Electric Battery Energy Storage and Thermal Energy Storage

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ABSTRACT

Energy storage at buildings can shift electric load to low-cost or low-emission periods, reducing the overall cost and environmental impact for operating buildings. This storage includes electric batteries, which directly shifts the metered load, and thermal energy storage, which shifts thermal-driven electric loads like air conditioning. While these are often seen as competing technologies, there can also be synergies between the two. In this paper, we discuss high-level advantages and disadvantages of thermal energy storage versus electrical batteries. We show how thermal storage coupled with an HVAC system often has a lower upfront cost than electric batteries—displacing electric batteries with thermal storage can reduce the initial $/kWh$_e$ cost of a new storage system. We also show how batteries can be more flexible in their response to signals designed to limit a building's peak demand. Using thermal storage with batteries can often lead to optimal solutions. Previous research has shown how this can reduce the cost of ownership, increase battery cycle life, and maximize the demand flexibility for different scenarios. In this work, we supplement this with experiments that combine a 30-ton chiller, a 160-tonh ice storage tank, and a 40-kWh electric battery. These are used together to reduce peak demand. We show how in the hybrid system, the chiller can operate at part load, at a high efficiency, reducing overall energy use, increasing the effective energy density of the thermal storage, and reducing its electric equivalent first cost. We also show how the efficiency of the HVAC&R equipment coupled to thermal storage, both the baseline equipment without storage and the equipment operating during discharge, has a strong impact on the electric equivalent first cost of thermal storage.

1. INTRODUCTION

Buildings in the United States consume 75% of generated electricity, which is generated from a combination of fossil (60%), nuclear (19%), and renewable sources (21%) (US EIA, 2024). In general, the generation matches the consumption, and generation has traditionally been dispatchable, providing electricity to match the demand. This requires electricity generation with stored energy that can be converted to electricity on demand. Most of this stored energy are fuels, such as coal and natural gas. Most forms of renewable energy sources provide variable electricity generation, with no stored energy in the form of fuel. While some renewable sources are dispatchable, like geothermal and biomass combustion, variable generation like wind and solar are the fastest growing, and currently account for 10.2% and 5.7% of total electricity generation, respectively (US EIA, 2024).

Aligning renewable generation with consumption at buildings will require a combination of demand-side and grid-side energy storage. Loads in buildings include thermal end uses, such as space heating, space cooling, and water heating, and non-thermal end uses like lighting and computing. Thermal energy storage is one option for thermal end uses. It is charged using inexpensive electricity, and then provides heating or cooling later with minimal electricity. Electrochemical batteries are a second storage option, which can meet thermal loads, but also non-thermal electric loads. However, compared to thermal energy storage, they have higher costs, use less abundant materials, and suffer from cycling degradation (Odukomaiya *et al.*, 2021).

The prevailing approach to combining behind-the-meter electrical and thermal storage is to use thermal storage to meet thermal loads, and electrical storage to meet electric-only loads. Researchers have looked at how to reduce battery size by displacing it with thermal storage (Hu *et al.*, 2020). In prior research, we showed through simulations how battery and thermal storage sizing impacted annual utility costs, battery cycling, and the total cost of ownership (Brandt *et al.*, 2022). In all cases, either thermal storage alone, or thermal storage with batteries offered the lowest overall cost of ownership. This analysis considered only hypothetical equipment in a modeling environment. This leaves questions about whether the equipment would behave in the way we assumed in our modeling, and how a controller for a combined system would work to achieve these synergistic benefits.

There are two aspects we investigate in this paper. First, we explore how a hybrid system that combines thermal and electrical storage would be controlled – demonstrating the coordination between these two pieces of equipment. Second, we investigate how the choice between thermal and electric storage depends on the efficiency of the HVAC&R equipment. In particular, the efficiency of the equipment that charges the thermal storage, and whose operation is being displaced during discharge, depends strongly on the ambient temperature, as well as the supply chilled-water or hot-water temperatures, and the capacity for variable speed systems. These efficiencies have a large impact on the electric equivalent performance, and electric equivalent first cost. In contrast, the roundtrip efficiency of electrical batteries do not depend strongly on ambient conditions, and the amount of electrical load that is shifted is easily predicted.

