The Best of Both Worlds: Combined Thermal and Battery Storage for Widespread Building Decarbonization

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ABSTRACT

To meet 2050 decarbonization targets, widespread building electrification is a critical complement to clean power generation. Behind-the-meter storage (BTMS) (e.g., battery electric energy storage [EES] and thermal energy storage [TES]) integrated with buildings or building end uses to store and supply energy at optimal times can minimize burdens associated with operation, planning, and upgrades to the electrical grid sometimes triggered by building electrification. Such BTMS systems can serve the dual purpose of providing enhanced resilience at the building and grid level, and support the deployment of renewable generation needed for wide-scale decarbonization. While TES can cost-effectively shed and shift thermal loads, it cannot generally backup or shift non-thermal building end uses. EES, by contrast, is more expensive, but applicable to all end uses (i.e., thermal and electrical loads). Combined together, these storage systems can be traded off against one another to perform optimally in meeting demand flexibility, decarbonization goals, and energy resilience of the buildings at a lower total system cost. This paper proposes a framework to define BTMS benefits, provides four illustrative electrification scenarios using TES and EES, and discusses the combined TES/EES benefits with building energy modeling results. The paper also highlights potential barriers to adoption of BTMS and a path forward.

Introduction

Recent studies on deep decarbonization pathways have demonstrated the critical role demand-side solutions can have in reducing burden on electrical grids and consumers. When deployed at scale in U.S. buildings, energy efficiency, demand flexibility, and electrification account for nearly half of all emissions reductions in simulations co-optimized with the decarbonization of electricity supply (Langevin et al. 2023). Such co-optimization is crucial to avoid scenarios that put undue strain on electrical grids or require lengthy permitting and construction processes.

Indeed, the costliest and least promising route to building decarbonization is the blind growth of power supply and distribution capacities to accommodate widespread electrification absent joint commitments to efficiency and demand flexibility. On the grid side, such an approach would make the phase out of fossil-fuel sources far less feasible without substantial investments in grid-scale storage capable of reliably bridging intermittent wind and solar (Denholm and Hand 2011). On the building side, consumers would see a sizable increase in utility bills. At the grid edge, upwards of 48 million low-ampacity electric panels would need to be replaced (Merski 2021) that could trigger cascading upgrades to local transformers and wire trenching at a cost prohibitive to most building owners. Although utilities may bear the upfront cost of these upgrades, those costs are passed on to ratepayers through service charges. Behind-the-meter storage (BTMS), be it thermal energy storage (TES), electrical energy storage (EES), or combinations thereof, is uniquely situated to address these issues. It is also synergistic with the more traditional demand-side solution of making buildings more energy efficient. Yet, building-sited EES and TES could increase overall carbon emissions (Zheng et al. 2021; Hirschey et al. 2022) due in part to roundtrip efficiency losses and the prevalence of revenue maximizing operational objectives (Arciniegas et al. 2018; Condon et al. 2018).

According to the U.S. Energy Information Administration (EIA) large-scale battery storage installations have outpaced small-scale storage by a factor of ~4 in terms of power capacity (EIA 2023). This begs the question—what innovation pathways to widespread BTMS implementation exist? If we consider the laptop computer, battery life has been the primary driver for gains in laptop efficiency, compelling the development of low-power operating modes (sleep mode), automatic screen brightness adjustments based on ambient light conditions, and optimized processor and operating system performance. Likewise, insofar as BTMS exists to provide resilience to buildings during blackouts, the efficiency of the loads it supports enhances this resilience benefit. In fact, historical innovations of laptops, which are themselves a sort of stand-alone "microgrid," provide several best practices relevant to BTMS in buildings. The interoperability of laptop peripherals, both in terms of their physical ports and digital communication protocols, is an important lesson in standardization yet to be fully learned by the building sector. The storage component itself as either peripheral or embedded "at the point of use" is a design choice that, while settled for laptops, remains an open question for building end uses. As value propositions (or policy mandates) for demand-side solutions to deep decarbonization gather steam, the reinforcing link between BTMS and energy efficiency may indeed follow an innovation pathway reminiscent of laptop computers.

This paper evaluates how BTMS in buildings improves the viability of deep decarbonization pathways, considering several residential building electrification scenarios and BTMS integration strategies. We define BTMS as storage solutions in buildings downstream of the utility meter (TES, EES, or both), as distinct from grid-scale or neighborhood-scale storage solutions. We consider BTMS installations that are either centralized to support many loads within a building at once, or decentralized, often embedded at the point of use (i.e., within an appliance). We analyze four possible electrification scenarios relative to the "worst case" building decarbonization scenario outlined above that only utilizes power capacity growth: (1) efficiency only; (2) efficiency + TES; (3) efficiency + EES; and (4) efficiency with optimized mixed use of TES and EES. We analyzed the scenarios with an example use case using annual building energy simulations. The concluding section of this paper considers barriers to widespread adoption of these technologies.

Behind-the-Meter Storage Applications

While energy storage at any scale is fundamentally a medium to store energy at one time and supply it later, BTMS use cases in buildings are distinct from grid-scale storage applications. A review of grid-scale storage technologies is beyond the scope of this paper, but their cumulative effect is to provide five specific capabilities to grid operators and planners: (1) arbitrage, the storing of low-cost energy for later use when prices are high; (2) firm capacity, the ability to meet peak electricity demand; (3) ancillary services that ensure grid reliability; (4) deferral of transmission and distribution infrastructure upgrades; and (5) generator black start capabilities (NREL 2019). BTMS operation is likewise able to provide arbitrage to building owners whose utility offers time-of-use rate pricing, or by storing electricity from on-site generation such as rooftop photovoltaics. Thoughtful integration of BTMS in buildings can defer (or completely avoid) the need for building infrastructure upgrades, such as the installation of new circuits or the replacement of electrical panels during an electrification retrofit. In some cases, such integration has the same impact that grid-scale storage does in the deferral of distribution upgrades, i.e., in cases where the electrification of a neighborhood would trigger transformer or substation upgrades. Of course, BTMS can also provide resilience for whole buildings or critical loads at times when the grid is unavailable. As extreme weather events increase the frequency of blackouts, consumers are valuing resilience highly in their appraisal of cost-benefit for BTMS, complicating a straightforward "payback period" calculation. Still, the EIA reports that U.S. customers averaged seven hours of power interruptions in 2021, leaving over 8700 hours available each year for "ancillary" BTMS services (EIA 2022).

