategies which can shift thermal loads, such as thermal energy storage resulting in a reduced electric peak demand overall.

Figure 1 shows a concept of the required electrical infrastructure that exists for buildings to be able to meet and manage thermal gains and losses. While electric batteries have great potential to reduce electric grid demand costs, both behind the meter and at the utility scale, thermal batteries and thermal reduction strategies may hold this same potential for significant peak savings in building HVAC.

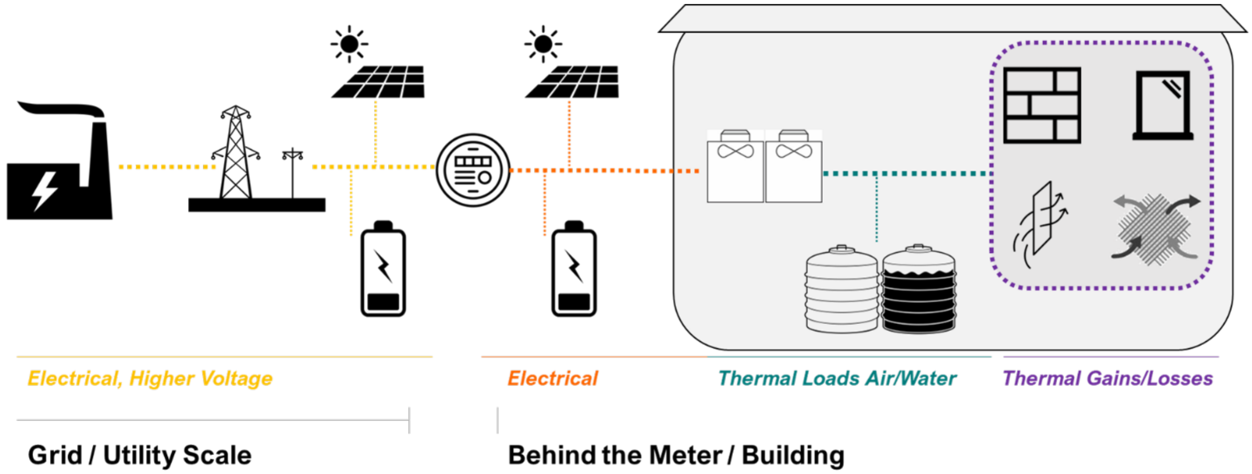
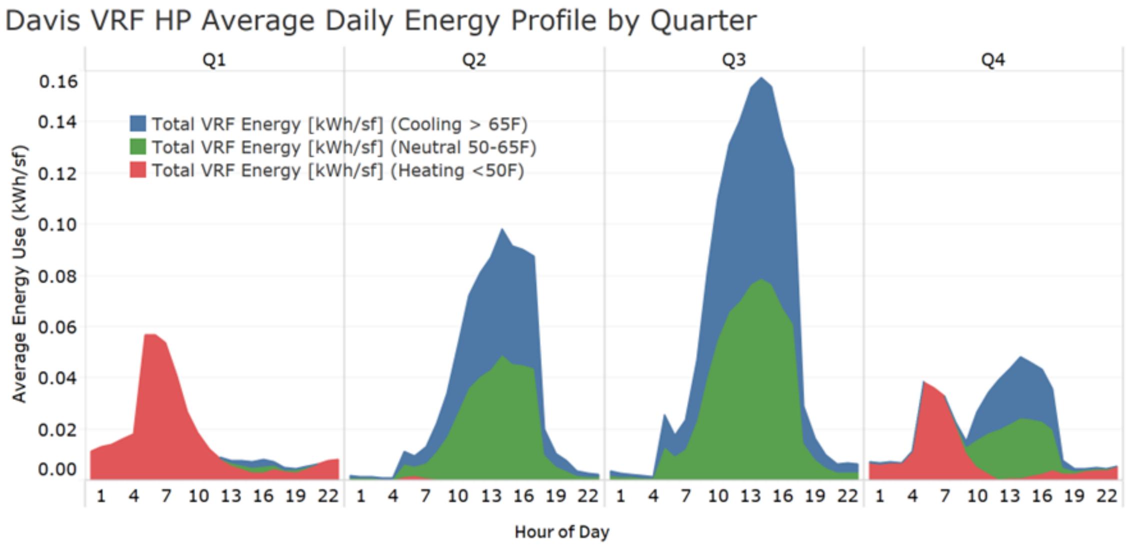


FIGURE 1. CONCEPT DIAGRAM OF THE ELECTRICAL INFRASTRUCTURE REQUIRED TO MANAGE AND MEET BUILDING PEAK THERMAL LOADS

Past research projects by the Code Readiness team of two commercial buildings are shown in Figure 2, which demonstrate the building peak demand of all-electric HVAC systems in CA climate zones (CZ) 12 and 15. At these sites, peak HVAC energy consumption in the summer occurs during 4-9pm, which overlaps with forecast summer afternoon peak electricity costs and grid carbon emissions as shown in Q3 in Figure 3. Peak winter HVAC energy consumption occurs in the morning from early morning warm-up. This overlaps with peak electricity costs and forecasted grid carbon emissions (4-9am) as shown in Q4 Figure 3. As more buildings transition to all-electric HVAC, there will likely be high coincident peak demand. Focusing on reducing building peak HVAC energy consumption and shifting thermal load to align with renewable generation will be key to achieving both a decarbonized built environment and a stable grid.



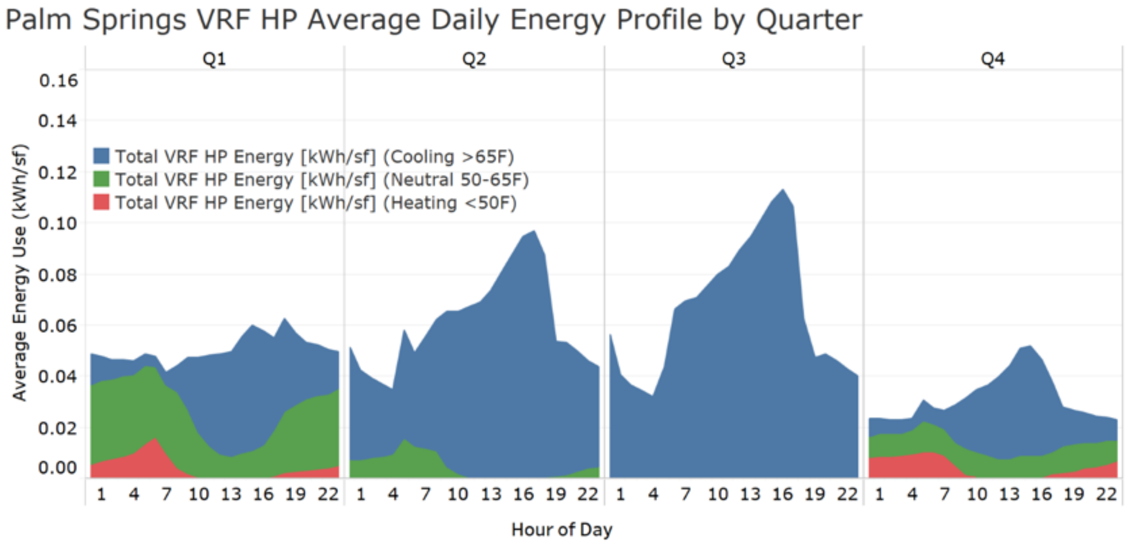


FIGURE 2. ANNUAL VRF COMPRESSOR ENERGY USE FOR COOLING, NEUTRAL, HEATING, OVER TYPICAL DAY PER QUARTER, IN HOT TO EXTREME CLIMATE SITES, CZ12 (TOP) AND CZ15 (BOTTOM)

Source: Bulger, Weitze 2024

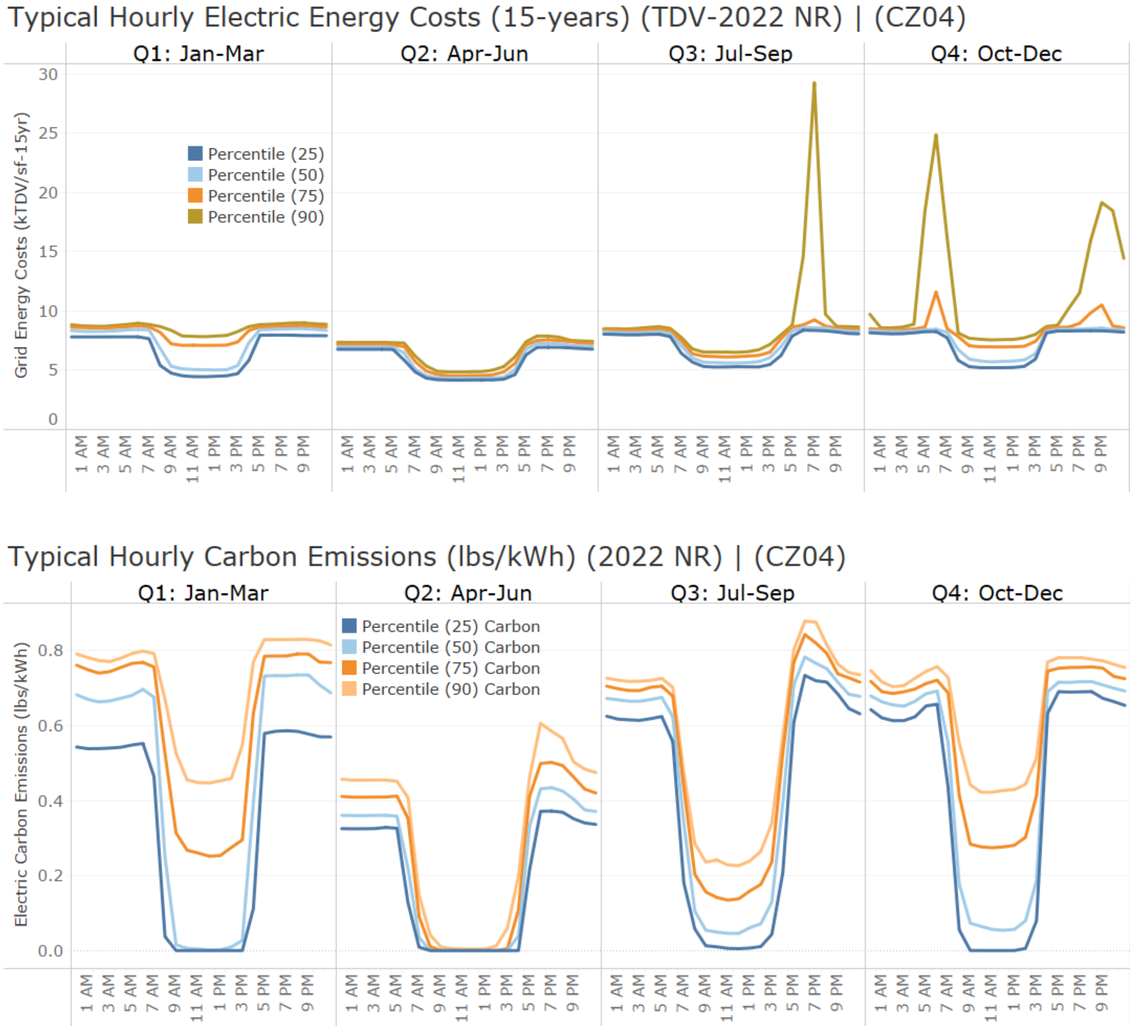


FIGURE 3. FORECAST LIFE CYCLE ELECTRIC ENERGY COSTS (TDV) FOR 15 YEARS (T24 2022, CZ4) (TOP) AND FORECAST GRID ELECTRICITY CARBON EMISSIONS (T24 2022, CZ4) (BOTTOM)

Source: Bulger, Weitze 2024

This report, the deliverable of Phase 1 of this project, provides a comprehensive technology and market assessment of thermal load reduction and management technologies. The report outlines the benefits, barriers, and current market landscape of these technologies and identifies several peak thermal load reduction and management strategies. The report concludes by specifying building code and standard enhancements that would support a decarbonized and resilient built environment in California.

Phase 2 will build upon these findings, utilizing modeling analysis to evaluate the strategies identified in this report and quantify the peak energy, annual energy, and cost savings associated with a selection of these strategies. Phase 2 will result in a report titled *Energy Modeling Analysis: Peak Thermal Load Management Strategies.*

OBJECTIVES

The objective of this study is to identify strategies to reduce and/or manage peak thermal loads that can be implemented into Title 24, Title 20, and other building codes and standards.

The research team had the following research objectives for Phase 1 of the study.

- Outline the benefits and barriers of different peak thermal load reduction and management strategies.
- Identify Title 24 ACM or compliance software capabilities and limitations when modeling thermal storage and load shifting strategies and technologies.
- Identify non-California building energy code compliance approaches that support building peak thermal load management or reduction and should be incorporated into Title 24.

To serve the above research objectives, the research team developed the following research questions.

- What design practices are being used to size hydronic heating and cooling systems with thermal storage and which practices could potentially be incorporated into a TES sizing guideline?
- Which building envelope thermal performance criteria can be further optimized and how can they be verified in design and/or construction?
- What modern sources are available for standard internal heat gain estimations by building and space type which can impact the thermal load balance and how do they differ for assumptions used in Title 24 today?
- What thermal envelope metrics or limits could be specified in an energy code to enhance the existing language and potentially can drive higher-performance envelopes?

METHODOLOGY

MARKET ASSESSMENT

The research team first conducted a market, literature, and data review of strategies to reduce and/or manage peak thermal loads in the following categories: thermal envelope , internal gain reduction, HVAC controls, and thermal energy storage (TES). A longer list of technologies were considered and shown in Table A though not included in this study to focus research efforts. The team evaluated each strategy for its capabilities, limitations, cost, modeling or calculation barriers, current market placement, and barriers to market adoption.

TABLE 2. THERMAL LOAD MANAGEMENT AND REDUCTION POTENTIAL TECHNOLOGIES FOR HVAC

Technologies Evaluated	Technologies Not Included in this Study
Load Reduction •Envelope Insulation •Air Leakage •Window Systems •Thermal Bridging	Load Reduction •Ventilation Heat/Energy Recovery •Active Ventilation Controls •Heat Recovery Chillers •Heat Recovery from Waste Heat Sources •Decentralized HVAC Systems
Load Management •Thermostat Controls •Thermal Energy Storage	Load Management •Demand Response Controls •Geothermal Storage

The research team gathered data from online scientific journals, reports from national laboratories, national and state codes and standards, and manufacturer materials.

SURVEY

Upon completion of the market, literature, and data review, the research team began the detailed interview survey. First, the team developed separate sets of interview questions for three categories of subject matter experts (SME): envelope designers and specialists, thermal storage and controls technology specialists, and code and market stakeholders. The team then developed a list of SMEs for outreach and engagement and conducted 1-hour interviews with each SME. The team summarized key interview takeaways in a summary spreadsheet. Table 3 includes a count of all the organizations interviewed, grouped by SME category and sub-category.