Here we use laboratory experiments that include an electric battery and thermal storage to demonstrate the controls of a hybrid energy storage system to meet a single objective—in this case, load leveling. We also investigate more realistic operation of a chiller plant during discharge to investigate how additional benefits can be realized by combining thermal and electric energy storage, and discuss other factors that may impact the decision on selecting thermal storage, battery storage, or both. Finally, we discuss how the thermal end use influences this decision (e.g., space heating vs. space cooling).

2. EXPERIMENTAL METHODS

The chosen use case is a retail store in Phoenix, AZ, as in (Brandt *et al.*, 2022). The building includes 600 kW of roof-mounted photovoltaics, which moves the building peak electric demand from the mid-day peak cooling period to the evening hours. To align with the laboratory equipment tested for this use case, we scaled the load and PV generation down by a factor of 10. The electric load profile is shown in Figure 1, which is a single day. The building is assumed to include two types of storage, which are not included in the baseline load profile in Figure 1. The first is an ice storage tank, which is charged (frozen) with the chiller and discharged (melted) by meeting the building's cooling load. The second is an electrochemical battery, connected at the building behind the meter through an inverter/rectifier. The goal of the storage is to reduce the electric demand during the 3-hour peak period in the evening, as indicated by the green line in Figure 1.

The experiment consists of a chiller, ice tank, a battery inverter, an emulated electrochemical battery, and a custom controller. The subsections below describe this equipment and its operation.

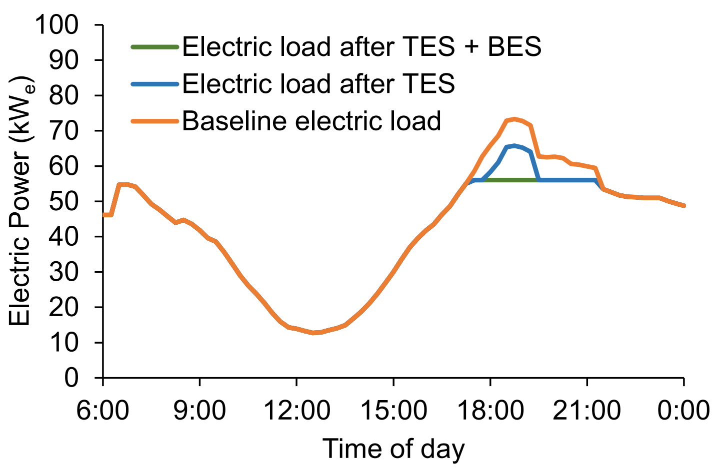

Figure 1: Baseline electric load profile, including electric load limit goal of 56 kW that is maintained by modulating the chiller, thermal storage, and battery storage. The goal is to shave an estimated 17 kW from the baseline case.

2.1 Chiller plant and ice tank

The chiller plant consists of a variable-speed Trane™ chiller and a Calmac™ ice tank (Figure 2). The chiller uses R410a as the refrigerant and has a nominal capacity of 30 tons (105 kW_{th}). The evaporator of the chiller cools a 30% propylene glycol loop, which is used for charging or meeting the building load, and the condenser rejects heat through a water loop. The ice tank is filled with water, which is frozen or melted with the 30% glycol fluid within a large, internal plastic heat exchanger. The ice tank has a nominal capacity of 162 ton-hr (570 kWh_{th}).

The plant is connected to two heat exchangers: one on the glycol loop (blue line), and one on the condenser water loop (red line). The first heat exchanger imposes a simulated building thermal load by connecting to a laboratory heat source. The temperature returning from the load heat exchanger is controlled through a modulating valve on the research hot-water side of the heat exchanger. The second heat exchanger provides a simulated heat sink to reject the condenser heat, such as a cooling tower. On the glycol side, there are three valves. The load bypass valve is open when the chiller charges the ice tank, and bypasses the load. The chiller bypass is used when the ice tank is used to meet the entire cooling load. The ice-mixing valve tempers the cold glycol exiting the ice tank so that the temperature going to the load is at the setpoint (~5.5 °C or 42 °F).