Given the diversity of energy storage use cases and the distinctions specific to those for BTMS, we propose a framework describing BTMS benefits defined by three utilization modalities that we use to describe case study scenarios in subsequent sections:

1. **Resilience, efficiency, and control (REC benefits)**: The robustness of resilience that BTMS can provide (per kWh) is contingent on the size and number of building loads to be supported during blackouts. Therefore, resilience benefits of BTMS are tightly coupled to efficiency improvements and control strategies that avoid wasted energy, either through more energy-efficient operation or shedding of non-essential loads. In other words, there is positive reinforcement between resilience, efficiency, and control measures in buildings. Advanced control strategies may also predict the need for resilience, thereby optimizing EES and TES charge state in the time leading up to a blackout. This synergistic interplay between resilience, efficiency, and control we collectively refer to as REC benefits.

2. **Third-party mediated benefits (TPM benefits)**: Several BTMS benefits require a third party to facilitate or enable in the first place. Utilities allow for electricity price arbitrage by providing dynamic time-of-use rates, which vary regionally and by tariff, and are subject to change based on local policy. Utilities may also give customers the option to opt into demand-response programs in exchange for credit on their electricity bill. BTMS can provide peak load shifting and load balancing in response to a grid signal and could even provide ancillary grid services such as fast-frequency response (Cai and Braun 2018; NERC 2020). These benefits are only impactful to grid operators when many buildings participate, and as such, aggregators of distributed energy resources (DERs) have emerged in the realm commonly referred to as virtual power plants (VPPs). Building owners may choose to "lend" BTMS services to the operation of a VPP, wherein a cloud-based aggregator utilizes these assets in electricity rate arbitrage markets. An analogous (though woefully decoupled) BTMS use case targeting emissions reduction would rely on a third-party carbon intensity signal from the grid rather than a price signal. Here, we refer to all benefits contingent on the enabling practices of a third party (i.e., not only the building owner) as TPM benefits.

3. **Electrification viability with equipment right-sizing (ERS benefits)**: An often overlooked but critical use case of BTMS is the downsizing of electrical loads without

impacting equipment performance or occupant comfort. Article 220 of the National Electrical Code (NEC) provides requirements electricians use to calculate branch circuit, feeder, and service loads that ultimately compel upgrades of power distribution infrastructure within or near a building undergoing electrification retrofit (NFPA 2015). These upgrades may be new wire runs to accommodate 240-V outlets, new electrical panels (especially in homes with panel capacity of 200 A or less), or in the worst-case new utility transformers and accompanying wire trenching. Upgrade costs can be substantial and may require extensive permitting process or wait for electricians. BTMS at the point of use can allow for plug-and-play electrification equipment that avoids these issues. For instance, a heat pump (HP) integrated with TES has lower capacity requirements than one without, and EES embedded in major appliances can provide surge power that avoids the need to plug into a designated 240-V outlet. Bidirectional electric vehicle (EV) charging and whole-home EES systems supply "extra" building capacity beyond what the utility provides, and thus likewise can be used to avoid infrastructure upgrades with code-compliant control provisions. To that end, NEC 2023 permits alternative load calculations based on the maximum ampere setpoint for an energy management system rather than relying on the traditional accounting in Article 220, although to date only seven states have adopted the 2023 version of the NEC (NFPA 2024). In any case, ERS benefits refer to the extent that BTMS can enable electrification by limiting power draw and thereby avoiding infrastructure upgrades.

These benefits can be provided by EES, TES, or a combination of both. However, each has its own advantages and disadvantages including differences in costs, safety, and load applicability. TES materials are inexpensive and readily available (e.g., water, salts, organic molecules) but battery materials are expensive with limited availability (e.g., lithium, cobalt, manganese). There are safety concerns about using large EES in buildings that have a non-zero fire hazard. The main disadvantage for TES in buildings is that it can only meet heating or cooling loads, while EES can be used for any electric load. Being energy dense, EES has a smaller physical footprint. The next section describes different scenarios that include EES, TES, or a combination of both as well as potential benefits of these systems.

Methods and Scenarios

We considered four hypothetical whole-home electrification scenarios, summarized in Table 1. We contrasted each scenario with a baseline "worst case" electrification retrofit that fails to incorporate efficiency measures or BTMS, leading to maximal upfront and operational costs. While the specific use cases for the BTMS technologies we outline are niche in terms of their present market penetration, the goal of the scenario analysis is to demonstrate technical potential of using BTMS in a stepwise manner, beginning with typical electrification and efficiency measures and adding TES, EES, and mixed-use BTMS sequentially. The scenarios consider a typical single-family detached home of 1980s in climate zone 5A as defined by the International Energy Conservation Code (IECC). The baseline (Scenario 0) assumed the home is electrified and has 100-A electrical service.

Table 1. Summary of whole-home electrification scenarios. Centralized integration supports many loads within a building at once; in embedded integration, a battery or a TES is integrated at the point of use with a system or appliance.

	Efficiency improvements	TES integration		EES integration	
		Centralized	Embedded	Centralized	Embedded
Scenario 1	x				
Scenario 2	x	x	x		
Scenario 3	x			x	x
Scenario 4	x	x	x	x	x

Scenario 1: Electrification with Efficiency Measures

Efficiency measures at the building level enhance the benefits of electrification and make it more viable. While greenhouse gas emission reduction is an obvious benefit of energy efficiency measures, there are several benefits of energy efficiency. These benefits include*:* reduction in energy use for services, like space heating and cooling; reduction in operational costs and energy utility bills, which is particularly beneficial to disadvantaged communities with disproportionate energy burdens; and reduction in overall energy demand, resulting in reduced supply interruptions and improved energy access (IEA 2019). Efficiency measures can improve indoor and outdoor air quality due to reduced on-site combustion and infiltration, and subsequently, health and wellbeing of building occupants.

