Integrated Thermal Energy Storage - Opportunities and Barriers to Market Transformation

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ABSTRACT

Electric grid is increasingly strained by rising peak demand, extreme weather events, and widespread building electrification. Conventional HVAC systems are not designed to handle large coincident loads from fully electrified buildings, resulting in costly grid upgrades, higher utility bills, and reduced reliability. Without load flexibility, efficiency gains alone are insufficient to ensure long-term affordability and resilience.

Integrating thermal energy storage with heat pumps and heat recovery chillers can provide a scalable solution. Thermal storage enables load shifting, peak reduction, and redundancy while improving equipment efficiency and reducing operating costs. We present the Time Independent Energy Recovery (TIER) architecture, a system that decouples heating and cooling production from demand, allowing for flexible energy use across time.

To accelerate adoption, we outline a market transformation strategy focused on identifying key barriers such as high first cost, unfamiliarity among designers, lack of performance metrics, and misalignment within incentive programs. Using a theory-of-change framework, we engaged California investor-owned utility (IOU) program administrators, the design engineering community, and major equipment manufacturers to co-develop market interventions. These include standardized design pathways, performance valuation methods, procurement guidance, and targeted incentives.

Expected outcomes include the development of utility program templates that reward load flexibility, integration of TIER strategies into design practice, cost reductions through market scaling, and future inclusion of thermal storage pathways within energy codes.

Introduction and Background

Building Energy Consumption and Electrification

Buildings account for approximately 40% of total U.S. primary energy consumption (EIA 2024), with HVAC loads for space heating, cooling, and water heating representing more than 45% of building electricity use (DOE BTO 2023). In the commercial sector, space and water heating contribute 37% of building's energy consumption, and are predominantly served by natural gas boilers (CEDA 2024). Transitioning these loads from fossil fuels to electric alternatives has been central to decarbonization, particularly as some jurisdictions are prohibiting natural gas in new construction; others are disincentivizing it; and still others are adopting building performance standards that would require emission reductions through replacement of gas appliances (Stein & Gill 2024).

Electric grids as a result are strained by rising peak demand from the electrification of buildings that previously relied on natural gas. Buildings account for over 70% of U.S. peak electricity usage (DOE EERE 2019), and the transition away from fossil fuels is placing new coincident load demands on distribution infrastructure, driving costly upgrades and raising questions about grid reliability. Whole-house electrification via conventional heat pumps could increase aggregated peak loads by 70% nationally and more than double peaks in 23 states (Waite et al., 2020), underscoring the inadequacy of direct fuel-switching without demand management. As grids are increasing renewable energy production (CAISO 2023), the growing need for grid stability requires flexible loads that can absorb surplus renewable generation and reduce demand during evening ramp periods (ACEEE 2024). For large commercial buildings, this transition is especially challenging, due to high peak loads, which can strain the local grid when coinciding with other building heat demands (Bistline et al., 2021).

Large commercial buildings have been using gas-fired hydronic heating and chilled water loops. This was a mature technology that slowly gained energy efficiency improvements over several decades. Decarbonization forced the HVAC industry to innovate peak demand management solutions. With a push towards electrification, electric heat pumps and HVAC systems have become popular in recent years. However, current HVAC systems cannot effectively handle the loads from large all-electric buildings and often need to be integrated with alternate sources (Kent et al., 2022; Nadel & Perry, 2020). To meet the urgent need to rapidly decarbonize buildings, the HVAC industry needs targeted support to overcome the design challenges and barriers around system complexity and integration (Kent et al., 2022).

Initial attempts have revealed the limitations of relying on standalone technologies. To generate heat using electricity for large buildings, the four widely used options are: (1) air source heat pumps, (2) boilers, (3) electric resistance, and (4) heat recovery chillers (HRC). Heat pumps (that extract heat from ambient air via vapor compression cycle), are often inefficient in cold weather (Valancius et al., 2019), have limited operating ranges, and require a large footprint (Stein & Gill, 2024), making them impractical for many existing buildings. While HRCs can generate hot and chilled water with much higher efficiency, their primary drawback is the need for simultaneous heating and cooling loads (Stein & Gill, 2024), limiting their effectiveness on their own. For most U.S. electricity grid contexts, implyinghigher lifecycle carbon emissions than natural gas in the near term.