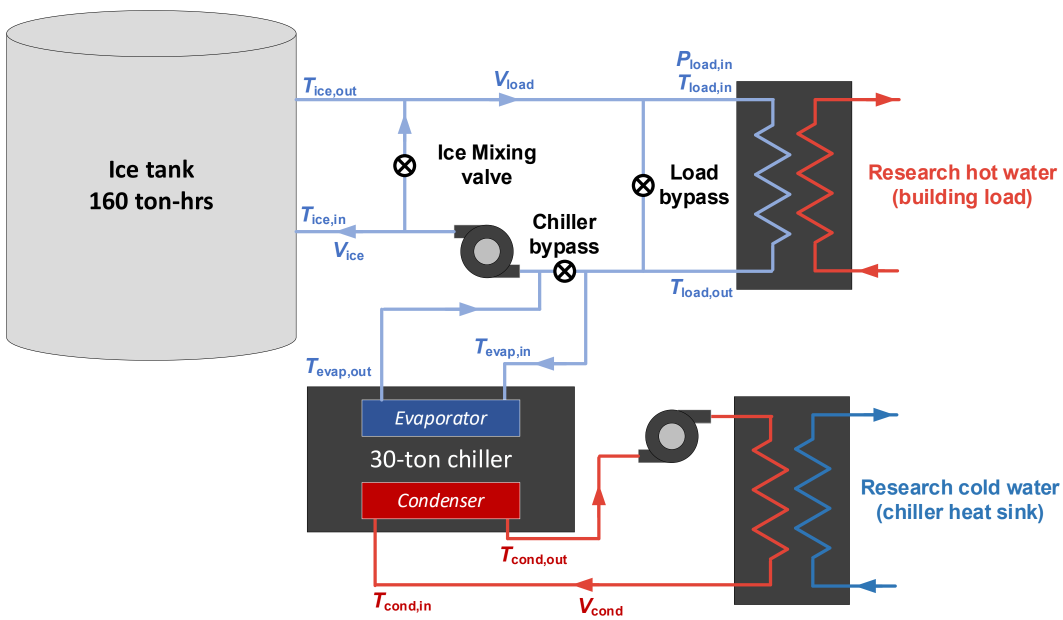

Figure 2: Chilled water plant with ice storage tank. System is modulated through chiller speed and the ice mixing valve. The building load heat exchanger simulates a realistic building load by controlling return glycol temperature to the plant, while the heat sink simulates a ooling tower by controlling return water temperature to the condenser.

2.2 Battery emulator with inverter

Figure 3 shows the battery system, along with data acquisition and control, which is discussed in the next section. The battery system consists of two components: a DC battery emulator, which is a 600-V DC power source / sink controlled to act like a 30 kW Li-ion battery with a 40 kWh capacity, and a grid-forming inverter / rectifier that either inverts DC power to 480 VAC power, which emulates the discharge of a stationary battery, or rectifies AC power to DC power, which emulates the charging of a stationary battery.

The power to/from the battery emulator is connected to a 480 VAC circuit, which is the same panel that the chiller, glycol pump, and condenser water pump are connected to. Power meters in the electric panel measure the electric power to/from the inverter, and therefore includes inverter losses, as well as the electricity for the pumps and chiller. To ensure experiment timing and execution, a real-time data acquisition and control handles the data intensive tasks of the experiment (e.g. analog and digital communications, and control loops). This control system communicates with the battery emulator using a TCP/IP interface, and dictates how the battery emulator should operate. Charging and discharging of the battery is controlled through a MODBUS TCP interface with the inverter/rectifier. Controller details are discussed in the next section.