There are two types of measures a homeowner in Scenario 1 can use to improve building energy efficiency when electrifying: *appliance upgrades and envelope retrofits/upgrades*. While switching to LED lights and induction cooking would constitute efficiency measures, more substantial energy savings would come from upgrading space heating and cooling appliances. Switching to HPs for heating can reduce energy use by 65% as compared to furnaces and baseboard heaters, a significant savings on energy in this scenario considering space heating demands in colder climates. Likewise, a heat pump water heater (HPWH) would provide efficiency gains over the incumbent gas heater. Of course, while total energy consumption is reduced by switching to HP technologies, electricity consumption is increased from the new electric loads, so that the upfront cost of the appliance upgrades will likely include the cost to upgrade the 100-A electrical panel and run new branch circuits to the HPs. These electrical upgrades are especially likely in this scenario as HPs in cold climates will generally include backup resistive heating for the coldest days with characteristically high-power draw.

Upgrading building envelope (i.e., exterior wall, roof insulation, air sealing, windows) can reduce energy use while increasing occupant safety and comfort. During extreme weather events like heatwaves, storms, and wildfires, insulated building envelopes have the potential to improve passive survivability by maintaining indoor thermal comfort for a longer period even if there is an outage. As envelope technologies influence building heat transfer, combining envelope retrofits with smart building control technologies and advanced metering can not only improve efficiency, but also enable demand flexibility both during extreme events/blackouts and otherwise. Thus, even without TES or EES, efficiency upgrades provide a degree of building resilience with synergies similar to those we identify as REC benefits for BTMS.

Mumme et al. (2022) found that envelope improvements alone can reduce energy use by more than 50% and reduce peak-to-valley ratio by ~20%, which can reduce grid overload and benefit the utilities. However, without BTMS there is no ability to shift load without impacting building performance, so the TPM-like benefits we define for BTMS would be limited to thermostat setpoint setbacks in this efficiency-only scenario. Still, a homeowner with a well-insulated envelope will be less likely to experience thermal discomfort during such a DR event.

Scenario 2: Electrification with Efficiency Measures and TES

Scenario 2 is the addition of thermal storage to Scenario 1. Thermal loads currently make up over 40% of total annual building electricity use (EIA 2022). With future electrified heating loads expected to increase in buildings, annual heating electricity use may increase above 250% (NREL 2018) while the peak period thermal loads may exceed 75% of building energy consumption. While TES can only serve heating or cooling loads, the fact that thermal loads are a main driver of peak loads means that thermal storage can play a major role in shifting them.

One approach to Scenario 2 is the integration of TES into equipment at the point of manufacture or at the point of installation as a stand-alone component. The latter can provide flexible, plug-and-play compatibility, reducing installation costs. This equipment-integrated TES can strategically control charging and discharging to avoid backup electric resistance heating needs of HPs during extremely cold periods or during defrost mode. Subsequently, it can align operation with low-cost and/or low-carbon grid conditions, and reduce utility costs (TPM benefits), or improve efficiency by operating during favorable ambient conditions. It can also improve resiliency (REC benefits) by maintaining heating or cooling capacity during power outages. Finally, TES can maintain capacity during high peak load situations (extreme heat and cold), which allows HPs to be downsized with a lower maximum electric power (ERS benefits).

A second approach is a TES-integrated building envelope that includes storage embedded into the walls, roofs, ceilings, and other structural and non-structural components, or stand-alone modular TES connected with building envelopes through thermal loops for space conditioning.

Equipment-integrated TES and stand-alone modular TES connected with building envelopes are effective at leveraging diurnal swings by taking advantage of the difference between the highest and lowest temperatures in one day and corresponding difference in the coefficient of performance of an air conditioner or HP. This approach can enhance the efficiency of the overall space conditioning system, exhibiting roundtrip efficiencies over 100% that are not possible for EES systems due to charging and discharging losses (Deetjen et al. 2018).

Passive TES integrated in the envelope can also provide REC benefits by enhancing the thermal mass of the envelope, offering more stable temperatures during heat or cold snaps and co-incident power outages. Ongoing work at ORNL demonstrates that thermally anisotropic building envelopes integrated with TES can reduce envelope-generated heating and cooling energy consumption in buildings and peak demand by 30-50%. The synergistic opportunity of TES to improve equipment efficiencies and shift peak loads can facilitate the equitable electrification of thermal loads while minimizing associated building electrification grid impacts, and provide REC, TPM, and ERS benefits.

Scenario 3: Electrification with Efficiency Measures and EES

In the third scenario, we consider what benefits electrical storage (but not thermal) can provide in conjunction with efficiency measures for the whole-home electrification retrofit in question. We assume for this scenario that the homeowner takes the same building energy efficiency measures as Scenario 1 and additionally installs an EES system centrally as well as strategically at points of use (see below). We further assume the installation and use of controls necessary to optimize REC, TPM, and ERS benefits.

Resilience to blackouts is perhaps the most straightforward use case for residential EES. Although it varies by location, a large, centralized EES system will cost ~$1000/kWh based on national average (Wakefield 2024). By combining EES with the efficiency measures in Scenario 1, the homeowner in this scenario can downsize the central EES capacity significantly without impacting backup power capabilities relative to the baseline scenario with no efficiency improvements. Alternatively, the homeowner could opt to increase the length of time the home can operate on backup power rather than reduce EES capacity and upfront cost. Either option constitutes a REC benefit from EES, wherein the homeowner can choose between reduced upfront costs or enhanced resilience. The addition of a control layer may go some way toward achieving both these benefits at once, by prioritizing backup for essential loads only, such as the HP, HPWH, refrigerator, home medical equipment, or certain lights. EES integrated at the point of use—that is, appliances with embedded batteries or plug-in batteries co-located with end uses—could provide supplemental resilience to loads not supported directly by the centralized EES control system while providing several additional benefits to the homeowner.

Point-of-use EES offers the homeowner specific ERS benefits that a central, stationary EES system cannot provide. By utilizing power from the on-board battery during use and charging while idle, manufacturers can engineer major appliances that would traditionally require a 240-V outlet to run off a more typical 120-V outlet instead, thereby providing ample power for the task at hand without exceeding 15/20-A current limits of existing wiring. For this scenario, the homeowner could avoid costly electrical work associated with running new branch circuits to the kitchen and laundry room by installing a battery-embedded, 120-V induction stove and clothes dryer. Given that these major appliances will be plugged into existing outlets, they also avoid the need for free physical space in the electrical panel or a re-assessment of utility service and panel ampacity needs. While 120-V HPWHs without EES are available and suitable for certain homes and climates, embedding a small battery makes it possible to include a backup resistive heater for short-term situations where the HP is insufficient to meet hot-water demand.