TABLE 3: SME INTERVIEW SUMMARY

SME Category	SME Sub-Category	Number of Completed Interviews
Envelope Designers and Specialists	Architects	2
	Passive House Expert	2
	Envelope Consultants and/or Waterproofing/Siding Inspector	4
	Energy Consultant	1
Thermal Storage and Controls Technology Specialists	Mechanical Engineer	2
	BEM Software Developers	2
	TES Manufacturer	2

Code and Market Stakeholders	CA Code Stakeholders	1
	ASHRAE 90.1 TC Member	1
	Non-CA Code Stakeholder	2
	National Labs	2

RESULTS AND DISCUSSION

Peak electric demand, summertime afternoons and winter mornings, can be reduced in a variety of ways. This report focuses on identifying thermal load reduction and peak thermal load management strategies. **Thermal load reduction** is accomplished through energy efficiency strategies such as improving the thermal performance of the building envelope. Adding insulation, reducing air leakage, and improving the thermal performance of building elements such as windows can significantly reduce the heating and cooling needs of the building, reduce the entire thermal load profile, as illustrated in the first chart in Figure 4, and cut HVAC energy consumption leading to operational cost savings. Optimizing the building envelope enhances thermal comfort for occupants through stable indoor temperatures, and also contributes to building resilience; high-performance envelopes are able to maintain comfortable indoor conditions over a longer period of time during a power outage or extreme weather event. Additionally, a high-performance envelope can often lead to smaller sized HVAC equipment, offering first cost and maintenance cost savings.

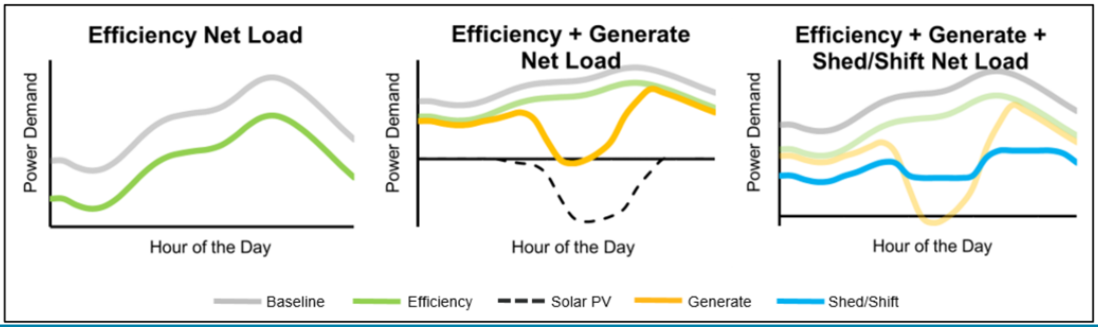


FIGURE 4. EXAMPLE LOAD REDUCTION AND MANAGEMENT STRATEGIES

Source: Neukomm et al. 2019

Peak thermal load management is accomplished through shifting loads to different times of the day to align with renewable generation and/or lower utility rates, as illustrated in the blue line in Figure 4. Examples include HVAC controls that pre-heat or pre-cool a building, or through thermal energy storage (TES) which acts as a thermal battery by charging or discharging hot or chilled water depending on building heating and cooling needs. TES can allow a building to utilize its heat pump to charge a tank with chilled water throughout off-peak nighttime hours and use that chilled water throughout the day and afternoon. By shifting loads and reducing peak electrical demand, TES can lead to substantial cost savings, particularly in large commercial buildings where peak demand charges can constitute a significant portion of total energy costs. Additionally, TES can facilitate energy recovery and improve the efficiency of air source heat pumps by shifting operation to periods with optimal conditions.

The following section is divided into two categories: thermal load reduction strategies, and peak thermal load management strategies. Each section includes a technical and regulatory overview, a summary of the modeling landscape, and a comprehensive summary of the leading strategies. In total, the research team identified seven strategies, which are listed below.

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

Thermal Load Reduction Strategies

Technical Overview

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. High-performance or high-efficiency buildings are characterized by low thermal loads, meaning the building requires minimal space heating and cooling. A building's thermal load can be impacted by many factors; the most impactful of which are the location and climate, followed by the envelope (floor, roof, walls, fenestration), thermal mass, and internal heat gain. Of those elements, the building envelope design and construction is often the most controllable element, and therefore was the focus of the research team. High-performance envelopes are characterized by the following features:

- **High-Performance Opaque Assemblies**: Opaque envelope assemblies are the building envelope components besides fenestration, such as wall, roof, and floor assemblies. The assemblies include the build-up of all components including insulation. A well-insulated building is one with continuous insulation.
- **Air-Tight Envelope**: Air-tightness is the quality of the air barrier and air sealing conducted, such as air sealing practices around the fenestration frame, sill plate, and top plate. An air-tight envelope requires a continuous air barrier.
- **Minimal Thermal Bridge Losses:** A thermal bridge is an area or element of the envelope that has a higher thermal conductivity, creating a path for heat transfer. For example, at the junction of a wall and floor materials, or a balcony that extends through the thermal boundary. The heat loss of a thermal bridge point can be quantified by calculating the Chi-value. The heat loss through a linear joint can be calculated by multiplying the Psi-value by the length of the bridge. High-performance envelope design would be free of thermal bridges.
- **High-Performance Fenestration:** Fenestration performance is defined by the assembly solar heat gain coefficient (SHGC) and the U-factor, which is the amount of heat flow through the assembly. Manufacturers are able to achieve extremely low U-factors with triple pane glazing, non-metal framing materials, and advanced glazing practices, such as vacuum insulated glazing. High-performance fenestration is defined by low heat loss, U-factor, and a curbed SHGC.

Figure 5 illustrates some of these important concepts.

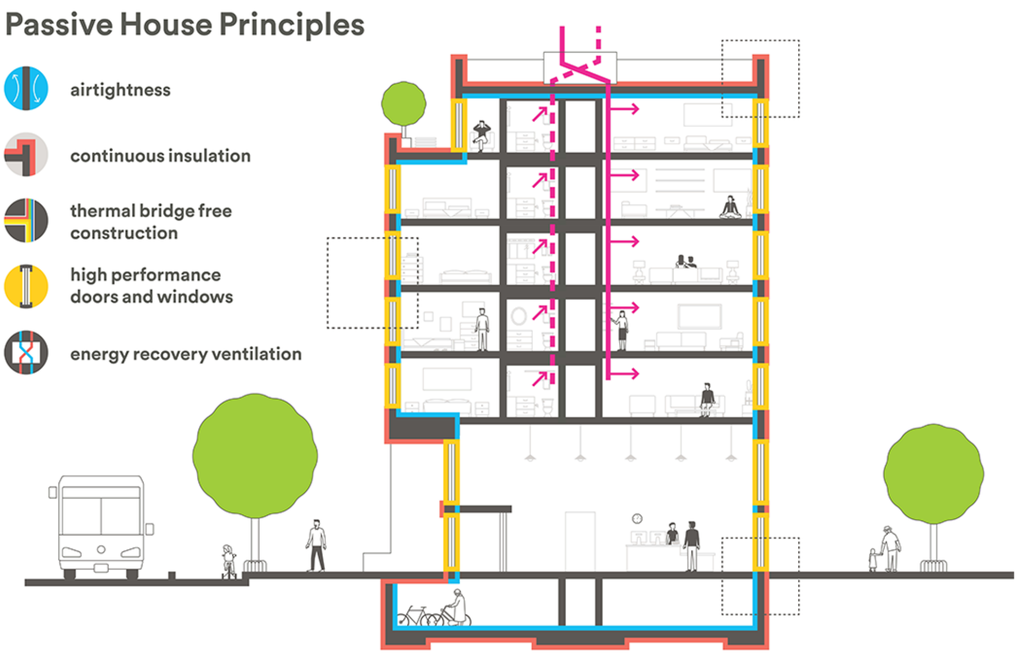


FIGURE 5. DIAGRAM OF CORE PASSIVE HOUSE PRINCIPLES

Source: Building Energy Exchange n.d.

The following Table 4 provides a consolidated summary of each thermal load reduction envelope element.

TABLE 4. THERMAL LOAD REDUCTION ENVELOPE ELEMENT MARKET SUMMARY

	Improved Opaque Assemblies	Thermal Bridging	Fenestration Assemblies	Envelope Air Tightness
State of Adoption	Widely adopted	Included in latest national model codes, IECC, ASHRAE 90.1 for future adoption. Adopted in WSEC 2021.	Commercially available	Requirements in (version of ASHRAE 90.1), Adopted in WSEC 2018 and 2021 codes.
Capabilities	Any exterior walls, roof, ground, window pane U-factor	Improves accuracy of envelope performance	Triple pane assemblies, higher performance frames	Details, applied air barriers, air sealing tape
Barriers to market adoption	Thickness of assemblies, product availability and installation/cost	Verification mechanisms, additional design detailing	Cost and availability of products	Costs and complexity of large scale air testing
Design Cost	Neutral	+$ Moderate cost	Neutral	Unknown
Material Cost	+$ Moderate cost	Unknown	+$$ High cost	Wide range
Labor Cost	+$ Moderate cost	+$$ High cost	Neutral	+$ Moderate cost
Benefits	Improved occupant comfort Heating/cooling energy savings Heating/cooling peak energy reduction			

	Improved Opaque Assemblies	Thermal Bridging	Fenestration Assemblies	Envelope Air Tightness
Energy Modeling barriers	None	Separate tool to calculate the psi or chi values.	Separate tool to calculate overall performance.	Accuracy of simulating wind-driven leakage.

<u>Internal Gains</u>

In NR buildings, internal heat gains are considered a significant portion of the thermal loads. In building energy modeling, these gains are made up of both an estimated peak factor that anticipates how many people and how much equipment will be producing heat and an anticipated frequency of usage, accounting for the regularity of heat. Assumptions for standard internal heat gains by building use are defined in the set of software tools used in California by the CEC to weigh changes to new building energy codes and understand which strategies might be cost effective over a building's life cycle. While the assumptions for internal gains represent only a portion of the standard assumptions, model results are highly sensitive to internal gains assumptions which can lead to an uncertainty in the cost effectiveness of system efficiency measures.

A review of internal gains is included in Appendix B. Building Internal Heat Gains including a review of the Massachusetts Stretch Code and a PNNL research project looking at all NR space types and modern equipment power densities. From both surveys, internal gains tend to be lower on a space-by-space basis than those found in Title 24 today. As a result, building energy models are likely to overpredict building cooling needs and underpredict building heating needs. Information from this research will be used in the modeling analysis phase of the project, which will evaluate the impact of different internal gains assumptions on different building types.

Summary of the Regulatory Landscape

The research team reviewed thermal envelope performance requirements for non-residential buildings in Title 24 to establish an understanding of current requirements in the 2022 Title 24 and the newly adopted 2025 requirements. The team then compared Title 24 mandatory and prescriptive requirements to other state building envelope standards and requirements. The following sections provide an overview of the relevant codes and standards grouped by envelope element.

Regulation of Opaque Assemblies

The majority of state building energy codes include certain mandatory requirements for envelope performance. California's Title 24 includes minimum envelope assembly requirements for all buildings to prevent excess thermal loss in new construction buildings. Title 24 establishes maximum U-factors for each component of the envelope; roof, wall, floor, including windows and vestibules as of 2025. With maximum U-factors depending on the construction type and climate zone (CZ) of each component. However, Title 24 also has other prescriptive requirements which can be traded-off with other efficiency measures, such as HVAC, water heating, and lighting: a building designer can specify a lower performing envelope than the prescriptive minimum if they compensate with other efficiency improvements.

IECC and ASHRAE 90.1 also use maximum U-factors to limit thermal loss in the building envelope. Figure 6 provides a visualization comparison between Title 24, IECC, and ASHRAE

90.1 code envelope component requirement, converted into R-value[3] (equal to 1/U-factor). In this comparison, there is no defined leader in high R-value requirements: Title 24 leads in the insulation entirely above the roof deck (IEAD) and mass wall categories. IECC and ASHRAE 90.1 jointly lead in metal building roofs, raised mass floor, and other floor categories.

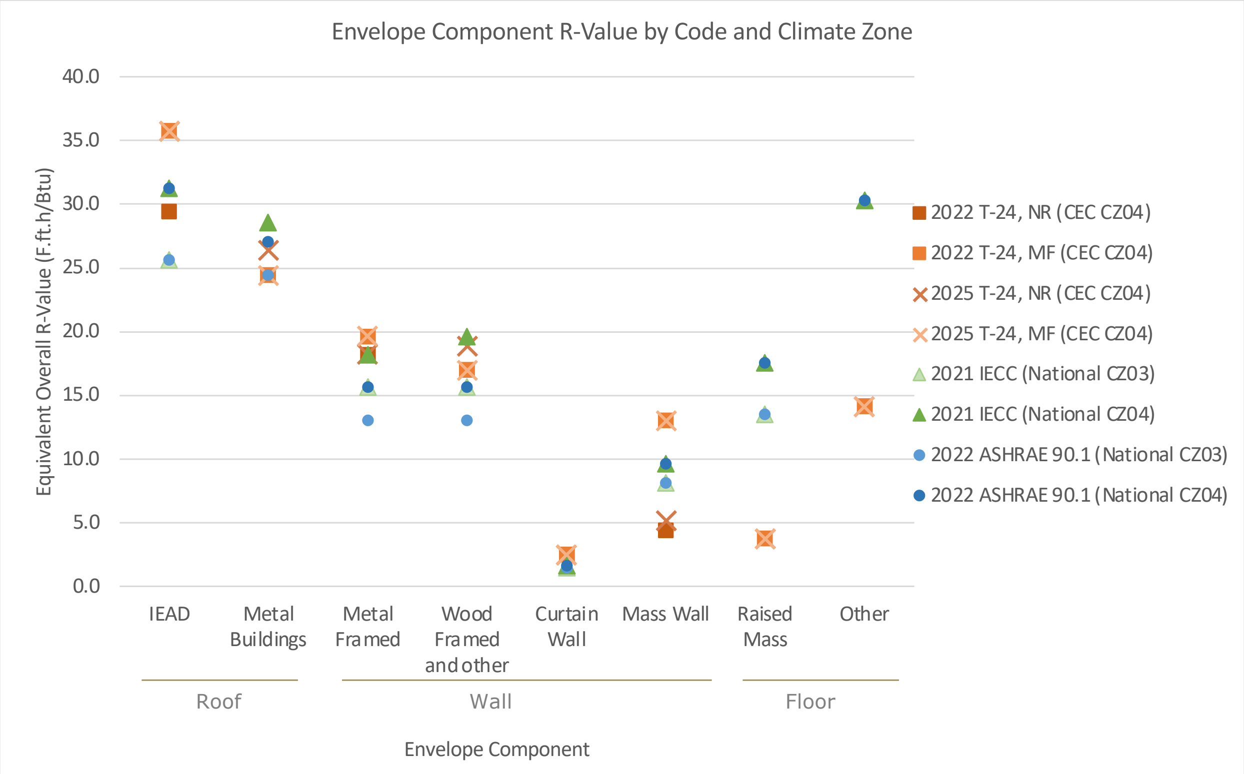


FIGURE 6. MINIMUM ENVELOPE COMPONENT R-VALUE PER ENERGY CODE

The research team reviewed other standards that take a different approach to building envelope efficiency, they apply additional code criteria to enhance thermal envelope efficiency or reduce the amount of energy trade-offs allowed with the envelope. These approaches include ASHRAE 90.1 2022, IECC 2021 and 2024, Oregon code, Massachusetts state stretch code, ASHRAE 227P, and Washington state Energy Code:

ASHRAE 227P Passive Building Design Standard defines a total thermal loss maximum factor, which is calculated based on heating degree-days, heating peak temperature, and the building floor area.