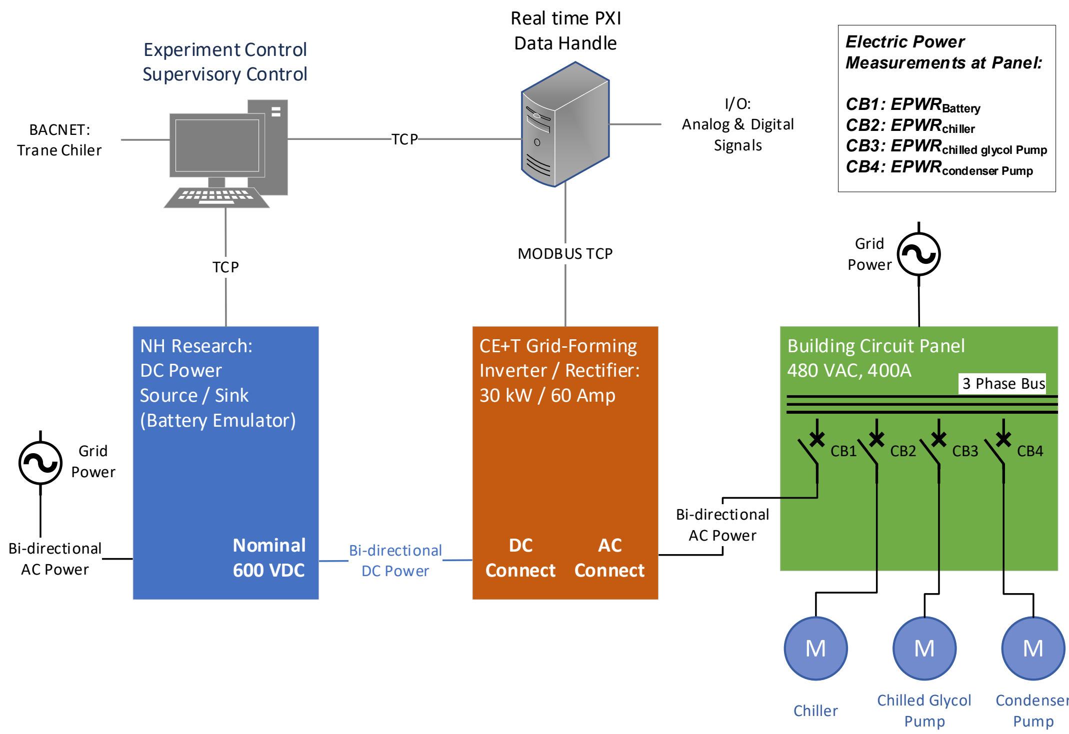

Figure 3: BES emulator system draws power from the grid to simulate a battery. The 600 VDC bus connects to the inverter/rectifier that interfaces with the building's circuit panel. The experiment and supervisory control system manage the experiment using multi-faceted communications network of analog and digital signals.

2.3 System controls

A supervisory controller is used to control the battery inverter and chiller (Figure 4). The chiller plant consists of onboard system controls that manage real-time operation. Supervisory control setpoints are communicated to the plant to select its mode of operation and chilled water temperature setpoint via BACNET communication protocol. The supervisory controller is shown in the upper left corner of Figure 4. It receives the non-HVAC building electric load, the desired electric load setpoint, and the chiller electric power. The controller determines the setpoints for the battery and chilled water plant, and selects the chiller mode. The two modes used here are "chiller-only" mode, which is used when there is no load shifting required (building electric load < building electric power limit) and "hybrid discharge," where the system operates the chiller and the ice tank simultaneously to meet the building load.

The controller converts the electric load shaving required to a setpoint for the chiller outlet temperature (between the chiller and ice tank; $T_{evap,out}$ in Figure 2). In parallel, an experiment controller sends a signal to the fluid conditioning module, which controls the imposed load on the chilled glycol loop based on a simulated building thermal load (see Section 2.1). The chiller capacity ramps up or down as the temperature setpoint or imposed load changes. The plant controller operates the ice mixing valve such that the plant output matches the imposed thermal load. Proportional-integral control is then used to adjust the electric power setpoint for the battery inverter and this chilled water temperature setpoint for the chiller.