In addition to avoided costs associated with electrical upgrades, batteries embedded in appliances have a much lower cost per kWh, with companies in the space targeting reductions down to ~$100/kWh (which is competitive with EV storage costs but an order of magnitude less than traditional building EES systems). While the market for battery-embedded appliances is nascent and costs this low are yet to be realized, the potential lies in reducing customization and labor at scale. By installing the battery on the factory floor and delivering it to the homeowner with “plug-and-play” operation, manufacturers can integrate storage in a standardized, automated manner relative to on-site installations of whole-building EES requiring an electrician. This EES integration approach also enables a more rigorous check on quality control and safety, taking place at the factory rather than in the home. Therefore, standards setting organizations can certify EES product integration and avoid the need for on-site inspections.

Regardless of integration strategy, both central and end-use-embedded EES can provide the homeowner with TPM benefits, although in practice centralized EES presents an easier control/dispatch problem. Utilities differ in terms of their DR program offerings, but the majority offer some option to commercial and industrial customers, and residential DR programs are growing in number (FEMP 2024a). Such programs incentivize the building owner to curtail load in response to a DR signal, typically triggered by periods of high electricity demand that strain the electrical grid and lead to blackouts. In exchange for participating in the requested curtailment, building owners are compensated by their utility, lowering building operational costs. Response to a DR event is often met by electrical HVAC systems and facilitated by cloud-connected thermostat setpoints, but EES integration allows any electrical end use (or indeed the entire building) to participate in DR by shifting power draw from the grid to on-site batteries. Unlike the smart thermostat solution, a home with proper EES sizing should not see any impact in performance or comfort during the DR event.

In 2020 (and with updates in 2021) the Federal Energy Regulatory Commission issued Order No. 2222 to facilitate DER aggregation in regional electricity markets (FERC 2020). The order reduces barriers to the integration of EES with other DERs in markets that trade capacity, energy, and ancillary grid services. This enables the EES installations in Scenario 3 to participate in large-scale, coordinated services that grid operators can call on to shift load up or down at megawatt scales, hence the “power plant” in VPP. By 2030, the cumulative impact of VPPs could reduce peak demand in the U.S. by 60 GW, compensating building owners directly for their participation and ratepayers broadly through grid reliability (Brehm et al. 2023). As with the proliferation of battery-embedded appliances, VPP participation is in the earliest stages of widespread adoption, but the technology exists and is poised to grow rapidly in any economy-wide decarbonization trajectory. TPM benefits associated with EES may rapidly evolve from niche to commonplace within the lifetime of equipment being installed today, especially if bidirectional EV charging becomes the norm (FEMP 2024b).

Scenario 4: Electrification with Efficiency Measures and Optimal Use of TES + EES

Using EES and TES together can lead to a better outcome than only TES or EES. Just as efficiency reduces the required EES size, adding TES can likewise reduce the EES size. Homeowners seeking full resilience to power outages would still need EES for critical non-HVAC loads, as well as for operating the fan and/or pump for the HVAC system. However, because many of the critical loads are related to heating and cooling, and these loads are largest on the extreme hot or cold days when grid outages are more likely, TES is a good alternative to the costly, resource-intense whole-home EES system for providing much of the REC benefits. Alternatively, for a given EES size, adding TES can increase the duration that storage can provide acceptable services during an outage.

For TPM benefits, TES can provide load shifting in a similar way to EES, but again at a lower cost. The need to shift load is often driven by large, correlated cooling and/or heating loads during very cold or very hot days, which cause peak electricity use for the grid. The need for load shifting in the winter will increase as we electrify heating systems. As an example, TES can be charged by operating an HP during low-electric-rate periods, and discharged while the HP is off during high-electric-rate periods.

Electrification (ERS benefits) can be more viable with downsized and flexible HP equipment, which can be accomplished using TES or EES. TES can help smooth out large spikes in demand due to extreme temperatures or can provide supplemental heat instead of high-power electric resistance heaters during these extreme temperatures or during reverse cycle operation during defrost (which cools the building). Embedded EES can provide "extra" electricity to electric end uses that need bursts of power for short periods of time, such as stoves, dryers, and water heaters, thereby avoiding the need for 240-V outlet runs or electrical panel upgrades.

Using TES for the above benefits can lead to similar functionality as an EES-only system, but with lower upfront costs, lower operating costs, less embodied carbon, less expensive materials, and safer systems. TES costs have been recently estimated at around $25-

$75/kWh_th (this is equivalent to $75-$225/kWh_e, assuming a heat pump COP of 3) (Odukomaiya et al. 2021). This has been shown to not only minimize the total cost of ownership for the storage, but also increase battery lifetime by reducing battery cycling (Brandt et al. 2022). TES, if designed correctly, can also result in *lower* overall electricity use by allowing the HP to run at a reduced capacity or at times with favorable ambient temperatures. EES, on the other hand, will always increase electricity use due to roundtrip efficiencies that are always less than 1. As DR programs and VPPs with dynamic pricing gain traction, the operational savings and payback period for BTMS may greatly increase the economic viability of both TES and EES systems for homeowners. In the next section, we describe a quantitative analysis that illustrates some of these benefits provided by a combined EES and TES system.

Example Use Case for TES and EES

We used an IECC2021 single-family home from the prototype EnergyPlus® building model for Chicago, IL (ASHRAE climate zone 5A) (Mendon and Taylor 2014). We also considered a 1980s-era typical single-family detached home before any major energy renovations have been made (Scenario 0), as shown in Table 2. These renovations primarily affect the building thermal load, and the resulting HP electric energy use. We used the model with an unconditioned basement and an electric HP and HPWH. Because we are interested in the hourly load profile, and not just the total energy use, we modified several of the large electric loads (clothes dryer, cooking range, and dishwasher) so that the electric loads from the prototype building occur in events during a discrete 1- to 2-hour period, rather than being spread throughout the day.