Massachusetts state stretch code defines a maximum thermal loss of a building's envelope as well, stipulating minimum envelope performance values per building type. This standard effectively has a "envelope backstop" meaning that a building owners have a limited ability to trade off a high-performance envelope with other high-efficiency measures (HVAC, DHW), ensuring high-performance envelopes in all new construction buildings.

REGULATION OF THERMAL BRIDGING

ASHRAE 227P Passive Building Design Standard includes thermal bridging requirements between assemblies and provides multiple ways for designers to calculate these loss values. The requirement entails calculating the building's annual heating load and factoring in thermal bridge losses, to ensure the load does not exceed the ASHRAE 227P

[3] R-value is the capacity of an insulating material to resist heat flow. A higher R-value is more insulative.

threshold defined per city. Mitigating thermal bridging can help reduce the overall heat loss and achieve the stated target annual heating load. For example, the standard presents four calculation method pathways for determining the window installation thermal bridge, two leveraging precalculated values that can be used as defaults and two alternative methods to calculate design values based on 2D analysis. The basic method uses assumed thermal loss rate provided in the standard for different window-wall mounting locations.

ASHRAE 90.1-2022 requires a series of intersections of the exterior envelope (e.g., window to wall, and roof to parapet) be detailed and specific mitigation requirements on insulation placement and thickness be taken to reduce thermal bridging. Exclusions are provided including ASHRAE climate zones 0-3. These criteria do not indicate the reduced thermal performance; they only prescribe levels of insulation and techniques required.

The Massachusetts state stretch code (the predominant adopted state code) also includes thermal bridging requirements be taken into thermal loss calculations for building envelopes. The stretch code prescribes a set of loss factors.

In the latest draft of **IECC 2024**, new language has been included to mitigate thermal bridges in above-grade walls (C402.7) including requirements and exceptions for balconies and floor decks, cladding supports, structural beams and columns, vertical fenestration, and parapets. Notably, as in ASHRAE 90.1-2022, IECC Climate Zones 0-3 are excluded.

For the **2022 Title 24** cycle, the Codes and Standards Enhancement (CASE) team had a goal to mitigate heat transfer through major thermal bridges in buildings, including wall-roof intersections, wall-intermediate floor intersections, wall-fenestration intersections, and wall-exterior projections, including balconies and overhangs. The proposal was discontinued in the 2022 code cycle because there were too few third parties for field inspection and verification, and there was no established format for professionals to sign off on thermal bridging calculations. With the recent publication of many standards including methods to account for thermal bridging and verification mechanisms, the adoption of thermal bridging requirements in Title 24 Part 6 should be reconsidered.

Regulation of Air Tightness

2022 Title 24 requires envelopes be designed for air tightness, but it only requires verification of air tightness as a compliance option specific to multifamily buildings. Section 160.2(b)2iv(b) provides two options for multifamily buildings to either use exhaust driven ventilation and verify air tightness of the envelope through a compartmentalization approach (testing portions of the building at a time) or design a balanced ventilation system. NR buildings are prescriptively required to be designed for whole building air tightness in section 140.3(a)9C, but verification is optional. The Title 24 language provides the detailed acceptance criteria for whole building air leakage testing. However, the research team's interviews with designers in CA revealed that air-leakage testing in NR buildings today is not commonly done. Similar to other standards, if builders decide to verify air leakage, the project air barrier is then required to be less than 0.4 cfm/sf_wall at 75 PA. If a building exceeds this rate, it must be fixed and retested to show under 0.6 cfm/sf_wall at 75 PA only if the original test exceeded 0.6 cfm/sf_wall at 75 Pa. No retest is needed if the original test is between 0.4 – 0.6 cfm/sf_wall. Testing must be completed in accordance with ASTM 3158.

ASHRAE 90.1-2022 has similar requirements, though they are mandatory. For buildings under 10,000 sf, air leakage is required to be designed and tested to 0.35 cfm/sf_wall at 75 PA. Where tested results exceed 0.45 cfm/sf_wall, buildings must be fixed and re-tested to not exceed 0.45 cfm/sf. Testing in accordance with ASTM E3158. For buildings less than 10,000sf with one single-zone system, ASTM E779, ASTM E1827, or ASTM E3158 can be used.

ASHRAE 227P, the passive design standard, requires air leakage below 0.08 cfm/sf_wall for buildings under five stories, and 0.11 cfm/sf_wall for buildings five stories and above (at 75 PA in both cases). The air tightness must be verified by an independent third party using a single-zone whole building test in accordance with ASTM E799-19 or ASTM E3158 if it can be tested as a single zone. If the building cannot be tested as a single zone, then the whole building should be tested in accordance with ASTM E3158.

The **Massachusetts state stretch code** prescriptive and performance paths include requirements to perform air leakage testing using whole building or dwelling or a combination of the two. The standard sets an air leakage limit at 0.35 cfm/sf_wall (at 75PA), using ASTM E3158 (or E799 or E1827 for < 10,000sf) similar to the methods cited by ASHRAE 227P.

Regulation of Fenestration Assemblies

The research team reviewed prescriptive fenestration assemblies for IECC, ASHRAE, and Title 24. The 2025 Title 24 update draft does not improve upon the 2022 U-factors, which are currently better than IECC and ASHRAE in thermal performance.

The market seems to be trending toward very low U-factor windows, from single-pane to vacuum-sealed window assemblies. Product improvements are just one angle to reduce fenestration thermal bridging. Another approach is to improve window assembly and frame element regulation and heat loss calculations. ASHRAE Standard 227P provides a table of window-frame-only values and a formula by which window overall performance of U-center of glass and frames can be combined allowing more accurate calculation of frame and window performance. This formula is used as part of the dewpoint and indoor moisture and mold mitigation criteria. ASHRAE 227P also requires windows to be evaluated to reduce potential peak summer stress and improve building resiliency.

Summary of the Modeling Landscape

Of the four areas defining a high-performance envelope; high-performance opaque assemblies, air tightness, thermal bridge free, and high-performance fenestration, air leakage and thermal bridge modeling methods are the most variable or under-represented and are discussed below.

Thermal Bridge Accounting Methods

Title 24 compliance tools do account for assembly performance through assembly U-Values. The California compliance manager software CBECC does not account for thermal bridging and the other main compliance software for non-res, IES-VE, does not include the option for additional heat loss factors (Psi and Chi) in Title 24 analysis runs. To factor in thermal bridging, a modeler would need to complete a separate calculation in another software, and then manually derate the thermal performance of assemblies in the Title 24 compliance software to account for thermal bridging heat loss.

At a national level, COMCheck and PassiveHouse software have fields to include the heat loss factors. COMCheck is a prescriptive compliance tool that can be used to perform prescriptive envelope trade-offs for ASHRAE and IECC. COMCheck has preset heat loss factor values. PassiveHouse software has a separate tool to calculate the loss factors, which are then entered in the interface to account for thermal bridging. Standards like ASHRAE 227P provide reference values for different envelope intersections.

EnergyPlus is similar to Title 24 compliance tools, it does not include a field for the heat loss factors and requires a separate calculation tool in order to manually derate the U-value performance values to account for thermal bridging.

Envelope and energy consultants use THERM, Flixo, and Physibel's TRISCO and SOLIDO for separate thermal bridging analysis. Limitations in typical 2D thermal bridging modeling and integrating small subcomponents in analysis can lead to discrepancies between calculated and actual performance, especially concerning thermal bridging. Interviewed experts also noted that energy models do not account for misalignment of envelope components either in design detailing or during construction, and misalignment can be a large issue for thermal bridging.

Air Leakage Modeling Methods

Two Title 24 compliance simulation engines are used to simulate compliance: the residential and multifamily simulation engine, California Simulation Engine (CSE), and EnergyPlus, which is the simulation engine for CBECC. CBECC-Res uses both CSE and EnergyPlus engines depending on the occupancy per space. The CSE engine uses an advanced method that factors in wind speed and direction and allows infiltration and exfiltration to be simulated dynamically through the exterior envelope. For non-res modeling in CBECC, the model assumes a cfm/sf infiltration rate applied to the exterior wall area. IES-VE has the capability to model air leakage in a similar way to the CSE engine using macro-flow air leakage, however this option is not used in Title 24 compliance analysis.

For EnergyPlus, it is possible to model infiltration using a nodal air network for bulk air flow, however the set-up is highly complex and rarely used outside of software graphical user interfaces (GUI) like DesignBuilder. Typically, the infiltration uses the same methods used in CBECC with a cfm/sf applied to exterior wall area.

Identified Load Reduction Strategies and Products

Strategy 1: Building Envelope Thermal Bridging

Increased accounting of thermal bridges in design and assembly intersections can lead to more accurate estimation of thermal envelope loads and greater use of higher efficiency products to minimize energy loss through thermal bridging. Several building standards now require building designers to account for and mitigate the effects of thermal bridging between building assemblies as a point of building design.

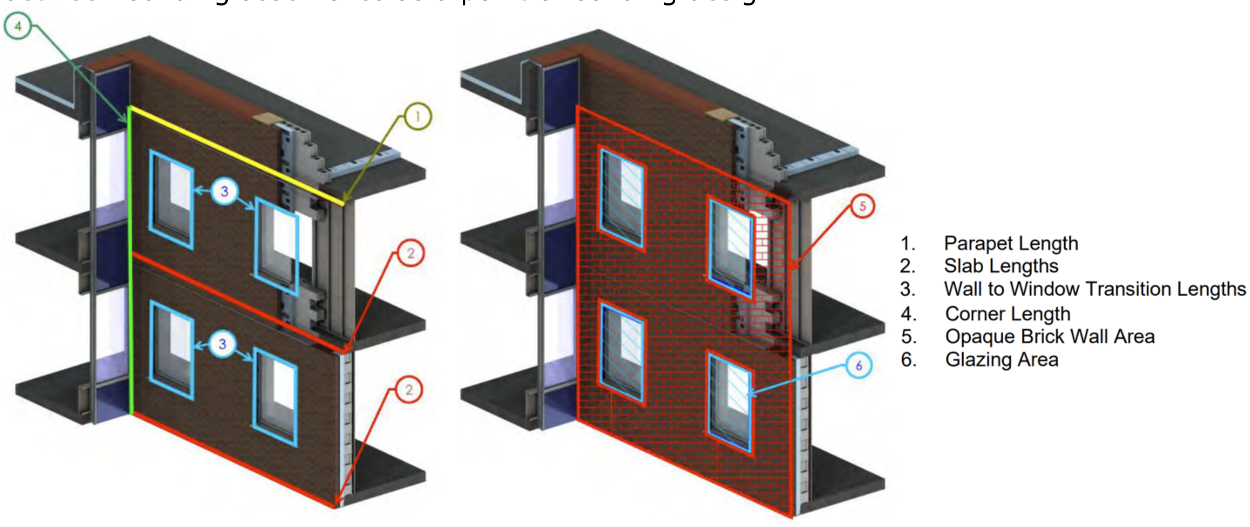


Figure 7. Illustration of Envelope Thermal Bridges

Source: Morrison Hershfield 2021

Summary of Findings

Proper detailing and accounting of thermal bridges in peak sizing and annual energy load calculations are crucial for achieving high-performance buildings by minimizing energy loss and ensuring building envelope integrity. Passive House specifies that buildings be free of thermal bridging, with requirements to simulate and mitigate all thermal bridges. Experts note that smaller buildings are more impacted by thermal bridges.

Several interviewees noted common challenges in addressing thermal bridges in components like metal flashing, window installations, canopies, balconies, and slab edges, which can compromise energy efficiency. Specific material and structural challenges were noted also, particularly with concrete slab edge insulation and continuous insulation on wood framing, due to structural requirements, moisture issues, and complex cladding attachments. Compliance with some code requirements, such as those for insulating stairwells and elevators in WSEC and SEC, often conflicts with architectural designs and practical implementation. Thermal bridging in existing buildings remains a significant challenge, with thermal bridge reduction measures often providing slower payback compared to mechanical system upgrades.

Education on thermal bridging is necessary for both Passive House and non-Passive House projects to ensure that all stakeholders understand its impact and the methods to mitigate it. Cost-effective solutions such as thermally broken z-girts and green girts were mentioned several times as common recommended methods to reduce thermal bridging without significantly increasing construction costs. Improved construction practices, including proper detailing to prevent thermal bridging around windows and other components, are essential for enhancing energy performance as well as avoiding moisture issues. Interviewed experts stated continuous insulation is becoming more common but requires careful implementation to avoid issues with metal penetration and to ensure its effectiveness. It was noted that not all contractors are comfortable working with exterior insulation, due to concerns of leading to moisture issues when installing a thermally broken furring system. Experts identified that strict verification processes are key to ensure proper installation, performance goals are met, moisture, and weather proofing issues are avoided. Lack of trained professionals was a perceived barrier that the research team identified early on in the development of this project. Interviewed individuals didn't share this concern: they stated that proper training and education is important to ensure the best construction practices are used, but felt there was a growing workforce to meet the demands.

New standard language, such as new requirements in ASHRAE 90.1, emphasize improved criteria for thermal bridging, but these need continual updates based on the latest data and practices. For example, IECC 2024 proposed including effective U-Factor values for spandrel panels, a typical source of thermal bridging in curtain wall construction. These values derate the performance of the spandrel panel insulation to an effective level based on frame type, glazing type, and rated insulation R-Value.

<u>Barriers</u>

- **Detailing and Accounting Complexity**
    - Slab edge insulation requirements for concrete structures pose structural challenges, and code language could be introduced/amended to address the complications.
    - Continuous insulation on wood framing is problematic due to moisture trapping and more complex cladding attachment.
    - Advanced 3D thermal bridging analysis is not yet mainstream due to lack of requirement in codes to use 3D modeling, relying on 2D heat transfer analysis (such as Therm or Flixo).
- **Lack of Education**
    - There is a lack of education on thermal bridging for non-Passive House projects.