Thermal energy storage (TES) offers a pathway around these limitations. TES involves storing thermal energy when generation is efficient and dispatching it during periods of peak demand or high cost (Sultan & Gluesenkamp 2021). This means that TES allows smaller, more efficient central plant equipment to satisfy large peak loads, enables heat recovery from cooling operations even when heating and cooling demands are not simultaneous, and supports grid-interactive efficient building (GEB) operation (Cabeza 2021).

Thermal Energy Storage

Thermal Energy Storage (TES) is a key enabling technology that decouples energy generation from its consumption. When integrated with heat pumps, TES enables load shifting from peak to off-peak periods, improves heat pump coefficient of performance (COP) through favorable source/sink temperatures, reduces peak electrical demand, and provides resilience during extreme weather events (Stor4Build 2026).

TES provides demand flexibility through load shifting and peak shaving (Neukomm et al., 2019), which allows HVAC equipment to operate at steadier, more optimal loads, improving efficiency and lifespan, reducing equipment size, and lowering both capital and operating costs

(Dincer, 2002). These benefits have been quantified in laboratory and simulation studies, yet market penetration remains remarkably low (Jayaprabha 2024).

While Thermal Energy Storage (TES) systems have emerged as a state-of-the-art solution for electrification, enabling peak load reduction, and driving the shift toward heat pumps, integrating TES into complex HVAC systems presents design and control challenges (Ermel 2022), (Sultan et al., 2023). ORNL literature review (Sultan 2023) synthesizes over 140 studies and identifies various HVAC configurations, controls strategies, and demand impact of heat pumps integrated with TES (HP-TES).

Integrated Thermal Energy Storage

Integrated Thermal Energy Storage refers to the incorporation of thermal energy storage directly into a building or system infrastructure, rather than treating it as a separate, standalone component. There are multiple versions of thermal energy storage systems such as condenser water storage, hot water storage, chilled water storage, and ice and phase change material (PCM). This section particularly focuses on TES integration with heat pumps.

Configurations and Benefits

TES can be integrated with HPs via various configurations as reviewed in ORNL research (Sultan 2023). The commonly investigated configuration (classified as air distribution HP-TES), places TES in supply or return air ductwork, or in hydronic loops serving air handling units (AHUs). Another type of integration is with the vapor compression system. TES coupled directly to heat pump condenser or evaporator components, or as a standalone stratified tank in the refrigerant circuit, demonstrates the strongest performance across all metrics and the shortest payback periods in the HP-TES literature. Ice storage configurations within vapor compression systems (VCS) have been particularly well-studied for commercial applications.

The research defines an indirect configuration where heat transfer is mediated by heat pumps. In this arrangement, the heat pump uses the TES tank as its primary heat source or sink rather than exchanging heat directly with the conditioned space. This allows the HP to operate within a more favorable lift envelope during both charging and discharging, substantially improving COP (Sultan 2023).

The literature review concluded that vapor compression system integration delivers the strongest peak demand reduction and the best financial performance while air distribution integration offers the best retrofit accessibility.

Limitations and Challenges

The literature also identifies critical research gaps specific to HP-TES. The majority of studies are simulation-based; experimental validation in commercial buildings is rare. No standardized configuration taxonomy or performance rating protocol exists, making cross-study comparisons difficult. Controls optimization for real-time grid-interactive operation remains underdeveloped.

A fundamental thermodynamic tension exists between heat pump efficiency (which favors low temperature lifts), and TES charging requirements (which favor higher storage temperatures); this tradeoff can erode the COP gains.

Other challenges of integrating TES with HP include size and design complexity, temperature management, controls complexity, thermal losses, and maintenance.

Despite these challenges, the integration is gaining traction as control technologies improve, costs come down, and the need to decarbonize heating and cooling becomes more pressing. Many of these obstacles are being addressed through better simulation tools, smarter controls, and documented research to improve operations.

Thermal Storage and Heat Recovery

Large commercial buildings struggle to manage peak demand while transitioning to all-electric systems. Current solutions in the market, such as air-to-water heat pumps (AWHPs), often need to be paired with TES for efficient load management; however, the design and controls for TES integration with HVAC leads to further complexity and often TES ends up using more energy when charged during unfavorable conditions (Hirschey et al., 2023).

The key to solving these issues is coupling thermal energy storage (TES) with heat recovery. TES has long been used as an HVAC strategy for peak shifting, primarily as a cost saving strategy through reduced demand and peak utility charges, but rarely as an energy recovery mechanism.