From the building simulation results, we selected the 3-day period with the highest average HP load, which was also the coldest three days from the TMY3 weather. The ambient temperature was always below 20°F and was below 5°F for 40 hours straight (the coldest temperature was -6°F). Our analysis assumes a cold climate HP that is sized to meet the heating load at these cold temperatures, and therefore no backup electric heating is required. We also neglect the impact of defrosting the coil, which is important but outside the scope of this study.

Table 2. Building Envelope Specifications for Two Houses Considered for Scenarios

Vintage	Wall insulation	Ceiling insulation	Windows	Infiltration
1980s (Scenario 0)	R-7 (U = 0.81 W/m^2-K)	R-19 (U = 0.41 W/m^2-K)	R-2 (U = 2.84 W/m2-K) SHGC = 0.6	10 ACH50
IECC2021 (Scenarios 1-4)	R-18 (U = 0.30 W/m^2-K)	R-40 (0.14 W/m^2-K)	R-3 (U = 1.70 W/m2-K) SHGC = 0.33	3 ACH50

Notes: 12 kbtu/hr = 1 ton = 3.5 kW (power); Tonh = 3.5 kWh = 12 kbtu (energy); EER = btu/Wh

Results and Discussion

The results of the building simulations are summarized in Table 3. In the first two scenarios, there is no TES or EES. Scenario 0 is the baseline, which is the typical single-family detached home from the 1980s. The maximum HP capacity required is 25.5 kW_{th} (87 kbtu/hr), and the max electricity draw is 19.5 kW_e. By introducing efficiency measures that bring the home up to the equivalent of IECC2021 building code, the HP capacity drops to 10.9 kW_{th} (37 kbtu/hr), which is in line with typical HP sizes available for residential buildings. The maximum electric load also drops by 42%. Although the results shown here are not necessarily sufficient to size the panel (e.g., 19.5 kW, or 81 A), it is indicative of how much of an impact efficiency can have on downsizing the panel.

Table 3. HP Thermal Capacity and Building Electric Capacity for Each Scenario Along with Sizes of TES and EES for Scenarios 2-4. Determined based on the worst-case three-day period in Chicago, IL (Jan 26-28), using TMY3 weather.

Scenarios	TES size (kWh_th)	EES size (kWh_e)	Max HP capacity (kW_th)	Max elec. capacity (kW_e)
Scenario 0 (Baseline)	0	0	25.5	19.5
Scenario 1 (Efficiency only)	0	0	10.9	11.3
Scenario 2 (Efficiency with TES)	47.6	0	7.3	9.4
Scenario 3 (Efficiency with EES)	0	46.0	10.9	6.8
Scenario 4a (Efficiency with TES & EES)	47.6	17.4	9.4	6.8
Scenario 4b (Scenario 4a with EES both central and appliance embedded)	47.6	13.9 & 3.5	9.4	6.8

The hourly data from the building simulation are shown in Figure 1 for Scenario 1 (efficiency only with no storage). The total building load is the top green line, which is the sum of the non-HVAC load (gray) and the HP load (orange). Figure 2 shows the modeling outputs for Scenario 2 in which we added a TES sized to reduce the HP capacity as much as possible for these three days. We sized the TES assuming that it would completely flatten the load—charge the TES when the thermal load is less than the average thermal load for the 72 hours and discharge the TES when the thermal load is higher than the average. This 47.6 kWh_{th} TES allows the HP to be downsized by 33%. If we assume a storage that is 50 kWh/m^3, which may be typical of some phase change material storage systems (Woods et al. 2021), then this would be roughly 1 m^3 in volume. The smaller HP also lowers the max electric power draw by 17%.

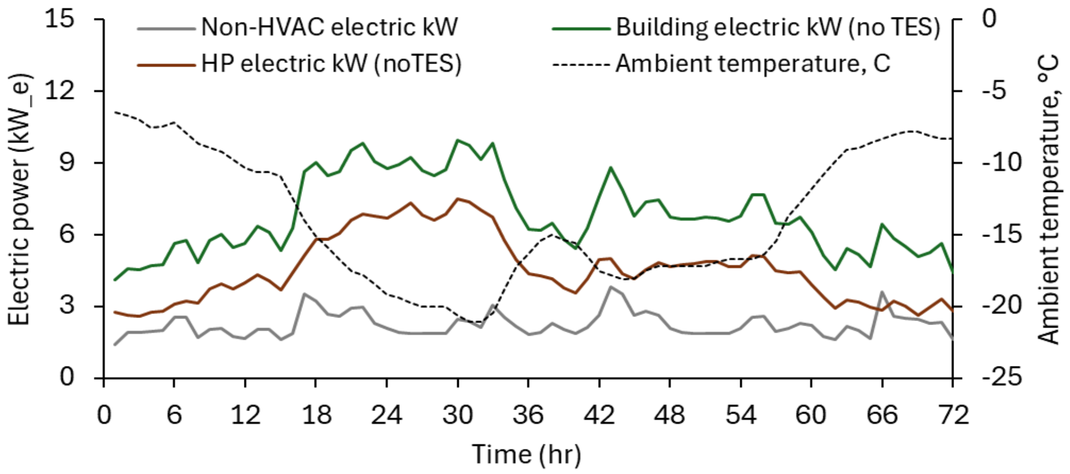

Figure 1. Electric power consumption for scenario 1 (efficiency only) on the worst-case 3-day period in Chicago, IL for TMY3 weather (Jan 26-28). The ambient temperature is also shown.