    - Contractors often struggle with implementing continuous insulation, particularly when using mineral wool, which requires a thermally broken furring system.
- **Lack of Code Compliance Requirement**
    - Title 24 does not currently have a code requirement for thermal bridging mitigation. Demand for thermal bridging analysis and accounting is driven by code requirements.

Data Gaps

- **Advanced Analysis and Performance Data**
    - Calculations of thermal bridges in CA climate zones for representative construction practices and types, which could be used as defaults for more accurately represent the envelope performance in code.
    - Current thermal bridging criteria and requirements exist in both ASHRAE 90.1 as well as the British Columbia Building Envelope Thermal Bridging Guide (Morrison Hershfield 2021). These both could serve as a resource in the development and evaluation of thermal bridging risks.
    - Lack of case studies and best practices specific to California buildings would be the best next step to determining what level of thermal bridging mitigation exists and the potential improvement in accuracy.
- **Cost-Effectiveness Analysis:** Lack of comprehensive thermal bridging cost-effectiveness analysis.
- **Field Demonstrations**: Lack of performance data from real buildings in California demonstrating energy savings to support cost-effectiveness calculations.
- **Performance of Different Materials and Systems**
    - Detailed thermal analysis of curtain wall systems and spandrel assemblies are not accounted for accurately in most codes. The spandrel panels are opaque sections in curtain walls often used to conceal structural elements and insulation. Thermal analysis would focus on how well these assemblies prevent heat transfer and the role of different insulation materials in improving thermal performance.
    - The impact of metal plates and fasteners on thermal performance is not fully accounted for. Understanding the impact of metal plates and fasteners on thermal performance would involve understanding the heat conduction through these small but numerous components and exploring design or material changes to reduce heat loss.

Opportunities

- **Enhance Codes and Standards**
    - Update codes and standards to account for thermal bridging losses. This includes incorporating advanced 3D thermal analysis and performance data into code requirements to ensure more accurate modeling and predictions.
    - Consider adding a verification procedure to ensure that construction practices align with design intent and code requirements. This includes field visits and inspections to verify proper installation.
- **Increase Education and Training Initiatives**
    - Enhance education on thermal bridging for all construction projects to ensure that stakeholders are aware of the importance of proper detailing, modeling, installation, and verification.

  - Train contractors on the implementation of continuous insulation, particularly with thermally broken furring systems.
  - Ensure that field visits and installations match design drawings and encourage owners to focus on long-term benefits instead of short-term costs.
- **Adopt Cost-Effective Solutions**: Promote the use of cost-effective solutions like thermally broken z-girts and green girts to reduce thermal bridging without significantly increasing construction costs. Implement thermal breaks for balconies and set limits to metal penetrations through continuous insulation. Other common approaches include cantilever designs and knife plates for thermally broken balcony attachments. Model codes, such as IECC 2024, have proposed to restrict balconies from penetrating the thermal envelope.
- **Advanced Analysis and Field Performance Data:** Conduct field data collection of buildings to compare the performance with modeled predictions. This includes temperature and humidity levels, heat flow measurements, and energy consumption data. Compile case studies highlighting successful detailing and modeling practices for thermal bridging mitigation.

STRATEGY 2: BUILDING THERMAL ENVELOPE BACKSTOP

Many building energy codes allow for efficiency trade-offs between different building components when utilizing a performance pathway for a whole building. The two enforcement methods for envelope trade-offs are defining an envelope backstop (i.e., a set of minimum thermal efficiencies), or setting a minimum trade-off criterion for the whole building envelope through a performance assessment. Figure 8 illustrates how energy code criteria regarding thermal envelopes relate to one another based on the level of efficiency they achieve, with prescriptive criteria defining the highest efficiency requirements, mandatory minimums defining the lowest efficiency requirements, and performance backstops in between.

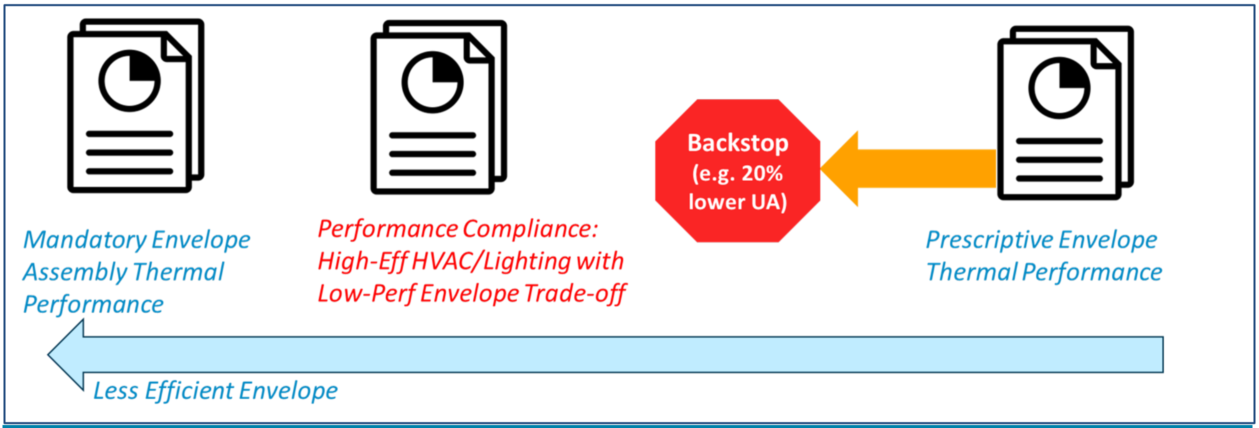


FIGURE 8. ILLUSTRATION OF AN ENVELOPE BACKSTOP

As an envelope backstop, Title 24 utilizes a set of minimum thermal efficiencies for each envelope component (windows, walls, etc.). While this approach provides some backstop to efficiencies it is limited by the need to allow flexibility in construction. Several other energy codes utilize a whole building envelope approach where the overall thermal gains and losses are limited to a specific value or to a percentage of the envelope performance of a standard baseline building. An overview of these energy codes are outlined below.

- **Title 24 Mandatory Requirements:** The mandatory requirements provide a backstop for covered envelope components resulting in a limit on peak thermal losses. For example, using the large office prototype model, the mandatory envelope is 72% above the prescriptive requirements on a UA[4] basis.

- **ASHRAE 90.1 2022 ECBM and PRM:** Both ECBM and PRM are one of the performance compliance pathways in ASHRAE 90.1, it now requires that building envelope performance must meet the prescriptive code or shall not exceed the base envelope performance factor by more than 15% in MF, hotel, and housing projects, and 7% in all other NR buildings. The standard requires that annual thermal loads be calculated in addition to a separate whole building energy calculation.
- **MA State Stretch Code:** This code requires that the annual thermal loads of specific types of NR and MF buildings do not exceed a climate-specific threshold, utilizing a compliance metric of Thermal Energy Demand Intensity (TEDI).
- **Passive House:** Requires projects either meet a peak load limit of 3.17 Btu/hr-sf or an annual heating thermal energy limit of 4.75 kBtu/sf-yr with an additional allowance for cooling for dehumidification.
- **WA State Energy Code (WSEC):** For buildings utilizing the performance pathway, this code requires that peak thermal losses in heating of the envelope on a UA basis for heating do not exceed the standard baseline by 20% or more.

TABLE 5. TABLE COMPARING VARIOUS BUILDING CODES AND MINIMUM ENVELOPE PERFORMANCE APPROACHES

	Mandatory Minimum by Envelope Component	Prescriptive Minimum by Component	Performance Minimum at Winter Peak Conditions	Performance Minimum, Annual Thermal Losses
Title 24, 2025	✓	✓		
ASHRAE 90.1 2022	✓	✓		✓
IECC 2021	✓	✓		
MA State Stretch Code		✓		✓
Passive House			✓	✓
WA State Energy Code (WSEC)	✓	✓	✓	

Summary of Findings

An envelope backstop is an effective way to limit the potential trade-off of the envelope performance for buildings utilizing a whole-building compliance pathway. Selecting appropriate backstops requires balancing construction cost and practicality while ensuring that buildings remain economically feasible and comfortable for occupants.

The two primary approaches to setting envelope backstops can be divided into two categories, weighted U-value area calculations and annual simulated thermal performance:

Weighted U-Value

The weighted U-value area (UA) calculations observed were set with limits on performance either by envelope component or for whole building performance, where each individual component needs to meet mandatory requirements, and the overall building UA must be limited to a certain percentage above that of a building that used prescriptive U-values for all components.

ASHRAE 90.1, IECC, and WSEC include a whole building UA calculation method called the Component Performance Alternative. The method provides a calculation to

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

determine if the proposed design meets or exceeds the baseline on a UA basis. In IECC 2024, this path also includes thermal bridging assumptions and derated spandrel performance. Furthermore, the update in IECC 2024 includes a correction for excess glazing in the design.

For projects seeking whole building compliance, the city of Seattle evaluated setting the limit of envelope-tradeoffs with other systems such as lighting and mechanical to 0%. This would effectively require all buildings to meet the prescriptive code on a whole-building basis at peak conditions. Experts interviewed believed the trade-offs can be significant for an envelope and over a buildings life will not be replaced as frequently as the more efficient HVAC systems.

Annual Simulated Thermal Performance
One example of the simulated performance methods is TEDI in Massachusetts, which effectively provides a thermal envelope backstop based on limited space loads. ASHRAE 90.1 includes a simulated comparative approach (Appendix C) that will become a common approach as newer versions of ASHRAE are adopted by local jurisdictions. It uses a calculated energy performance factor for a baseline model using prescriptive envelope thermal performance which is compared to the design for energy performance with only the envelopes changing between the two models.

There are requirements using the metric for ECBM and PRM where the proposed can exceed the baseline by 7% or 15% depending on building type allowing some trade-offs. As the ASHRAE envelope backstop approach is included in COMCheck, one expert stated that it would lead to an increase in use and familiarity with COMCheck among practitioners. The Appendix C method is included in COMCheck and requires entering surface area, orientation, and thermal performance of the envelope components to perform the envelope backstop calculation.

While envelope backstops are important, some jurisdictions are promoting an increase to prescriptive envelope efficiencies where it may be less common for buildings to utilize a performance compliance pathway and to increase the stringency of a standard reference building when it is used.

<u>Barriers</u>

- **Impact on Building Design and Market**
  - Glazing manufacturers and fabricators have concerns that envelope backstops might reduce the glazing in buildings and increase the opaque wall area, and potentially reduce sales for glazing manufacturers and fabricators. The implementation of backstops has faced pushback on codes and standards committees, especially regarding fire rating and specialty glazing exceptions, highlighting the need for careful policy development and stakeholder engagement. However, there is a potential significant market benefit in the sale and use of high-performance glazing, which could be better supported through education and advocacy.

<u>Data Gaps</u>

- **Implementation and National Variations**
  - Several jurisdictions, including Vancouver, Canada, Massachusetts, the City of Seattle, the State of Washington, and New York City, have implemented envelope backstops. However, there is a lack of performance data on the success of different envelope backstop implementations in driving energy savings.

<u>Opportunities</u>

The research team identified the following envelope backstop compliance approaches. In the development of either opportunity, the research team recommends further research to determine what the backstop limit should be to minimize and eliminate the worst performance envelope assemblies.

1. For buildings utilizing the performance pathway, add a requirement that peak thermal envelope losses may not exceed the prescriptive requirements by a certain percent, at peak conditions on a UA basis.
2. For buildings utilizing the performance pathway, require that building not exceed thermal envelope loss targets (loads) on an annual basis.

Strategy 3: Increased Air Tightness Requirements

Increased air tightness practices, even in mild climates, can reduce thermal losses and impact the annual efficiency and peak sizing of heating and cooling equipment. Air and water leakage are often considered and discussed simultaneously in design to ensure the building envelope is robust, able to manage moisture, and maintains high indoor air quality.

Summary of Findings

The involvement of envelope consultants in the design process varies by region, with higher engagement on the coasts (east and west) than the middle of the country. East and west coast consultants focus on maintaining water tightness and durability, which is why envelope consultants are more commonly involved in large-scale projects such as multifamily buildings, commercial offices, and other significant structures. Boston is an example of a city making significant strides towards adopting comprehensive envelope performance in design, effectively mandating Passive House standards for commercial construction. This represents a shift towards systems thinking and holistic integration of building components.

Different construction techniques and design considerations can also make air tightness challenging to reduce. Vented roofs and sliding doors/windows pose significant challenges for maintaining airtightness. Storefront systems, which constitute a significant portion of fenestration, often suffer from installation issues like gasket relaxation, leading to increased air leakage over time.

The type of building ventilation system can be critical for airtight buildings to manage moisture and ensure high indoor air quality, particularly in multifamily construction. In multifamily buildings with decreasing unit sizes and increased occupancy, traditional methods like trickle vents and operable windows are insufficient for ventilation needs and moisture control. Exhaust-only systems with small penetrations in the air barrier can create significant issues by pulling in un-conditioned air and moisture due to negative pressure. Enhanced systems, such as ERVs (Energy Recovery Ventilators) with advanced filters, can provide better protection, especially during events like forest fires.

Building form factor influences the impact of poor air tightness. Smaller buildings are more affected by poor air tightness, requiring detailed attention to ensure energy efficiency and performance.

ASHRAE 90.1 has air leakage requirements for buildings under 10,000 square feet, with discussions on expanding to larger buildings. The aim is to improve building performance by reducing air leakage, which is recognized as a straightforward and effective method with ongoing discussions about expanding mandatory air leakage testing requirements to larger buildings to ensure comprehensive performance improvements. The current air leakage limit in ASHRAE 90.1 for buildings under 10,000 sf is 0.35 cfm/sf @ 75 Pa. This requirement is currently in place in cities like Portland, Oregon. Experts interviewed said that smaller buildings are an appropriate target for air leakage requirements because they are a significant portion of national building floor area and air leakage testing is easier in small buildings, with fewer pieces of equipment and staff needed on-site to test.

In the 2021 Washington State Energy Code (WSEC), air leakage targets and testing are required for all buildings. Washington introduced air leakage testing in their 2015 code, which required documentation of results without a need to pass a target of 0.4 cfm/sf @ 75 Pa. The 2015 Seattle Energy Code (SEC) lowered the target to 0.3 cfm/sf at 75 Pa. However, regional consultants said that, even without the need to pass the test, there was an impetus for developers to seek a pass result for compliance credits (C406.9 2015 Reduced Air Leakage) and marketability of the building. Notably, the 2015 WSEC and 2015 SEC did not require testing of smaller (less than three stories) mixed-use buildings including both commercial and residential uses. Washington's approach is different from ASHRAE, which targeted smaller buildings (<10,000sf) first where the cost burden is perhaps larger relative to the project cost.