The concept is defined as Time-Independent Energy Recovery (TIER), an all-electric central plant design first described by Stein in ASHRAE (Stein 2021) and more fully analyzed by Stein and Gill (2024) at the ACEEE Summer Study. TIER represents a sophisticated hybrid multi-source configuration applied at commercial building scale.

A traditional TES installation is typically sized for cooling peak shifting; its goal is to ride through a utility afternoon peak pricing period without running chillers. In contrast, the Time Independent Energy Recovery (TIER) system employs TES for maximizing heat recovery utilization (Gill, 2021). The TIER TES tank is sized to ensure that on a design heating day, the building's heating loads can be met by using heat recovered from cooling operations at other times.

TIER addresses the fundamental limitation of heat recovery chillers (HRCs): their dependence on simultaneous heating and cooling loads. Large buildings rarely have substantial concurrent heating and cooling demand on the coldest design days, when ventilation outdoor air provides much of the required cooling, and heating loads are at their peak. By coupling TES with HRCs and trim ASHPs, TIER enables efficient heat recovery even when loads are temporally mismatched, delivering the thermal benefits of geothermal exchange without the high cost and long-term performance degradation inherent to geothermal bore fields (Stein and Gill 2024).

This strategy fundamentally shifts the goal from simply moving an electrical load in time to drastically reducing the total energy required, thereby addressing the significant heating peak demand that challenges all-electric buildings.

Time Independent Energy Recovery - TIER

Time Independent Energy Recovery (TIER) offers an integrated approach by combining heat recovery chillers, TES, and AWHPs to address the challenges faced by all-electric large buildings. Unlike traditional TES applications that focus primarily on shifting or reducing cooling peaks, TIER leverages TES for heat recovery, improving efficiency and transforming TES from a passive component into the core of an active energy management plant (Gill, 2021).

Critically, when the TES tank is sized to store recovered heat, it allows for a dramatic reduction in the required AWHP capacity. This significantly lowers the plant's first cost, physical footprint, and its contribution to the grid's peak demand. In California's mild climates, the energy recovered from cooling loads alone can satisfy heating loads for most of the year. The AWHPs only operate when needed and to an intermediate temperature, which allows for higher efficiencies.

The TIER system addresses many of the HP-TES integration challenges identified above. The temperature management challenge is addressed particularly. Rather than storing hot water at elevated temperatures, which would penalize heat pump COP, TIER stores condenser water at tepid temperatures (60–80°F under normal conditions, with excursions to 40°F on design days), allowing the heat recovery chillers to operate at very low lift and high efficiency.

Peak sizing and equipment cost are also mitigated. Because the TES tank accumulates energy over many hours, the AWHP needs only to be sized for approximately 20% of the design heating load. The larger usable temperature differential of condenser water storage also reduces tank volume requirements compared to hot or chilled water alternatives, alleviating space constraints, in some installations the condenser water TES tank could be combined with required fire water storage, eliminating the space penalty entirely (Stien and Gill 2024).

System Overview

All TIER plants share three core components (as shown in figure 1): (1) a TES tank serving as a thermal buffer between heating and cooling operations, (2) heat recovery chillers as the primary heating plant, and (3) trim ASHPs or electric boilers sized for only a fraction of peak heating load. The TES tank decouples the timing of heat rejection from heat consumption, allowing HRCs to operate efficiently throughout the day even when heating and cooling loads are not simultaneous.