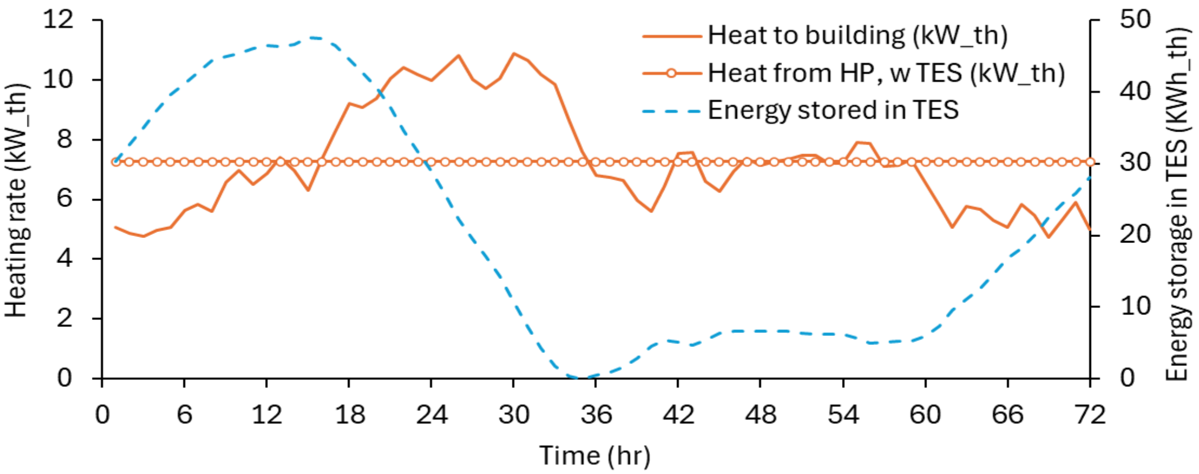

Figure 2. Heating rates on the worst-case 3-day period in Chicago, IL for TMY3 weather (Jan 26-28). Heat to the building (solid orange line) for Scenarios 1-4; heat from the HP matches this line for Scenarios 1 and 4. For Scenarios 2 and 4 (with TES), the HP pump provides a constant heat output (orange line with circles), while the TES is either charged or discharged. The energy stored in the TES (blue dashed line) is either increasing, during charging, or decreasing, during discharging.

For Scenarios 3 and 4, we added an EES to reduce the maximum electrical power. In Scenario 3, the HP is still sized to meet the entire load and there is no TES (Figure 3). The EES is sized primarily to address the HP electric load between hours 16 and 34, with the energy stored in the EES shown in the purple dashed line. This Scenario requires an EES of 46 $\mathrm{kWh_e}$; for scale, this is equivalent to 3.5 Tesla Powerwall batteries. With this EES, the maximum electrical power is reduced by 40%. How much the electrical capacity should be reduced is a separate question that depends on the benefits being provided by the storage (REC, TPM, ERS benefits described above). If the maximum electric load only needs to be reduced by 30%, the EES size drops to only 23 $\mathrm{kWh_e}$, or reducing by 20% requires only a 7 $\mathrm{kWh_e}$ EES.

For Scenario 4, the TES has reduced the maximum electric power (from dashed green line to solid green line in Figure 3(b)). Reducing the electric power to the same level as Scenario 3 (40%) requires a 17.4 $\mathrm{kWh_e}$ EES. Similar to Scenario 3, we could instead reduce the original Scenario 1 building load by only 30% or 20%, in which case the EES can be only 2.7 $\mathrm{kWh_e}$ or 0.5 $\mathrm{kWh_e}$, respectively. This size EES could easily be embedded in appliances that often cause these short spikes in electric power, as discussed in the *Appliance-Embedded EES* section below.

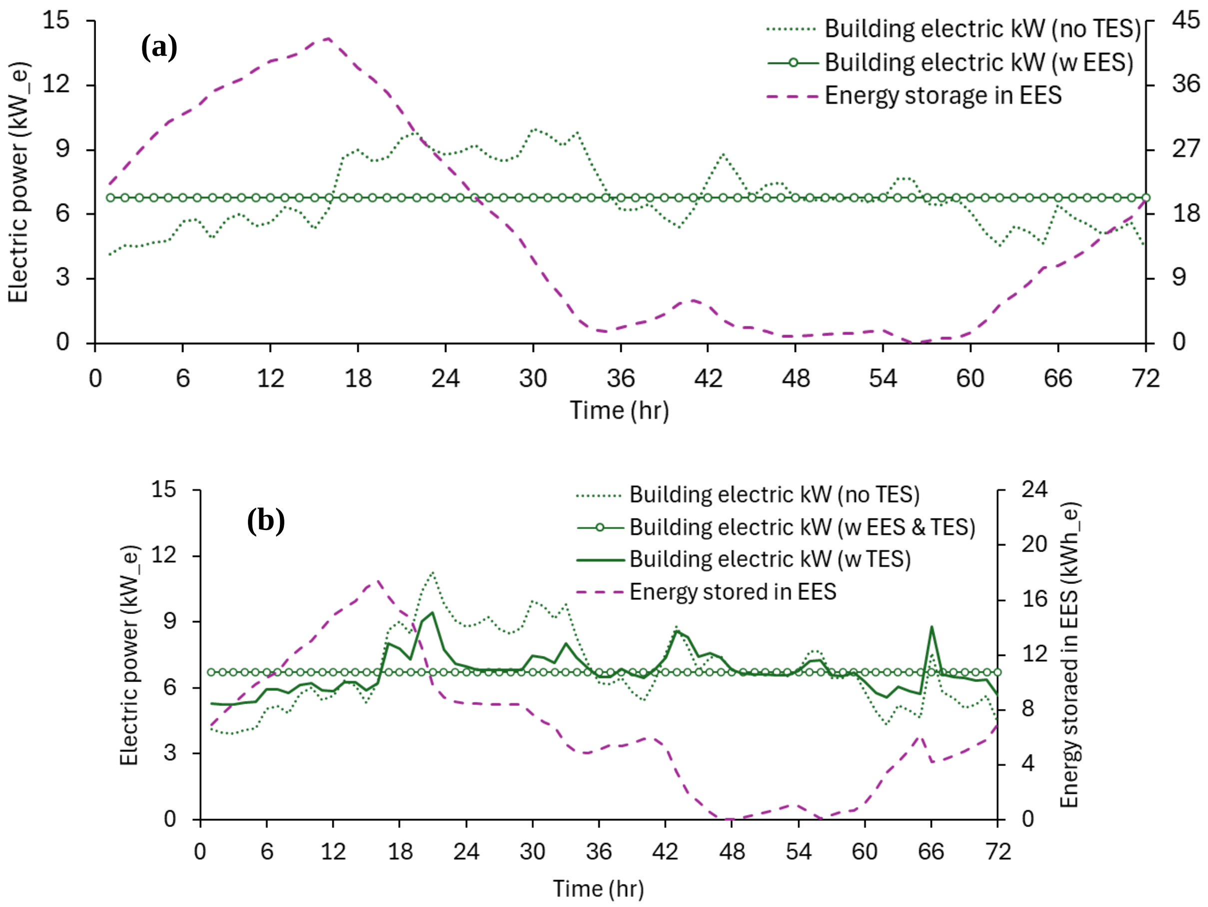

Figure 3. Electric power on the worst-case 3-day period in Chicago, IL for TMY3 weather (Jan 26-28). (a) Building electric load for Scenario 1 (light dotted green line), along with the final electric load for Scenario 3 when using solely EES (purple dashed line) to lower electric capacity to new level (green line with circles). (b) Building electric load for Scenario 1, new building electric load with TES for Scenario 2 (solid green line), and final building electric load for Scenario 4 using EES to minimize electric demand (green line with circles). The energy stored in the EES (purple dashed line) is either increasing, during charging, or decreasing, during discharging.