The WSEC 2015 reduced air leakage efficiency credit target was set at 0.25 cfm/sf @ 75 Pa, setting the stage for the 2021 requirement that is in place today. An envelope consultant in the Washington market estimated the cost of air leakage testing has a lower limit, making it a greater burden for smaller buildings. For example, a cost of $10,000 for testing was estimated for both a 200-unit building and a significantly smaller building. However, the costs of mitigating failures can be more significant in larger buildings, which experts said leads to increased use of the WSEC 2015 air tightness efficiency credit. Developers aim to meet the higher efficiency credit, which usually ensures meeting the lower prescriptive requirement, even if the testing falls short of the higher efficiency credit target they would avoid high mitigation costs from the prescriptive requirement. Developers often seek the cheapest options in construction, though tax credits and incentives can help offset costs for targeting higher efficiency goals.

The research team heard from façade consultants operating on the west coast that most projects now have envelope consultants for waterproofing and moisture to mitigate façade failure risks. Codes have adopted more stringent air leakage requirements based on analysis that considers thermal performance but does not account for costs of moisture mitigation. Interviewed consultants noted this gap as well: building energy code analyses do not account for both the energy benefit and the moisture mitigation of comprehensive air sealing. A holistic analysis that includes costs of thermal and moisture mitigation would be more appropriate.

Experts interviewed had skepticism about the cost-effectiveness calculations used to justify air leakage standards. They pointed out that assumptions in these calculations often do not reflect real-world conditions, such as the actual leakage rates in new buildings. Regions in California face challenges in implementing similar requirements due to cost-effectiveness concerns. The mild climate in coastal California reduces the perceived urgency for strict air barrier standards. The framework for energy efficiency cost criteria in codes, such as Title 24, can hold back progress by either isolating the cost effectiveness criteria to single technologies or only accounting for the direct benefits rather than the indirect benefits, such as potential impacts on HVAC, envelope lifespan, or building resiliency. Other jurisdictions like Massachusetts and Washington have moved faster by adopting broader cost-effectiveness criteria and focusing on decarbonization mandates.

<u>Barriers</u>

- **Lack of Comprehensive Best Practices:** There are few comprehensive design guides that balance vapor permeability, thermal efficiency, indoor air quality, and air tightness. Incorrect design and installation of moisture and air barriers can lead to elevated moisture risks, potentially compromising the long-term durability and performance of the building envelope.
- **Testing Challenges:** Testing larger buildings includes increased staff and equipment needs and potentially multiple visits to test individual floors during construction.

- **Market Reluctance:** There is market hesitation to adopt high-performance solutions due to higher initial costs and uncertain return on investment.

Data Gaps

- **High-Performance Façade Cost-Effectiveness Analysis**
  - Lack of data on the economic value of high-performance façades, specifically regarding avoided costs related to litigation, replacement, and retrofitting, in particular for non-residential buildings. This gap extends to a lack of calculations and lifecycle cost analysis that would demonstrate how the payback period for high-performance facades might be shorter than anticipated.

Opportunities

- **Holistic Design Resources:** Develop enhanced educational tools and holistic performance metrics to address the needs for architectural teams to design and implement high-performance envelopes encompassing air tightness, thermal performance, and moisture permeability.

Strategy 4: Advancing Envelope Thermal Performance Requirements

Improved building envelopes can significantly enhance building performance and occupant comfort by maintaining more consistent indoor temperatures, particularly near the building perimeter. Consideration should be given to limiting the complexity of energy codes to increase compliance.

While energy codes set prescriptive insulation criteria for each assembly type (roof, wall, glazing, etc.) the cost effectiveness of additional insulation often varies for specific buildings. To enhance insulation requirements in wall, roof, or floor assemblies, some codes (e.g., Massachusetts' TEDI and ASHRAE 227P) set an overall envelope thermal performance target to improve overall insulation levels while still enabling assembly flexibility.

Summary of Findings

The first main finding was the importance of comprehensive envelope design and education. Several interviewees shared that there is a general need for industry-wide education on high-performance building practices and training for builders and contractors in airtightness, thermal bridging, and proper installation. Suggested approaches include following Passive House methods; while not necessarily meeting all requirements of the standard, it would be appropriate to move envelope design and performance forward. Determining the right amount of insulation and thermal performance for future buildings is essential, as envelopes are less frequently upgraded than mechanical systems.

Continuous insulation and reducing metal penetrations are widely supported by architects and envelope consultants as strategies for improving envelope performance. A few interviewees highlighted the need to design with moisture permeability in mind to avoid issues with moisture, mold, and material degradation from moisture that penetrates the barrier. It was noted by architects and those involved in model codes that contractors are becoming more comfortable working with continuous insulation, although it is still considered a premium in many markets in the US and education and training is needed.

The second main finding was the need to balance performance targets with practicality and resiliency. Meeting advanced envelope performance targets, such as those set by the TEDI metrics, presents significant challenges. Consultants in MA working with the new Stretch code noted that the whole assembly UA targets, and meeting the new TEDI peak heat loss targets, are very challenging for the construction community and are impacting most of the construction in the state that they are aware of.

Most interviewees noted the need for building envelopes to address resiliency for both current and future climates, and passive survivability in conditions including extreme weather events and power outages. They suggested consideration of adding resiliency into building codes covering indoor air quality and overheating assessments, particularly in warm climates such as in California. Addressing these resiliency issues was seen as a more important area of focus than addressing effective UA performance.

<u>Barriers</u>

- **Cost-Effectiveness Framework**
    - Title 24 is determined by a cost-effective calculation based on savings and doesn't explicitly use a decarbonization goal. This can lead to solutions that would be the most cost-effective way to work towards decarbonization goals but not the most cost-effective enhancement possible being unadopted.
    - Building resiliency is a core benefit to a high-performance envelope, however, this is not quantified in Title 24 cost-effectiveness calculations and there are limited examples of building codes considering resilience and passive survivability benefits.
- **Cost-Effectiveness Calculation**
    - High initial costs of high-performance systems, lack of ROI, and risk aversion in design and product selection.

<u>Data Gaps</u>

- **Lack of Real-World Data**
    - Data is needed on the performance of high-efficiency building envelopes, in particular for non-residential buildings. This data can help justify increasing the stringency of building envelope requirements.
    - There is a need for better quantification of the benefits of building envelope improvements, including addressing thermal bridging and air leakage and the metrics used to assess them

<u>Opportunities</u>

- **Increase Stringency of Prescriptive Pathway:** The prescriptive compliance pathway is seen as having a larger impact on construction projects compared to the performance compliance pathway.
- **Revise Cost-Effectiveness Framework**
    - Consider revision to envelope cost-effectiveness calculation to factor in the reduced size of the HVAC system: benefits include the reduced HVAC maintenance and replacement costs and may include the extended equipment lifespan.
    - Consider altering the cost-effective calculation framework to meet the most cost-effective way to meet decarbonization goals. Washington state has set decarbonization goals that determine the focus of new codes. Using the decarbonization target as the goal, the state determines the most cost-effective way to reach the goal.

PEAK THERMAL LOAD MANAGEMENT STRATEGIES

TECHNOLOGY OVERVIEW

To optimize building energy efficiency cost-effectively, the first step is to minimize the thermal load thereby reducing the heating and cooling energy demand. The second step is to manage, load shift, or offset the remaining load through renewables, energy storage, or other load management tools. The research team explored this second step, thermal load management, by evaluating HVAC control strategies and HVAC TES technology applications for commercial and multifamily buildings. This included the review of HVAC technologies and controls, either shifting the time of use or reducing the intensity of thermal heating and cooling loads. The team primarily focused on the use of active TES products which are integrated into larger building cooling or heating systems.

THERMAL ENERGY STORAGE TECHNOLOGY

TES technology has attracted interest because of its ability to reduce demand on the electrical grid during peak instances, which has become a priority for California utilities and stakeholders due to the steep duck curve (EIA 2023). In the simplest sense, TES stores thermal energy by heating or cooling a thermal storage medium and holds energy for future use to heat, cool, or generate power. TES systems can be used on a large-scale for power generation, on a large- to medium-scale for industrial thermal process heat and district heating, or on a small-scale for single buildings. The focus of this research project and the following section includes technology that applies to medium-to-large commercial and multifamily buildings.

TES technology falls into three main categories: sensible heat storage, latent heat storage, and thermochemical energy storage. **Sensible heat storage** "is the most commercially deployed TES type and is applicable for both power generation and heating" (Balliet et al. 2023). Sensible heat storage is accomplished by raising the temperature of a medium. The amount of energy stored is dependent on the properties of the material, such as density, specific heat, and temperature change ability (Balliet et al. 2023). The material can be liquid (such as water or molten liquid salt) or solid (such as metals, sand-type particles, or a rock bed). For medium and large building use, sensible heat TES material is typically water or the ground (soil, rock, clay, etc.) in a low-temperature application (0-212°F). Water tanks are utilized as closed-loop thermal reserves in HVAC design, either as **direct cold storage, hot storage**, or in some configurations as an **ambient or neutral thermal energy storage** vessel.

Latent heat storage materials are known as phase-change materials (PCM) because they release or absorb energy when the material undergoes a change in physical state (Sarbu and Sebarchievici 2018). The benefit of latent heat materials is the high capacity of heat storing at a similar temperature range to sensible heat materials. There is an array of available PCMs, which Figure 9 categorizes into low-, medium-, and high-temperature materials. According to a 2018 evaluation by Sarbu and Sebarchievici, the most widespread materials are paraffin (high

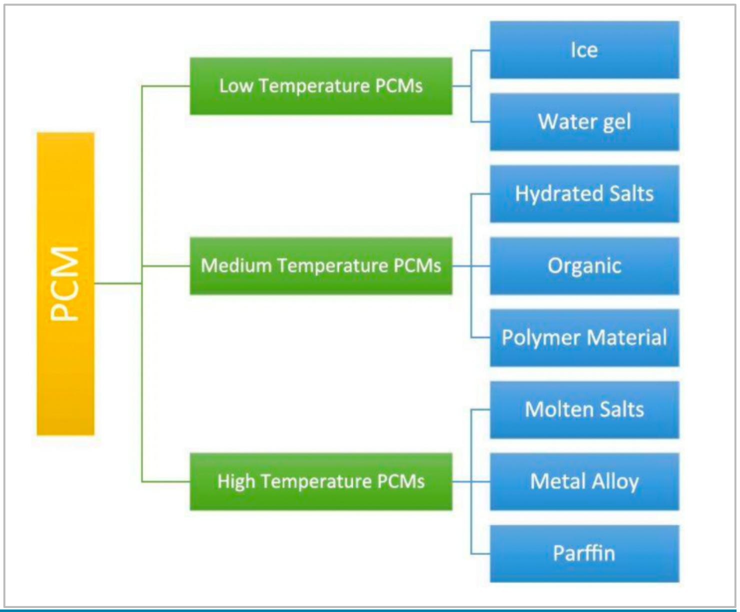


FIGURE 9. PCM TYPES BASED ON MELTING POINT

Source: Sarbu and Sebarchievici 2018

temperature, organic), hydrated salts (medium temperature, inorganic), fatty acids (medium temperature, organic), and ice (low temperature). Several of these PCMs are described below.

PCMs can be advantageous due to their high storage energy density and low heat loss (compared to a hot water tank). The barriers to PCM market adoption are high cost and material property and stability (Sarbu and Sebarchievici 2018).

The thermal storage tank products themselves still vary widely. In interviews with PCM TES product manufacturers (where PCM is used in combination with hydronic distribution) the team learned that a few storage tank products undergo testing, such as to evaluate the tank estimated useful life. Based on the team's research there is no specific thermal storage tank test standard in the U.S. currently.

Table 6 provides an overview of various TES product characteristics. Additional TES technologies and strategies can be found in Appendix A. Supplemental TES Technology .

Table 6. Table Summary of Sensible and Latent TES Attributes

	Water Tanks	Underground Tanks	Ice Storage	PCM Low-Temp	PCM Medium Temp
PCM Type	Sensible		Latent		
Typical Physical Size (range)	Large Tanks	Large Tanks	Small-Medium Tanks	Small Tanks	Small Tanks
Temperature Range (°F)	50-194	40-200	26-37	Up to 212	212-750
Energy Storage Capacity Range [1]	1 kWh to 1 GWh	1 kWh to 1 GWh	1 kWh to 100 MWh	1 kWh to 100 kWh	10 kWh to 1 GWh
Storage Energy Density (kWh/ft^3) [1]	0.4 – 2.3	0.7 – 2.4	2.6	1.6 – 1.7	1.2 – 1.9
State of Technology	Commercial	Commercial	Commercial	Prototype-Demonstration	Demonstration
Barriers to Market Adoption	N/A	High capital cost, Significant installation challenges	High capital cost, Increased maintenance	High capital cost	High capital cost
Capabilities	Simple product, low cost		High storage energy density, reduced footprint		
Limitations	Large footprint		High cost, potential for high design complexity		
Cost [1]	$0.1-$35/kWh		$60-$230/kWh		

[1] Sourced from IRENA 2020 study.

TES Controls

In TES systems, control strategies for active use tend to fall between two major types for charging and discharging: **peak shifting**, using the TES device at a set instance in time to provide 100% or a majority of the thermal conditioning, and **load leveling**, discharging the TES device over a longer period of time, often operating in parallel or in addition to another device actively cooling or heating, reducing the capacity needs of the primary device.

TES Sizing Practices and Challenges

The research team found that sizing and selection of thermal storage and load shifting technologies for building heating and cooling needs is done on a project-by-project basis with different factors being considered each time. Top factors observed in sizing these systems included:

- Physical size and placement
- First costs of a system and the incremental cost to benefit of a larger system
- Energy cost savings based on optimized time-of-use energy rates
- Resiliency for an ability to shift thermal load for a determined time window

Right-sizing TES is essential for the system to perform optimally. Per the ASHRAE Handbook for HVAC Systems and Equipment, "Thermal storage systems must be designed to meet the total load as well as the peak hourly load. To properly size a thermal storage system, a designer must calculate an accurate load profile and analyze the thermal performance of the storage equipment over the entire storage cycle" (ASHRAE 1993). Few designers use building energy modeling and fewer develop a building model specifically to evaluate the thermal load profile or profiles and size the system accurately depending on different use and weather conditions. In practice, physical space and first cost are often the primary limiting factor on the equipment.

Summary of the Modeling Landscape

Interviewed experts emphasized the value of various energy modeling tools to accurately size and align thermal loads. These tools include EnergyPlus and IES-VE, among others. These tools help in creating detailed load profiles that consider the specific conditions and requirements of each project.

While thermal storage has been used in commercial buildings, especially for cooling with ice or water, the ability to evaluate TES in building energy modeling software remains limited to a few advanced tools that are less familiar to most building energy modelers.