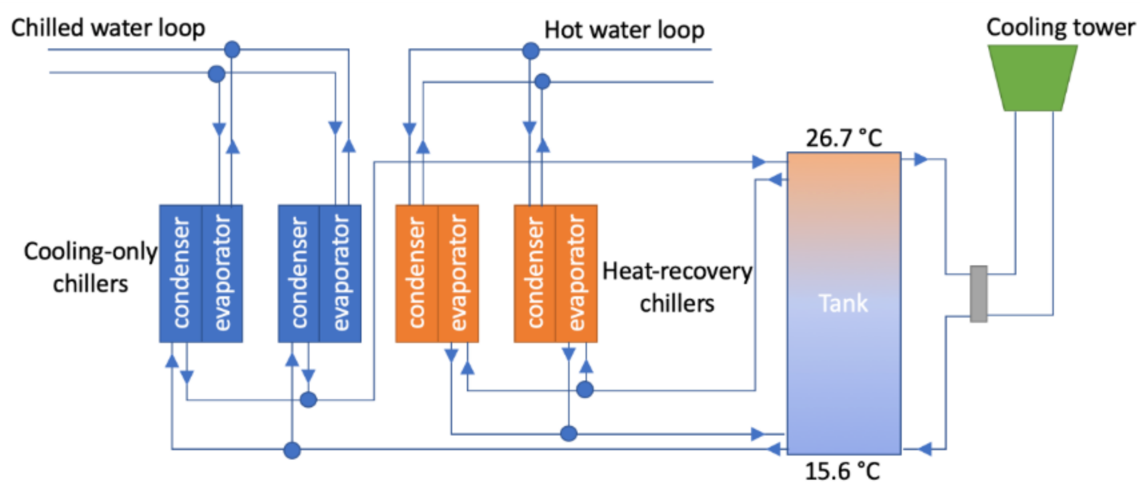

Figure 1: TIER system schematic diagram adapted from ASHRAE (Gill 2021)

Field Verification

A recent CalNEXT study conducted a performance evaluation of a TIER plant analyzing data across multiple operating modes and weather conditions. The heating and cooling COPs were compared to a conventional all-electric plant. The TIER plant maintained heating COP in the range of 3.5–5.5 with occasional days approaching 6.0, versus the baseline's 2.5–4.0 range with drops below 2.0. Results concluded that the TIER system achieves higher COPs compared to the baseline AWHP plant, while significantly reducing dependencies on AWHP operation. This validates the viability of TIER in large commercial buildings.

Despite a growing body of literature and field verification demonstrating performance advantages, adoption in commercial buildings remains limited. Energy Solutions led a market study with CalNEXT to identify the barriers to market adoption for TIER. This paper presents a comprehensive market transformation strategy, listing barriers and interventions.

Market Transformation

First we conducted a literature review to understand the barriers and potential interventions, then we interviewed market participants, including utilities, building owners, etc., then we analyzed the results to develop a list of barriers, possible interventions, and recommended interventions given the state of the technology.

Market transformation begins with an assessment of the market and technology landscape and identification of all barriers to adoption of the measure. Once barriers are understood, intervention strategies can be crafted and executed. Interventions can come from a variety of market actors, including both private and public sectors. For example, an intervention could look like an incentive program, federal tax credit, or a manufacturer's business plan for making their product more appealing to the market.

An ORNL study (Jayaprabha et al. 2024) conducted 87 structured interviews with stakeholders across the TES value chain including TES manufacturers, heat pump manufacturers, HVAC contractors, utilities, and researchers etc., representing the largest known stakeholder barrier study for residential TES.

This work developed a similar comprehensive market transformation strategy for TIER in commercial space. The barriers were identified via literature review as well as structured interviews with utilities and market actors.

At a high level, findings from the previous studies (Jayaprabha et al. 2024), (ACEEE 2024) and DOE guide (DOE 2024) integrate into broad categories that map closely onto the HP-TES integration challenges established earlier, while extending them with market barriers. The identified barriers for HP-TES are: economics and payback uncertainty, absence of standardized performance metrics, controls and operational complexity, workforce and knowledge gaps, regulatory and code barriers, and consumer awareness and supply chain gaps.

The intervention strategies, likewise, are documented broadly as: electric rate reforms, financial incentives and business models, standardization of performance metrics, product innovation, design tools and simulations, field demonstration and performance data validation, workforce development, and regulatory framework for grid integration. This work expands these barriers and interventions systematically for TIER in great detail and analyzes them in terms of difficulty.

TIER Market Transformation Strategy

Market transformation involves the deliberate, long-term strategy of intervening in a market to force disruptive technology to replace incumbent technology. There are numerous factors that can accelerate or hold back a given technology from being adopted, many of which have nothing to do with technological prowess.

At this stage, TIER is a compelling but still relatively unfamiliar option to the HVAC industry. Awareness and appreciation for the benefits of TES is catching on gradually, but a lot of work is still needed. A significant benefit for TIER is the fact that its subcomponents are not new; it's essentially a novel combination of the existing pieces of equipment (AWHPs, HRCs, cooling towers, and sensible TES tanks) in a new architecture. The primary innovation is in their integration and the control logic governing their operation, and the challenge with TIER is the complexity of controlling the system.