Figures 4(a) and 4(b) summarize the electric load reduction for Scenarios 3 and 4, showing the original building electrical power in the dashed green line, the non-HVAC load (which is unchanged for all scenarios) in the gray line, and the HP electricity use in the orange line. The EES charge/discharge power is shown in purple.

The above analysis assumes a controller that can determine how to operate the equipment (including charging and discharging of storage) to meet the reduced thermal and electric loads. Developing such controllers is non-trivial, but we assume an ideal controller here to illustrate the full potential of behind-the-meter EES and TES.

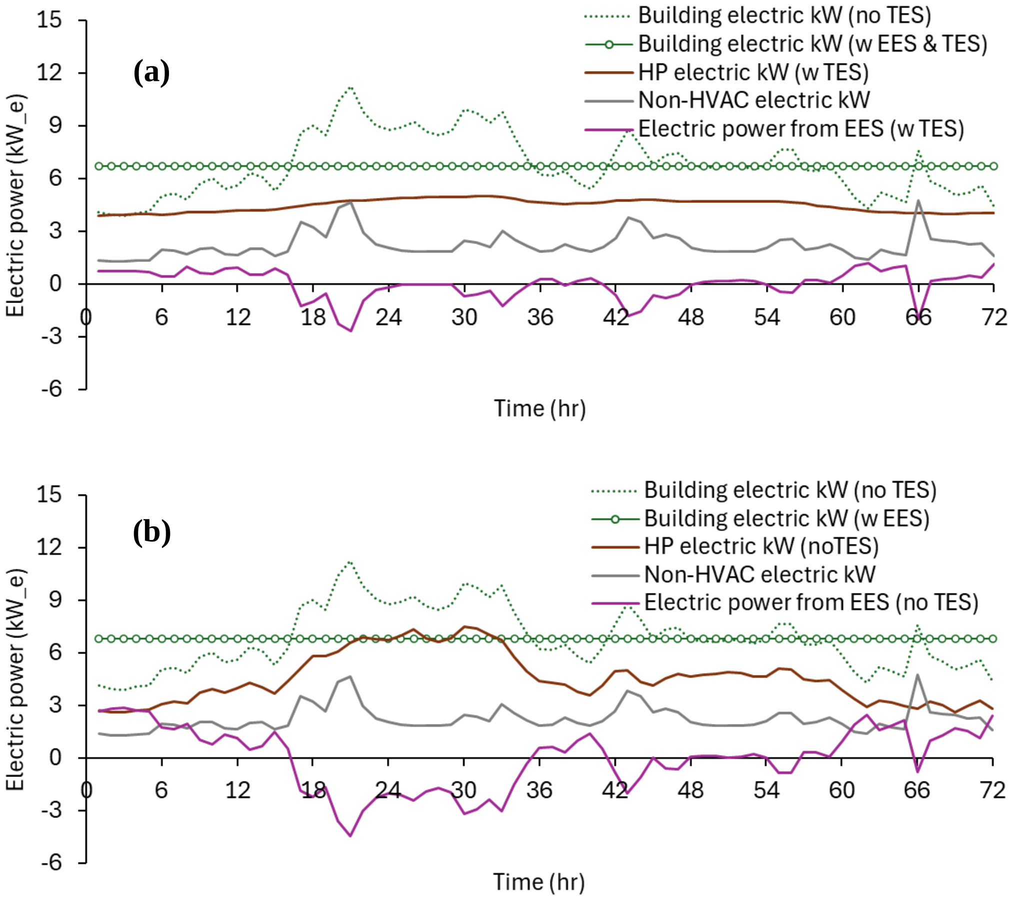

Figure 4. Electric load resulting from (a) using TES and EES, Scenario 4 and from (b) using only EES, Scenario 3 (b). The total load (green line) is the sum of the non-HVAC load (gray line), HP load (orange line), and the power provided by the EES (purple line). For the EES, positive is discharging, negative is charging.

Appliance-Embedded EES

As noted above, battery storage can be located within appliances in a building, or as a central storage used for any electric load. Here we consider the use of battery storage within the electric clothes dryer, with 3.5 kWh capacity. This can reduce the peaks in electricity that occur at hour 20 and hour 66 in the above figures. By using batteries within the dryer, it reduces the electric capacity of the central EES by 3.5 kWh. While the central EES is more flexible and can meet any electric load, embedding batteries within appliances can be cost-effective since it is packaged into the appliance before being installed in the house at no additional electric service.

A hybrid system that combines EES installed within an appliance, and TES installed within the HP, downsizes the battery from 46 kWh to only 13.9 kWh. This size is similar to residential EES available on the market (e.g., Tesla Powerwall). The TES allows for this smaller battery because, after electrification, the HP is the main driver in increased electric demand. This is illustrated in Figure 3. In Figure 3(a), the EES is dealing primarily with spikes in electric demand during the end of the first day and the start of the second day. These are due to water heating and appliances (including the electric dryer). Conversely, in Figure 3(b), the EES must offset much of the electricity used by the HP, in addition to the appliances and other electric loads. From hour 14 to hour 35, the EES is continuously discharging to offset the HP electric demand, which could have been met with TES.

Resiliency: Storage for Critical Loads

We considered the same building load profile to investigate some aspects of the REC benefits described above. Specifically, we looked at the hours for the same 3-day period (Jan 26-28) in Chicago, IL, and size either an EES or a TES and EES to meet critical loads for up to 6 hours. We define the critical loads as electricity to operate: (1) the HP, (2) the refrigerator, (3) 50% of the lighting load, and (4) 30% of the miscellaneous plug loads. We also assume the indoor temperature setpoint changes to 17°C (62°F), which eliminates the thermal load for a short period, and then reduces the thermal load once the indoors is 62°F.