In current versions of EnergyPlus and IES-VE, thermal storage can only be evaluated as a chilled water device, requiring substantial definition on how the tank is charged and discharged. In eQuest, an energy modeling tool frequently used today and of which the thermal engine was built upon to create EnergyPlus (DOE 2.2 and 2.3), hot water and chilled water storage is possible but requires specific detail to ensure proper functionality (DOE-2 2018).

Tools such as TRYNSYS and EDSL-TAS can evaluate thermal storage in any configuration, relying on the modeler to construct a detailed central plant and control sequences to ensure proper system operations (TRNSYS 2017, EDSL 2022).

Based on industry experience, the research team is aware that most building designers tend to develop a spreadsheet-based thermal storage calculator, using thermal loads from building energy modeling software and creating a custom spreadsheet to determine the operational energy of the central plant objects. As of fall 2023, the CA Codes and Standards Enhancement Team (CASE) and researchers at LBNL have begun evaluating what it would entail to add an additional thermal storage object to EnergyPlus to enable hot water or condenser water storage.

Summary of the Regulatory Landscape

Building energy codes have started using TES as a technology and efficiency strategy, specifically using additional efficiency credit options. Washington state energy code (WSEC 2022) and ASHARE 90.1-2022 both include optional credits for buildings using TES, either for chilled water for building cooling or service hot water for building domestic hot water use. For the California Title 24, 2025 Codes and Standards Enhancement (CASE) Process, the non-residential heating systems measure was put forward by the CASE team including requirements for large systems to include TES. Ultimately the requirements specific to TES were not included in Part 6, though they were being considered as additional efficiency requirements in Title 24 Part 11 (CalGreen).

ASHRAE Technical Committee 6.9 focuses on TES technologies and has active collaboration with the DOE research project Store4Build. This initiative aims to develop practical applications and guidelines for TES integration, supporting both standardization and market adoption.

Identified Load Management Strategies and Applications

Strategy 5: TES as an Ambient Thermal Energy Source

Ambient TES systems are a versatile configuration to store thermal energy at a neutral temperature for either heating or cooling as a thermal reserve. A building system would utilize a chiller, heat pump, or heat recovery chiller to pull thermal energy from the TES tank, raise or lower the temperature of the water to meet the exact building needs, and provide CHW or HW. Ambient TES is similar to a geothermal bore field but instead of using the ground as a thermal battery, ambient TES uses a tank of water or ice.

By using the ambient TES, chillers and heat recovery chillers can operate at higher efficiencies than traditional systems which push and pull thermal energy from the air through either fluid coolers or cooling towers. Because of this, buildings with ambient TES can reduce their peak load, sourcing thermal energy from the tank rather than from the extreme outdoor air conditions in summer and winter.

TES is also referred to as condenser water storage with examples of design solutions including Taylor Engineers Time Independent Heat Recovery (TIER) system (Taylor Engineers 2020).

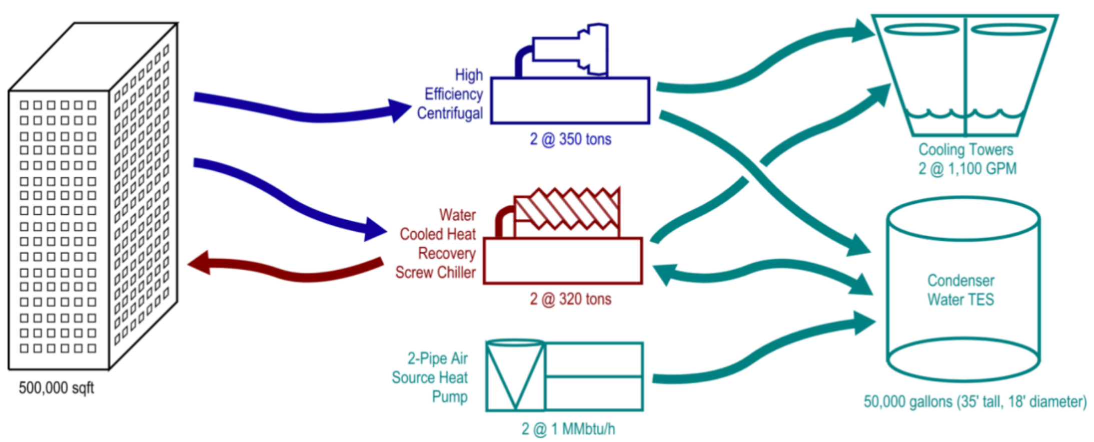


Figure 10. Example TES Tank Diagram: TIER Plant

Source: Taylor Engineers 2020. Arrows indicate the direction of heat flow (from the building, to the chiller, to the cooling tower, to the atmosphere for example).

The TIER plant takes heat rejected from cooling loads via high efficiency, low lift, centrifugal chillers and typically stores it in a TES tank at tepid temperatures between 60°F and 80°F. When energy is then needed for building heating, heat is extracted from the tank using water-to-water heat recovery chillers. According to Taylor Engineers, in California's mild climate zones the energy recovered from cooling loads using the water-to-water heat recovery chiller can be used to meet the subsequent morning's heating loads with an ASHP for additional heating as needed.

The primary benefit of an ambient TES configuration is the ability to recover thermal energy over a day or portion of days from cooling to heating. In these systems, the ideal benefit occurs on shoulder season days where there is some cooling required in the afternoon and some heating in the early morning. In the mid-afternoon, the system can provide cooling, pulling heat out of the building and reserving it in the TES tanks. The next morning, heat pumps or heat recovery chillers can source this heat, providing morning warm-up and heating to the building, operating at a higher efficiency point than direct pulling heat from the air. At peak instances, these systems are able to operate either the water-cooled chiller or heat recovery chiller at much higher efficiencies than air-source equipment, reducing the electric grid peak demand.

These systems tend to be used in larger buildings, campuses, hospitals or large offices, where a water-cooled chiller configuration would typically be the primary cooling system.

<u>Summary of Findings</u>

Ambient TES is typically considered on large scale projects, either at a campus, hospital, or office complex where a chilled water and hot water plant is common practice. Innovative approaches of ambient TES have included the use of large fire protection water storage tanks as TES in multifamily high-rise buildings, demonstrating the flexibility for different potential applications.

Multiple interviewees noted the challenge of developing reliable thermal load profile estimates needed to best optimize a TES design. The absence of standardized methods for sizing and integrating TES systems was highlighted as a major challenge. Unlike traditional equipment sizing which considers a peak day for cooling and peak instance for heating, sizing of a TES includes multi-day load profiles to ensure systems are designed for real-world conditions.

Several consultants mentioned that they do leverage building energy models to generate load profiles, however, they also desire benchmark load profiles and TES sizing to ensure accuracy. This involves checking the models against multiple benchmarks, such as square footage, climate conditions, and operational patterns, to ensure that the load profiles are realistic and reliable.

Interviewed consultants mentioned a core barrier to implementing TES is added system complexity. TES has the potential to increase equipment efficiencies, reduce the operational energy costs, and possibly increase the lifespan of heat pumps by enabling them to run at less extreme temperatures. However, the complexity of adding another element and control is a key concern for building operators and owners. Experts emphasized the importance of developing streamlined advanced control strategies to manage TES dynamically in response to grid signals and varying load conditions. Experts anticipate that effective control systems will be essential to maximize TES efficiency and grid interaction to truly maximize the benefits of TES.

Due to the potential high cost of these systems, several individuals interviewed considered whether IRA funding used for ground source systems could be expanded to include TES. Interviewed engineers stated that many ground source campus scale systems they design are now found to be cost effective over traditional plants due to the ability to use federal IRA funding.

An industry wide effort called Stor4Build program aims to push thermal energy storage (TES) into the market, supporting both standardization and practical application. The project is led by the DOE and involves collaboration with national laboratories and universities. The program is focused on demonstrating the benefits of TES and integrating it with various building systems. One of the primary goals is to get more utilities interested in TES by showcasing the benefits through working prototypes and successful demonstrations.

Key Barriers

- **Space Constraints**
  - Ambient TES may have a large footprint, many buildings may not be able to accommodate a large storage tank.
- **Lack of Sizing Standardization and Support**
  - Lack of standardization makes it difficult for engineers to design and implement TES systems efficiently, as there are no established guidelines to follow.
- **System Complexity**
  - The overall complexity of ambient TES systems, including the need for advanced control strategies to manage the dynamic operation of TES in response to grid signals and varying load conditions, is a challenge. This complexity and potential for operational risk can deter potential adopters.
- **Market Reluctance**
  - There is general hesitation in the market and among utilities to adopt ambient TES due to unfamiliarity with the technology.
  - Most designers and contractors have never designed or built a system with TES, resulting in a high level of cost uncertainty and cost risk.

Data Gaps

- **Reliable Thermal Load Profiles**
  - There is a need for better benchmarking of thermal load profiles against existing data to ensure accuracy and reliability.
- **Cost-Effectiveness Analysis**
  - Detailed ambient TES system cost-effectiveness analysis is needed to justify the initial investment, including the potential savings from reduced operational energy costs and increased equipment lifespan.
  - Equipment, installation, and commissioning and integration labor costs vary depending on the technology type and application.
- **Field Demonstrations**
  - There is a lack of comprehensive field data and real-world case studies demonstrating the long-term benefits and performance of ambient TES systems. This data is crucial for validating models and convincing stakeholders of the viability of TES.
- **Advanced Control Sequence Strategies**
  - There is a need for more research and development in advanced control strategies that can dynamically manage ambient TES systems. Effective control systems are essential for maximizing TES efficiency and grid interaction.

Opportunities

- **Develop standard sizing, integration, and control sequences** which can be applied to building designs and building energy models to showcase and study the benefits of ambient TES.

- **Conduct field demonstrations:** Real-world TES demonstrations can help build confidence among stakeholders and utilities, encouraging broader adoption.
- **Develop and demonstrate advanced control strategies** that can manage ambient TES dynamically in response to varying load conditions and grid signals.

Strategy 6: TES as a Primary Thermal Energy Source

Primary TES is the use of thermal energy storage at the temperature conditions required for directly cooling or heating a building and, in some configurations, primary TES can operate the building for a length of time in either heating or cooling mode while only operating pumps. These configurations will often charge or discharge the TES tank during off-peak conditions and then disable the chiller or heat pump partially or fully during peak events depending on the capacity of TES available.

In this configuration, a primary TES system would need to be dedicated to a specific end use, such as cooling only, heating only, or DHW only. In most instances, water will be stored within a few degrees of the building thermal target setpoint to provide a thermal buffer.

The J. Craig Venter Institute installed two 25,000-gallon thermal storage tanks with heat pumps to condition the 44,000 sf building. When built in 2011, the system used a custom-engineered storage tank design (Palmore 2012).

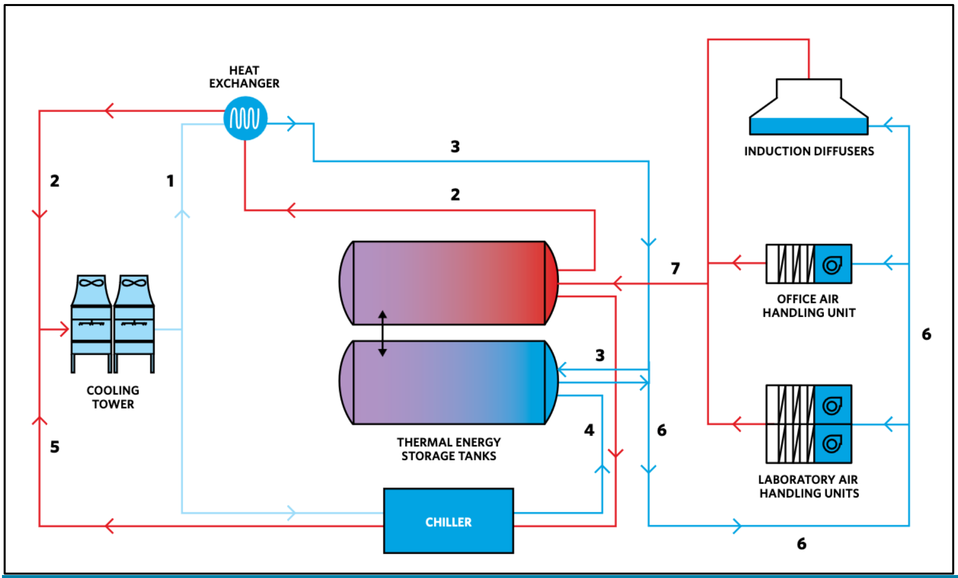


Figure 11. Primary TES Tanks in Cooling Mode at the JCVI building, San Diego, CA

Source: JCVI. n.d.

The building was designed with an ultra-efficient mechanical system to help reduce the building's energy profile. The tanks are dedicated to the cooling side, cooling (discharging) the tanks at night in summer conditions to make chilled water at the temperature needed to cool the building during the day.

FIGURE 12. PRIMARY TES TANK INSTALLATION AT THE JCVI BUILDING, SAN DIEGO, CA

Source: Palmore 2012

At this site insulation was applied to the outside of the tanks to ensure thermal energy remains within desired temperature ranges until needed. In domestic water heating, the tank insulation is the primary limitation to the length of time hot water can be stored. Some tank manufacturers vacuum-insulate their storage tanks, increasing the thermal insulation R-value and storage time (EASE 2016).

Primary TES, either dedicated to CHW or HW, can lead to significant reductions in building peak demand compared with an ambient TES approach by fully supplying CHW or HW thermal energy without a chiller or heat pump enabled. Further, this configuration benefits from being able to operate chillers or heat pumps during off-peak times, often at ambient outdoor conditions, at increased part load efficiency. The drawback of primary TES is the need for dedicated tanks for cooling or heating as well as the need for higher levels of tank insulation and extreme water storage temperatures. Tanks will often be charged a few degrees above or below the target building supply water temperature for CHW or HW. As was shown in the JCVI building, TES was configured as primary TES for cooling and as an ambient TES tank for heating. There are few turn-key HVAC and TES system products available; most projects require a customized design, although many can utilize standard off-the-shelf water storage tanks. Some water tank products are starting to emerge where the tanks and heat pumps are provided together with considerations for building applications and needs.

<u>Summary of Findings</u>

Primary TES paired with heat pumps can help manage peak electrical load demand on the grid. In a primary TES configuration, the tanks can be charged with thermal energy and then used to meet peak demands, either fully (without support from a heat pump or chiller) or in parallel (reducing the amount of heat pump or chiller capacity required). When pairing TES with heat pumps, one engineer found their project reduced the budget for HVAC, allowing for a downsized heat pump system, thereby offsetting the cost of TES. In addition to first cost savings, there are additional potential savings due to reduced electrical infrastructure or upgrade costs, and lower heat pump installation costs.