TIER Barriers Identification

Market transformation of TIER requires confronting a dual set of barriers (as shown in Table 1); those rooted in technology gaps (hardware, software, controls, modeling, and design) and the ones rooted in market dynamics (supply chain, customer awareness, and economic signals). Both categories need distinct types of interventions, though they are interrelated.

Table 1: Barriers to TIER market adoption

Type	Barrier	Description
Technology Barriers	Energy Modeling software limitations	To quantify TIER benefits in software and achieve code compliance or incentives.
	Code compliance limitations	Initial sites installing TIER require an "exceptional method" to achieve CA energy code compliance.
	Lack of a standard design approach	Concrete guidance, sizing rules, operating sequence, & control frameworks are needed for TIER to scale.
	HVAC Design software limitations	Typical load calculation software only partially supports TIER design considerations. Existing tools for quantifying the system are not widely known.
	Non-Standard Application of System Components	Specifying water-cooled chillers and AWHPs for TIER-specific envelopes (e.g., CW-HW for HRCs) is unusual. The market is unfamiliar with these configurations.
	Lack of Standard Performance Parameters	TIER lacks a standard terminology and framework for specifying and evaluating TES capacity, discharge rate, round-trip efficiency, and stratification. Heating IPLV ratings are needed for AWHPs and HRCs.
	Manufacturer-generated TIER materials are limited	Not all manufacturers are currently describing or promoting their equipment in ways that would align with TIER designs.
	Facility Engineer Operational Familiarity	The facility operator workforce is largely unprepared to maintain TIER plants effectively. Technology deployment success depends on operator competence.

	Controls complexity	TIER controls sequence is novel and time consuming to commission and debug, even for experts. This is a key barrier linked to other technical and market barriers.
	Electric panel upgrade impacts	Electrification may still require service upgrades in some buildings. "Low lift" TIER operation may mitigate this but the tradeoffs are not yet well documented. Different TES could exacerbate or minimize this issue (e.g., hot water TES could be less impactful).
	Existing HVAC system limitations	Hot water supply temperature, state of controls, hydronic piping layout etc. may need an upgrade before TIER installation is feasible in existing buildings.
	Insufficient data for modeling software	AWHP and HR chiller equipment require representative performance data to create accurate energy models in software such as EnergyPlus.
Market Barriers	Building owner awareness	An average building owner is unlikely to be aware of the opportunity to apply TIER-style designs to their planned projects or retrofits.
	Building owner willingness to adopt	Building owners may be unwilling to take a risk on a newer system design option at this stage of TIER's maturity in the market.
	Lack of market penetration	Newer technology is hard to sell when there are few examples of it functioning in the real world.
	Lack of appreciation in marketing	Without enthusiasm from architects, designers, and distributors, TIER cannot be effectively presented and sold to building owners
	Lack of a supply chain around TES equipment	The TES supply chain is immature. Ice TES is focused on cooling-related use cases. Waste heat recovery is not a common use case for sensible water TES tanks.
	Perception of a complicated process	The complexity and uncertainty surrounding TIER design, controls, and installation creates market hesitancy that limits participation.
	Space for TES in an existing building	TIER plants are space effective relative to a full AWHP plant. But when compared to an existing building with a boiler, TIER retrofit would take up more physical space.
	Misguided perceptions around HVAC TES	Historical impression of Ice TES may map onto TIER / waste heat TES potential market, creating unwarranted skepticism.
	Upfront cost of TIER relative to boiler retrofit	While TIER may have a negative incremental material cost compared to an all-AWHP plant, it remains more expensive than a gas boiler replacement. Contractors and designers add risk premiums for unfamiliar designs.
	Potential for on-bill impacts to the customer from electrification	This barrier refers to the "spark gap" between gas and electricity prices for many customers. Electricity is not cheap enough to guarantee on-bill savings for customers seeking to electrify their HVAC system.

A critical framing principle is that barriers are not static. As early barriers are addressed, new problems will arise, requiring incremental intervention strategies. Continuous reassessment of the technology's status in the market is essential to maintaining an effective intervention strategy, since the economy is highly dynamic.

Since TIER components; AWHPs, HRCs, cooling towers, and TES tanks are all commercially available, the barriers related to equipment supply and safety certifications are less severe than technologies requiring entirely new hardware.

TIER Intervention Strategy

After identifying and internalizing the full array of technology and market barriers, a set of intervention proposals is developed, grouped by categories as shown in Table 2. Interventions could be led by utility programs, state/local governments, or the private sector.