Figure 5 shows the sizes required for an EES to meet all these loads, as well as a combination of TES and EES to meet these loads when the TES is sized to meet the entire heating load, or half the heating load. The latter case could be because the TES is simply smaller, or it could be that it is a phase change energy storage meant to meet both the heating and cooling loads, and therefore the transition temperature is, perhaps, 10°C and the HP still operates to provide heating to the building. When the HP still operates, the TES is still around half the heating load because at a COP of ~2.0, the TES provides half the load to the evaporator, and the rest of the heat comes from the compressor. It is also evident that the storage size needed to meet critical loads for 1 hour is a 2.6 kWh_e EES. For a TES sized to shave half the load, we could have a 1.7 kWh_e EES with a 1.7 kWh_{th} TES. The storage is small for this first hour because the HP does not operate until the temperature drops to 62°F. To meet the critical loads for 3 hours requires a 13 kWh_e EES, or a 7.8 kWh_e EES with an 8.8 kWh_{th} TES.

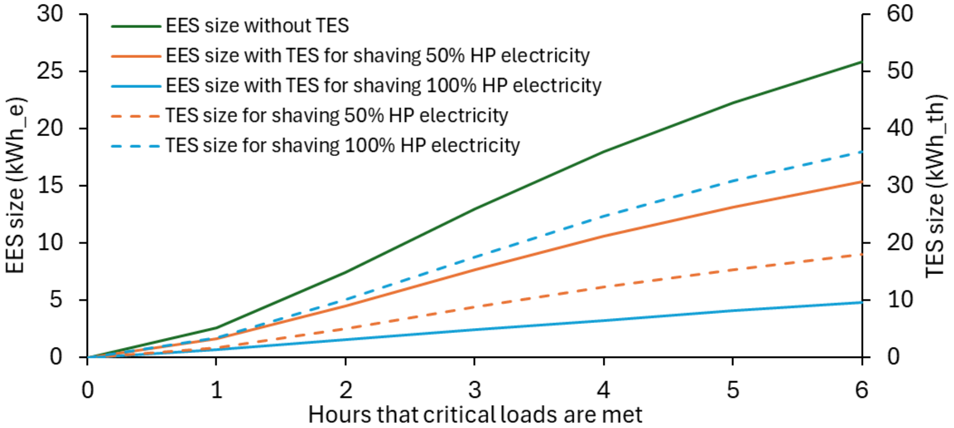

Figure 5. EES and TES size to meet building critical loads from 0 to 6 hours.

Conclusions

Energy storage has the potential to reduce energy costs and improve the resilience of buildings by changing equipment operation time while maintaining end-use service delivery during power outages. The development and deployment of next-generation TES, as well as improved integration of EES and TES in buildings, can foster sustainable, scalable, and affordable solutions to meet climate and energy sustainability goals of the building sector as well as energy equity. These goals include: (1) REC benefits: increasing resilience and the ability of communities to withstand stress from extreme weather events and grid disruptions, and reducing consumer energy burdens, and (2) TPM and ERS benefits: increasing demand flexibility to support grid decarbonization, building electrification, and reducing grid-edge infrastructure upgrade costs.

Integration of EES and TES into building systems and operation to maximize decarbonization is crucial to fully realize the potential of BTMS. Deploying TES and EES systems together in optimized packages can enable lower cost resilient systems and maximize value for building owners/occupants, grid operators, and society. Hybrid TES-EES systems can provide more flexibility, a broader range of grid services, and greater resilience at lower total system cost. TES can potentially shed and shift thermal loads more cost-effectively than EES but may be limited in the range of grid services that it can provide and cannot shift or backup non-thermal end uses. EES is more expensive but more generally applicable to all end uses, assuming heating, water heating, and cooking are electrified, and grid services. TES and EES have different power and energy characteristics, performance degradation due to cycling, cycling frequency constraints, and capital and operating costs. These can be traded off against one another to produce optimized designs that meet different cost, performance, and resilience criteria.

We must consider the barriers to widespread adoption of these technologies. A key challenge for TES is how to deliver benefits without taking up too much space. Large tanks of water are great at storing thermal energy, but they take up valuable square footage and are quite heavy, limiting their placement in a building. For this reason, most TES are relegated to large campuses or large commercial buildings. TES products need to get smaller and far easier and cheaper to install. Today there is a small but growing array of compact thermal-storage options in the market and in the R&D stage that can fit more flexibly into buildings or unused spaces.

At present, there are a lack of guidelines to inform the design of hybrid BTMS systems due to limited understanding of hybrid TES-EES systems. Existing energy modeling software, such as EnergyPlus, may need to be updated to better support design of hybrid systems and their controls. In addition, dispatch control methods that maximize decarbonization for various building types and utility rate structures need to be explored and developed. Control of hybrid TES-EES systems has significant impact on energy, cost, and emissions reductions. Without coordination, the two storage systems will not be optimally deployed, and may even incorrectly interpret and respond to one another’s operation, e.g., a battery may start charging because it senses a low power draw at the electric meter when the thermal storage starts discharging.

Because of their considerable impact on energy use and resilience as well as potentially tight integration between TES configurations and the building envelope, TES, EES, and hybrid TES-EES systems must be considered early in the design process. Detailed modeling tools like EnergyPlus, Modelica Buildings Library/Spawn, and URBANopt™ can already model hybrid TES-EES systems or can be extended in straightforward ways to do so. However, early-stage decision support and master planning use higher-level analytical tools that require fewer building details and incorporate economic analysis. These need to be expanded to account for TES, EES, and hybrid configurations and to evaluate capacity, grid service, resilience, and cost trade-offs.

To overcome the challenges of deploying hybrid TES-EES systems, these systems need to be affordable, high performing, and easy to install, operate, control, and maintain. This includes improving control strategies to maximize the value of hybrid systems to support decarbonization and stakeholder needs, tools for designing hybrid systems and their controls, and field demonstrations to build expertise and develop best practices. Only then can we realize the synergistic benefits such hybrid energy storage systems and envision their widespread adoption.

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