Currently, there is no industry consensus on how to size primary TES for with heat pumps. One engineer's approach is to ensure a four- to six-hour load shift capacity, which they believe is a reasonable target given current grid demands. Many hydronic heat pump plants (providing hot and cold water) are designed with buffer tanks which can be mistaken for TES tanks. While buffer tanks provide a critical function to ensure equipment operations, there is typically very little thermal capacity provided by buffer tanks.

Primary TES has the potential to improve heat pump equipment operation and equipment life by reducing short cycling when thermal loads are low. In many existing hydronic heat pump buildings, the heat pumps have limited turn-down capacity and in some cases are single- or two-speed systems (Weitze 2024). By using a primary TES configuration, the heat pump can charge the tank and allow the TES tank to serve all instances of low thermal loads at the building. Variable heat pump compressors recently entered the U.S. market for larger hydronic heat pumps: experts interviewed believed it will take several years for them to become standard and cost competitive with the fixed speed heat pumps used today.

One significant challenge is the lack of manufacturers providing integrated heat pump and TES solutions. Current primary TES implementations are bespoke, custom design and control systems. Similar to ambient TES configurations (see Strategy 5), there is a lack of standard control sequences and recommended plant configurations for primary TES as well. One expert interviewed sees a future where heat pump manufacturers might start offering integrated TES solutions to avoid failure modes and improve system robustness.

Primary TES is included in a select set of building energy codes as a means of providing additional efficiency credits a project could claim. In Washington, the WSEC provides efficiency credits for CHW or DHW thermal storage. For the CHW credit, buildings must meet a minimum of 2 ton-hours per design day ton (2 kWh per kW). For the DHW credit, systems must be capable of meeting the peak thermal demand without operating the heat pump and can obtain credit by either raising the temperature of stored water or increasing the volume of storage. Similarly, ASHRAE 90.1 2022 and IECC 2023 include additional efficiency credits for using TES. Beyond these outlined credit opportunities, support for TES, including rebates, are not widespread.

Key Barriers

- **Space Constraints**
    - Primary TES can have a large footprint, many buildings may not be able to accommodate large storage tanks, even those installed vertically.
- **System Complexity**
    - Although direct TES can be simpler than ambient TES. Direct TES does require advanced control strategies to manage the TES and heat pump operation in response to grid signals and varying load conditions. This complexity and potential for operational risk can deter potential adopters.
- **Market Reluctance**
    - Most designers and contractors have never designed or built a system with TES, resulting in a high level of cost uncertainty and cost risk.
- **Lack of Sizing Standardization and Support**
    - There is no industry consensus on primary TES sizing with heat pumps. Manufacturers need to develop integrated TES and heat pump solutions with standardized controls and sizing guidelines.
    - There is limited ability to quickly design and evaluate TES technologies. Current analysis methods, design guidelines, and energy modeling tools are custom and detailed. There’s an opportunity to streamline TES sizing best practices for mass market use.

Data Gaps

- **Reliable Thermal Load Profiles**
    - There is a need for better benchmarking of thermal load profiles against existing data to ensure accuracy and reliability.
- **Cost-Effectiveness Analysis:**
    - Additional analyses need to be completed to demonstrate the cost benefit ratio of utilizing primary TES.
    - There is insufficient data on the incremental cost of adding TES to a new building system. And the potential cost savings from down-sizing the primary chiller and heat pump equipment.

- **Field Demonstrations**
    - There is a lack of comprehensive field data or real-world case studies demonstrating the long-term benefits and performance of primary TES systems.
    - The incremental benefits of increased TES capacity in new buildings and the potential peak demand savings have not been quantified.

Opportunities

- **Develop standard sizing, integration, and control sequences** which can be applied to building designs and building energy models.
- **Conduct field demonstrations:** Conduct demonstration projects to demonstrate the reliability of TES and educate the market about TES capabilities.
- **Develop and demonstrate advanced control strategies** that can manage TES and heat pump systems dynamically in response to varying load conditions and grid signals.

Strategy 7: Small Scale TES Packaged Products

A specific type of TES was identified during the market assessment around smaller commercialized products which provide thermal storage for thermal loads, including cooling, heating, and domestic hot water for residential or multifamily housing and smaller commercial buildings. Several Phase Change Material (PCM) TES products are now available in the Northern US and Canadian markets. PCM TES technology stores thermal energy by using the latent heat of phase transitions. These products are smaller in capacity and size, often sold as an integrated system with 1- to 5-ton variable speed air-to-water heat pumps. The schematic below shows a configuration promoted by Samsung with a TES battery.

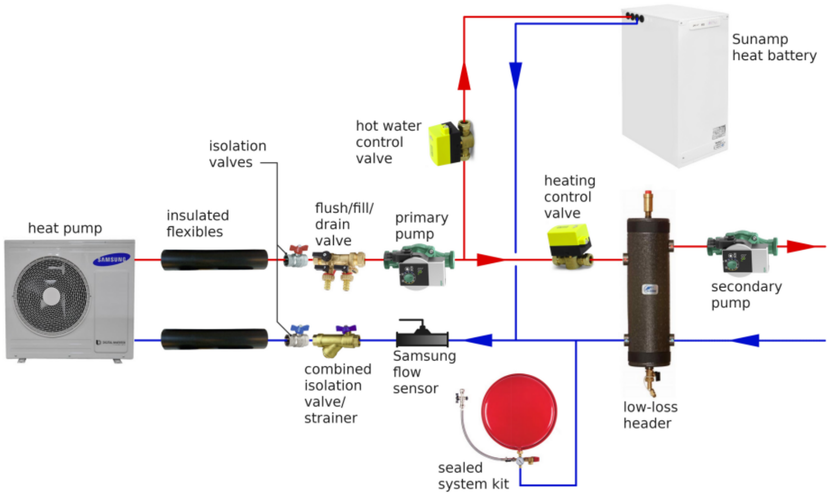


FIGURE 13: PIPING DIAGRAM FOR AWHP WITH PCM BATTERY FOR DHW

Source: Midsummer n.d.

Summary of Findings

PCM thermal batteries are compact and have a smaller footprint compared to traditional hot water storage tanks. In one example, a PCM battery reducing TES storage volume by 70% compared to the size of a DHW storage tank, making them suitable for space-constrained environments. The manufacturer Sunamp uses a salt mixture with a highly conductive heat exchanger that transfers heat to melt and freeze the salt solution.

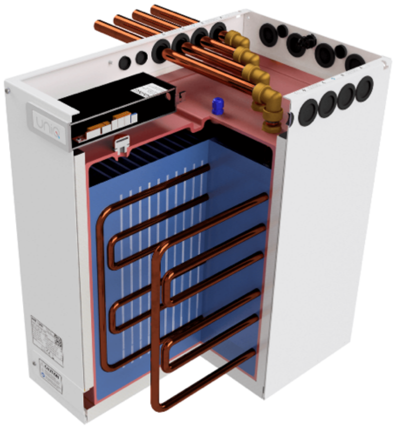


FIGURE 14: PCM BATTERY SECTION SHOWING INTERNAL HEAT EXCHANGER CONFIGURATION

Image Source: Sunamp B n.d.

PCM thermal storage batteries rely on designing each battery at a specific melting and freezing temperature. Suppliers offer products that can operate at a range of temperatures that can serve various applications. Most products currently use a 140°F (60°C) storage battery for DHW integration, providing 104°F (40°C) with several building owners and designers now requesting systems able to store heat at 200°F (89°C) to replace and augment hot water boiler and steam systems.

These systems are primarily used in residential applications with projects scaling the technology into multifamily or companies developing modular versions of the technology to increase the size.

ASHRAE standard 233P, "Testing, Evaluating, and Reporting of Phase Change Materials Performance," provides a test method to evaluate the performance of PCMs. This standard also provides a method of reporting the performance of different phase change materials in a standardized way based on laboratory testing which will lead to a further ability to develop reliable products for the TES market.

Key Barriers

- **Market Reluctance:** PCM TES is a newer product and has not built market confidence yet.
- **Lack of Industry-Wide Standards**
    - PCM TES products have differing lifespan or estimated useful life. An industry-wide testing standard is critical to evaluate and compare the performance of different PCM technologies and ensure a level of product reliability.
- **High Cost**
    - PCMs are naturally better insulators than conductors, and they require advanced heat exchanger designs to effectively transfer thermal energy. These advanced designs come at a higher cost than alternative systems.

Data Gaps

- **Field Demonstrations:** real-world PCM demonstrations are needed to quantify the savings potential, system and control performance, and back the long-term performance to build confidence among designers and installers.

Opportunities

- **Develop standardized testing and performance metrics** for PCM technologies, including lifespan test.

- **Deploy demonstration projects** to showcase successful integration and performance of PCM systems in real-world scenarios.
- **Implement incentive programs** to encourage the adoption of PCM technologies. As an example, programs like New York's Empire Building Challenge help building owners transition to PCM systems to meet decarbonization goals.

Conclusions

Maintaining a resilient electrical grid and stable energy costs during the next wave of building electrification will require peak electrical demand management. Of the many solutions, there is great potential to reduce and manage building-side thermal load. Load reduction strategies using common design techniques to reduce thermal losses and gains, which are used as standard practice in more extreme climates, could provide significant benefits in California to reduce peak demands and total building energy consumption. Load management strategies, such as using TES to recover thermal energy or charge and discharge thermal energy reserves, can shift load and reduce peak electricity demands from chillers and heat pumps while also improving the operational efficiency and life of this equipment. The research team reviewed different technologies and strategies under these two categories and identified seven leading approaches that could be leveraged in Title 24.

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 first four strategies are proven code approaches demonstrated throughout the U.S. Interviewed experts noted that states that have adopted these as a code or stretch code have found energy modelers, builders, and consultants adjusted well to the new envelope requirements. Those codes are planning to increase the stringency in future versions.

The final three strategies, or technologies, are earlier in adoption and are not well demonstrated yet. Experts noted there is great potential for TES technologies to reduce the cost and size of heat pump plants, and that there is a need to further research the potential for TES applications of all sizes, from small packaged thermal storage batteries to large modular thermal storage tanks.

Code and Standard Enhancement Recommendations

To align with national efforts and to drive efficiency in reducing thermal loads, the research team has generated a series of recommendations for further investigation and consideration in future code cycles.

- **Implement an envelope backstop for performance compliance of non-residential and multifamily buildings in Title 24**.
- **Require air leakage testing requirement for multifamily and nonresidential buildings in Title 24**, similar to efforts by ASHRAE 90.1-2022. Recommend a phased approach over multiple years or code cycles similar to efforts in Washington State, requiring projects test without achieving a limit, followed by a full requirement to test and pass a limit.
- **Improve envelope calculation accuracy of thermal bridging between assemblies** in Title 24 compliance software rules for predicting heating and cooling

needs. This could be through specific user inputs for thermal linear and point intersections or through simplified rules for default assumptions.

- **Account for thermal bridging in compliance models and ACM:** Update nonresidential building energy modeling rulesets for Title 24, Part 6 in the Alternate Compliance Manual to include thermal bridging intersection accounting and set default assumptions about thermal loss factors. Default accounting will improve the accuracy of the compliance models of seasonally heating and cooling needs.
- **Advance the envelope thermal performance cost-effectiveness calculation**, by considering the holistic first-cost benefits of HVAC equipment rightsizing and cost-tradeoffs.
- **Update the internal gains assumptions for non-residential space types in Title 24** compliance software and ruleset to be representative of modern building uses and resources used by the DOE or similar scale agencies.

Additional Opportunities

The research team found the below to be potential opportunities for additional research, collaboration, and progress towards the optimization of thermal load management in new and existing nonresidential buildings.

- **Develop resources, guidelines, or case studies on today's TES sizing best practices** including guidance for HW TES plant sizing to consider peak-day profiles rather than a peak hour.
- **Create a new requirement to the prescriptive pathway of Title 24 part 6 for additional efficiency credits** such as those used in ASHRAE 90.1, IECC, and WSEC; to promote the adoption of high-performance envelope strategies and TES configurations. Such code structures have been found to identify climate specific solutions which can inform future mandatory code change requirements.
- **Support partnerships between the California energy utilities and the U.S. Department of Energy (DOE) Stor4Build program** to standardize TES and develop practical applications and guidelines for TES integration.

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Appendix A. Supplemental TES Technology Research

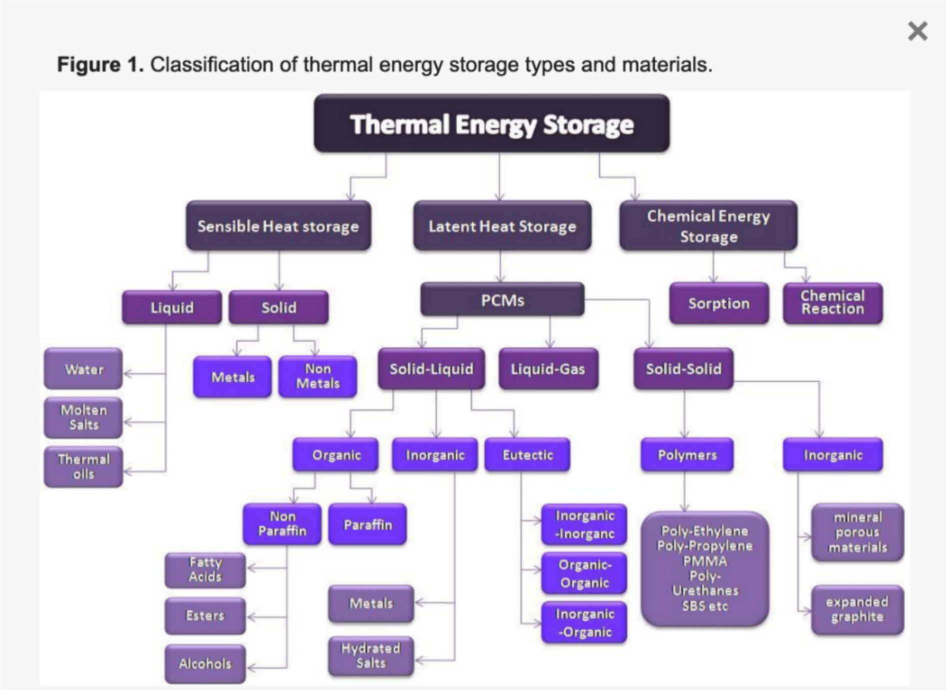

Figure A-1. Types of Thermal Energy Storage

Source: Podara et al. 2021

Sensible TES examples

Underground Storage

Another form of sensible TES is underground storage, using the ground as a storage medium. The typical application of underground storage is pumping heat transfer fluids or water through closed loop pipe arrays in the ground, placed vertically (boreholes) or horizontally (pipes in trenches). Boreholes (ground heat exchangers) are also frequently used in combination with heat pumps where the ground heat exchanger extracts low-temperature heat from the soil. (Sarbu and Sebarchievici 2018).