Table 2: TIER barrier intervention strategy

Intervention	Key Action
Further Research	• Additional studies on diverse building types, climate zones, configurations, demand response, and panel impact studies. • Creating a public database of these studies and TIER installations
Upstream Supply Chain	• Government-sponsored manufacturer challenges to develop TIER-aligned products, encourage vendor competition. • Collaborate with control vendors and manufacturers to create design guides and pre-programmed sequences.
Standardization & Modeling	• Add TIER to mainstream simulation and compliance tools, such as EnergyPlus and CBECC. • Develop ASHRAE guidelines, AHRI ratings enhancements • Build HVAC design tools and a TIER qualified product list.
Workforce Education	• Develop TIER case studies, and technical design guides. • Conduct designer and contractor training programs. • Raise awareness at conferences and trade shows.
Financial Incentives	• Market Support for TIER and TES to create flexible load incentives. E.g. Leverage IRS Tax Credit 48E, pursue SGIP eligibility, advance CEDA. • Incentivizing electrification readiness for many existing buildings as precursors to the actual installation of a TIER plant. • Introduce special tariffs for all-electric sites as spark gap incentive.
Policy	• Introduce TIER-related reach and voluntary building codes, align with Building Performance Standards, and improve AWHP and HRC representations in ASHRAE 90.1.

These interventions will help gain confidence in technology and address many market barriers. Certain barriers must be addressed earlier in the market development cycle, particularly those related to code compliance, energy modeling, and basic design guidance etc. before later-stage interventions such as deemed incentive measures can be viable.

Market Transformation Roadmap

We cross-referenced the barriers and interventions to identify which interventions address the greatest number of barriers. Key findings include:

- Standardization and modeling interventions address the broadest set of barriers, spanning energy modeling, code compliance, design tools, and performance standards. Adding TIER to EnergyPlus and CBECC is among the highest-leverage single interventions.
- Workforce education interventions are broadly applicable, addressing market awareness, designer and operator familiarity, and supply chain readiness.
- Financial incentive interventions are essential for early adoption but are most effective once foundational barriers (modeling, code, design guidance) have been addressed.
- Policy interventions are appropriate for later-stage market transformation, once adoption is sufficiently broad and consistent to support prescriptive compliance requirements.

Market transformation theory involves segmenting the market into categories such as "early adopters," "early majority," "late majority," "laggards," etc. For an innovative technology like TIER, it is important to focus early-stage interventions on the early adopters who are willing to take more of a risk for a technology with a less proven track record. These are building owners who may be motivated to electrify space heating for mission or public-facing reasons, or buildings with some type of corporate or government mandate to electrify. In addition, buildings with severe space constraints preventing an all-AWHP plant or another economic reason to be driven toward TIER should be a priority for early program efforts.

The market transformation theory of change for TIER progresses through three rough phases as shown in Figure 2.