Example Application:

- In 2021 Princeton broke ground on a district energy system leveraging thermal storage and a "geo-exchange" system; they use 850' deep bores to store and retrieve heat from the earth. This new system is allowing the campus to phase out nonrenewable heat sources (Valenti 2021).

Latent TES Examples

Ice Storage

Ice is an ideal material for cold storage, it has good heat capacity, is non-corrosive, and its liquid form, water, is readily available and inexpensive. Ice storage is commercially available and used in buildings and district cooling plants typically by freezing water using an ice generator during off-peak hours and storing cold energy. The cold energy can be discharged in peak hours via water or a heat transfer fluid, such as glycol (IRENA 2020).

Hydrated Salt PCM: Medium Temperature

Sunamp uses inorganic Sodium Acetate, a hydrated salt medium-temperature PCM, which is a non-toxic, non-flammable, food grade material. The Sunamp battery is a vacuum insulated box, inside in a high flow-rate heat exchanger immersed in the PCM. The sodium acetate PCM changes phases around 136 °F, at which point it forms a solid and has four times the energy density of water. The Sunamp product line is modular and has a storage capacity of 3.5-90 kWh (Sunamp A n.d.).

Fatty Acid PCM: Medium Temperature

PhaseStor is a PCM TES product that uses a bio-based PCM which is derived from organic non-food-grade fatty acids. This PCM is formulated for large scale TES and the material is unique because it remains in solid form, undergoing a solid to semi-solid change. Their product line is modular and has capacity range of 25-600 ton-hours (approximately 87-2,110 kWh). The technology works by pressurizing process fluid flows through heat exchangers submerged in the PCM, energy is absorbed or released when the PCM transitions from a solid to a liquid/gel between 40-45°F (PhaseStor 2018)

Thermo-Chemical Storage

The third type of energy storage is thermo-chemical storage, which stores and releases heat by a reversible endothermic or exothermic reaction process. Upon combination or separation of two substances, heat is absorbed or released. The research team did not focus on this storage technology, because thermo-chemical materials can store more energy than sensible or latent heat materials, and it is reserved for high-temperature applications (such as 200-1,195°C) and not used for medium to large non-residential buildings (Sarbu and Sebarchievici 2018).

Additional TES Applications

As of 2024, TES in HVAC are primarily applied in two different design configurations; either directly, with a TES device serving the heating or cooling thermal loads for space conditioning, or indirectly, acting as a heat sink which is charged and discharged by heat pumps or chillers, storing thermal energy similar to a ground exchange system.

Of the TES applications reviewed during this literature review, below are the two leading TES load management strategies ready for today's market, in addition to those described in the Peak Thermal Load Management Strategies section.

1. **Single Zone packaged units with phase-change/water batteries**

   Researchers at UC Davis and LBNL (Helmns D.) have been developing a system configuration and product proof-of-concept of integrating small PCM thermal storage devices with air-to-water heat pumps (AWHP) for use in small-to-medium building applications such as retail, small offices, and multi-family residences. The configuration is more actively being used in Europe with Sunamp batteries and the team is evaluating how rooftop units and packaged systems could be built up around these thermal batteries and heat pumps.

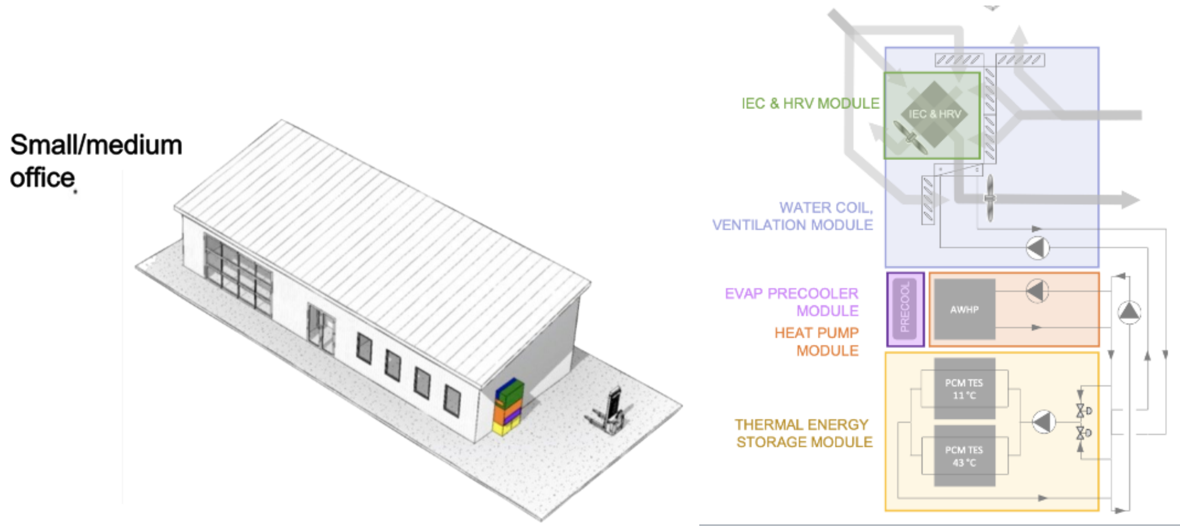

FIGURE. SYSTEM CONCEPT OF ROOF TOP UNIT WITH INTEGRATED PCM THERMAL BATTERY

Source: Helmns 2022

The goal noted in past research papers was to identify a battery that can store thermal energy lower than $50/kWh, be non-toxic, non-flammable, and persistent in more than 60k cycle lifetime. While the UC Davis study is evaluating field installations and lab testing of configurations, several examples of the same thermal storage battery were found in residential packaged systems in Europe, providing a thermal buffer for space heating, cooling, or domestic hot water.

2. Large phase-change water storage tank for medium to large buildings

Hermanson Company in Washington state used a 6,990 gallon phase change storage tank with a hydrated salt material as the PCM from the UK-based company PlusICE. The tank was configured with a centralized air-to-water and water-to-water heat pump plant for a medium-sized office building in Northern Washington state (confidential location) in 2022. The project used thermal storage to store ambient heat, acting similar to a condenser water storage device for both heating and cooling.

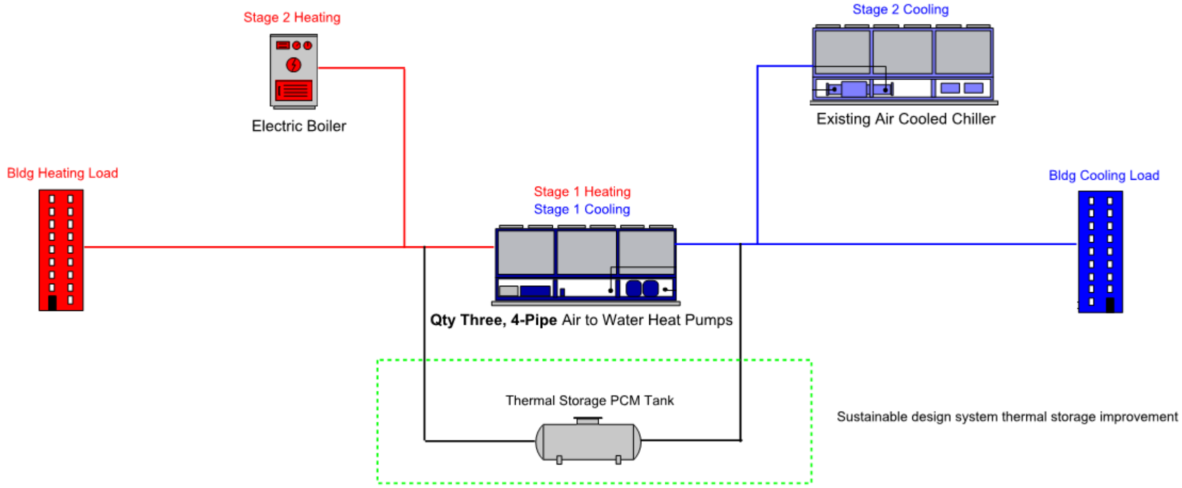

FIGURE. SYSTEM CONFIGURATION OF A CENTRAL HP PLANT WITH PCM THERMAL STORAGE TANK

According to the design, the plant was configured to operate in 6 modes:

TABLE. EXAMPLE OPERATIONAL MODES OF AN OFFICE BUILDING WITH TES CENTRAL PLANT

MODE	Status of Major Components
Mode 1 – Morning Warmup	- AWHP heats building from Data Center and TES Tank. - TES Tank discharging heat.
Mode 2 – Occupied Heating	- AWHP heats building from Data Center and return CHW. - TES Tank discharging heat.
Mode 3 - Heating with TES Tank Depleted	- AWHP heats building from Data Center and return CHW. - TES Tank depleted - Secondary AWHP heating from outside air source.
Mode 4 – Occupied Cooling	- AWHP cools Building and Data Center - TES Tank charges from WWHP - Air-Cooled Chiller low temp sent to DOAS
Mode 5 – Occupied Cooling TES Tank Depleted	- AWHP cools Building and Data Center - Secondary AWHP cools Building as-needed - TES Tank fully charged - Air-Cooled Chiller low temp sent to DOAS
Mode 6 – Night Set-Back	- Building thermostats setback - AWHP cools Data Center - TES Tank charges from AWHP

The building owner utilized the TES technology as a demonstration for their own developments and operations of multiple office buildings where they plan to own and operate the properties for many years. The main benefit the project hoped to identify was an ability to reduce heating energy and improve operational efficiency of the heat pumps at cold outdoor air peak instances. The overall estimated cost of the TES system added $300,000 to the project based on owner conversations. A subsequent project for the same owner evaluated the same technology with a local PCM tank provider, Phasestor.

Appendix B. Building Internal Heat Gains

Internal heat gains are considered a significant portion of NR building thermal loads. Gains are made up of both an estimated peak factor that anticipates how many people and what type of equipment will be producing heat, as well as an anticipated usage schedule that accounts for the frequency and regularity of heat from people and equipment. Design engineers typically assumed internal gains to anticipate and design for cooling needs, but using the same assumptions throughout the year can result in under-prediction of thermal heating needs. Both the peak factors and the fractional load schedules are important to accurately calculate the internal gain and how it impacts the overall building's thermal load strategies. With regards to the envelope, this understanding will help designers predict if buildings will need more insulation or less insulation in different use cases and climate zones.

The research team reviewed assumptions around internal gains to better understand how the assumptions used in Title 24 could be updated and what impacts these might have on thermal loads. The research team focused on gains of equipment in buildings, referred to as plug loads, in terms of the peak power density in watts per square foot of floor space. The research team found that the Title 24 internal gains values are generally higher than those used in other codes and standards: Title 24 internal gains values should be updated to be more accurate. The research team recommends leveraging the research conducted by the national labs when making this update.

Department of Energy (DOE) National Model-Code Building Prototypes

When complying with Title 24 under the performance pathway, plug load assumptions are set by the energy code and must be adhered to, whereas under ASHRAE 90.1, projects can specify the most representative plug load(s). The research team reviewed the Title 24 plug load assumptions and recent updates to ASHRAE 90.1 plug load assumptions (PNNL 2024). The ASHRAE 90.1 plug load values were developed by PNNL and are used during code stringency evaluation for weighing decisions; they are not published values in the ASHRAE 90.1 standard itself.

The recently revised plug load values were provided directly to the research team by PNNL in 2023 as part of an update PNNL conducted. The methods and final report are not yet available, however, all data sets have been made public and were used in the latest evaluation of ASHRAE 90.1-2022 (PNNL 2024).

The plug loads or receptacle power densities (W/sf) are lower in the PNNL updated values compared to 2022 Title 24. This can be seen in Table, which holds a sample of space plug load assumptions for each standard are shown in the following table as an example.

Table. PNNL Plug Load Comparison Table

Receptacle Power Density Examples	***PNNL Updated ASHRAE 90.1 Values***	***2022 Title 24***
	Load W/ft²	***Load W/ft²***
Office - conference meeting multipurpose	0.57	1.0
Library - Library reading	0.51	1.5
Office - Lounge breakroom all other	0.61	1.0
Office Area (>250 square feet)	0.69	1.5
Office Area (<250 square feet)	0.69	1.5
Multifamily - Corridor	0.11	0.0

State of Massachusetts, Thermal Energy Demand Intensity Internal Gains Assumptions

Massachusetts (MA) stretch code assumptions were also reviewed and compared to 2022 Title 24. MA stretch code recently adopted a thermal energy demand intensity metric (TEDI) and as part of the development of an approved calculation, the calculation method includes listed internal gains that are required for energy simulation. MA stretch code expresses assumptions for a thermal block type rather than per space, limiting the direct comparison to Title 24. As shown in the table below, the MA stretch code generally shows lower load assumptions for receptacle power than 2022 Title 24.

TABLE. MA PLUG LOAD COMPARISON TABLE

Receptacle Power Density Examples	MA Stretch Code Load W/ft²	2022 Title 24 Load W/ft²
Office (whole building average)	0.75	1.0
School (whole building average)	0.89	1.0
Gymnasium (whole building average)	0.46	0.5
Auditorium (whole building average)	0.46	1.0

Default Gain Usage Schedules

The research team also compared the default gain usage schedules in MA stretch code and 2022 Title 24. Most hours in the MA stretch code and T-24 2022 schedules assume a similar usage profile, with exception of equipment plug loads: MA stretch code assumed higher standby use at night (40%) versus Title 24 (5%).

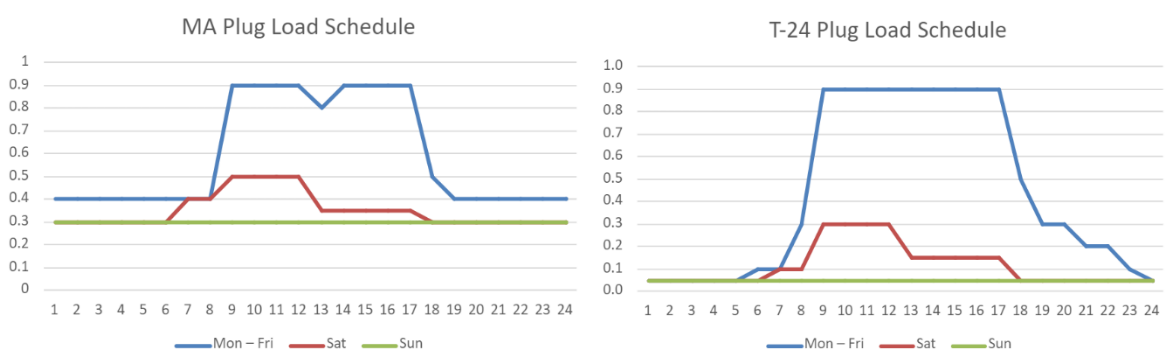

FIGURE. DEFAULT GAIN USAGE SCHEDULES FOR CA TITLE 24 AND MASSACHUSETTS STRETCH CODE