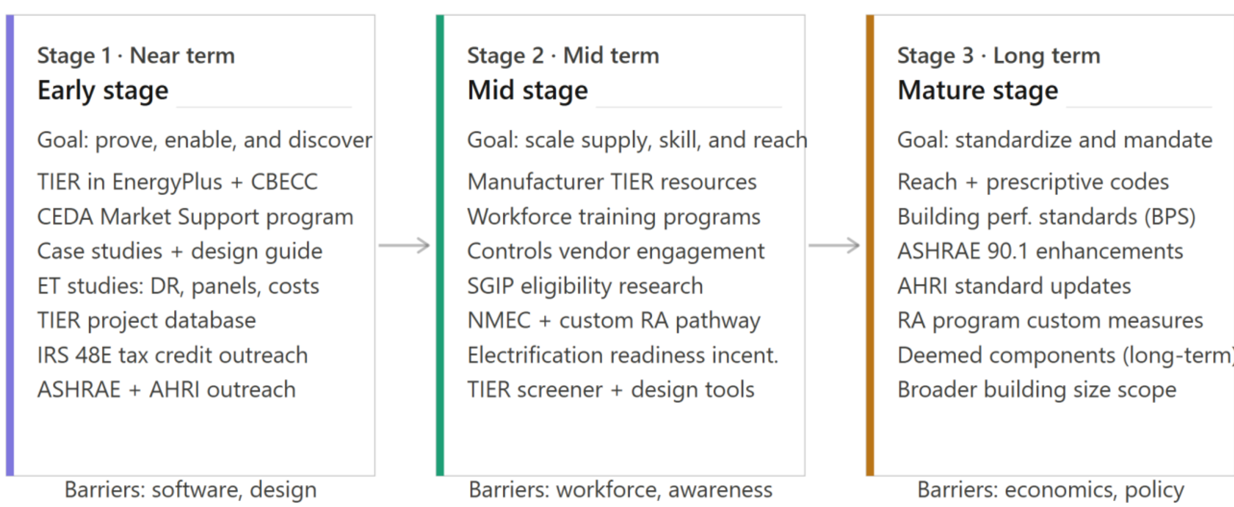

Figure 2: Market Transformation Roadmap for TIER

An ongoing CalNEXT study has advanced several of the interventions noted above, including the case study, simplified tool, design guide, and initial manufacturer engagement components. These are intended to advance the state of knowledge and ease of application of TIER in the market.

Market Engagement

Informational interviews were conducted with California Technical Forum (Cal TF), SDG&E, SCE, and PG&E to educate program administrators on TIER and gather their assessment of program delivery options. Key findings from these engagements are:

- Traditional resource acquisition (RA) custom programs are widely viewed as time-consuming and heavily regulated under CPUC oversight. Hence, it’s not a near-term priority for TIER given the technology’s current maturity level.
- Deemed measures were dismissed, and given TIER's site-specific complexity, unlikely to ever be appropriate in their current form.
- Market support programs were identified as the most compelling near-term program mechanism for TIER.
- Site-level Normalized Metered Energy Consumption (NMEC) was noted as a potentially more viable custom pathway than traditionally modeled custom programs for existing building retrofits, contingent on submetering plant equipment.
- New construction was consistently preferred over existing building retrofits due to the complexity of integrating TIER into legacy HVAC systems, though existing buildings hold the greater impact potential.

Near Term Program Opportunities

California Energy Design Assistance (CEDA): CEDA, overseen by PG&E and classified as a market support program, is the top near-term program recommendation. CEDA is already providing High Performance Measure support for two TIER constituent technologies: Space Heating Hydronic Heat Pumps and Heat Recovery Chillers. Expanding CEDA support to cover full TIER system configurations represents an immediate near-term opportunity.

IRS Tax Credit 48E: The IRS Tax Credit 48E, introduced with the Inflation Reduction Act of 2022 and active as of early 2026, enables commercial building owners to reduce the cost of thermal energy storage equipment by up to 40%. This should be communicated to potential TIER customers as part of project cost framing.

Electrification Readiness Incentives: An intermediate-stage program could incentivize precursor measures that prepare existing buildings for future TIER installation: HVAC controls modernization, hot water supply temperature reduction, building envelope improvements, and where necessary, electric panel upgrades. These measures have standalone value and reduce the complexity of subsequent TIER retrofits.

SGIP Thermal Storage: Future research should evaluate whether TIER plants can achieve the 5 kg/kWh carbon reduction threshold required for SGIP eligibility. This represents a potentially significant incentive opportunity if the threshold can be met, particularly for larger commercial buildings.

Conclusions

Integrated thermal energy storage enhances HVAC capacity and offers a technically proven pathway to decarbonize buildings, but TES with AWHP isn't a complete solution for all-electric large commercial buildings. The TIER system, on the other hand, offers a comprehensive solution by leveraging heat recovery in a novel configuration. Despite recent developments in the field that confirm its superior performance, market adoption of such technologies is low.

This paper presents a literature review of TES integration, TIER performance, and develops a comprehensive market transformation strategy by listing barriers and interventions.

Stakeholder research reveals that economic barriers dominate, driven primarily by electricity rate structures that fail to reward peak demand reduction. The absence of standardized performance metrics, inadequate design tools, workforce shortages, and fragmented regulatory frameworks compound the challenge. No single intervention can overcome these barriers; a coordinated strategy addressing economics, standards, workforce, technology, and policy simultaneously is required.

Realizing the full potential of TES for buildings requires sustained, coordinated action from the research community, policymakers, utilities, manufacturers, and market actors to align incentives, standards, workforce capacity, and regulatory frameworks at the pace demanded by grid reliability and climate imperatives.

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AI Disclosure

AI-assisted tools used: Claude
Used for: Brainstorming and developing figure 2.
Extent: Minor graphic design task
Human review: The authors reviewed and verified all content.