Chiller modulation is the primary method to affect plant electrical load. The chilled glycol and condenser pumps in plant systems often have rule-based operation based on chiller load and internal process parameters. Chiller modulation is generally a slow process compared to battery systems with limitations in modulation range. As will be shown in the results, the modulation of the chiller plant is generally limited to 60-100% of full capacity. Furthermore, upon step changes in chiller setpoint, the settling thermal delivery time can be up to 10 minutes. The slow operation of the chiller can be compensated by using the much faster acting discharge of a battery system. The settling time of the AC power output of the emulated battery system is less than 5 seconds (which is dictated by the internal software of the inverter/rectifier).

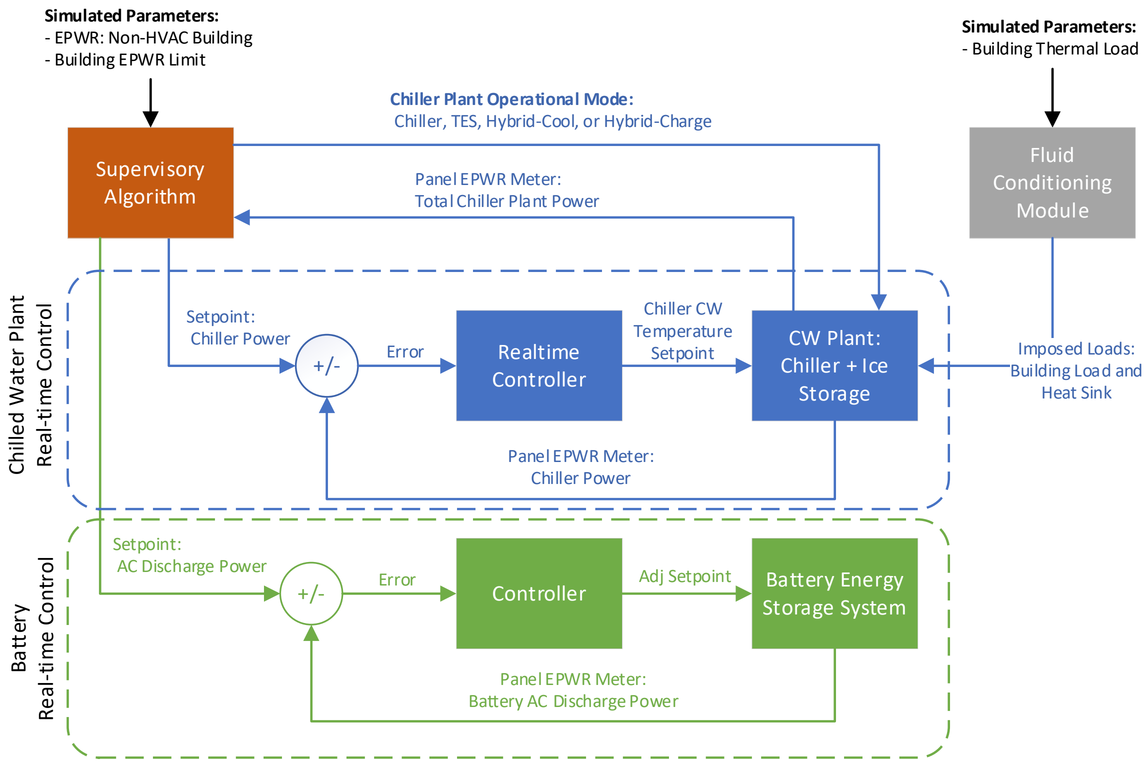

Figure 4: A supervisory control algorithm uses HVAC and non-HVAC electric power signals to determine how to run the chilled water plant and battery energy storage system. The supervisory controller also performs real-time feedback control for accurate setpoint following. The FCM simulates the building load and heat sink.

3. EXPERIMENTAL RESULTS

3.1 Discharging experiment

We ran the experiment for simulation hours 17:00 to 20:15 (5pm to 8:15pm), at which time the supervisory controller coordinates the chiller modulation, thermal storage dispatch, and battery operation to match the target thermal and electric load profiles. Figure 5 shows the chiller plant performance during the experiment. The chiller speed modulates from 100% down to 30% at first, but the chiller internal controller issues a step-change increase to 60% at about 18:30 (Figure 5(a)). The chiller no longer modulates below 60% for the remainder of the experiment.

Also shown in Figure 5(a) is the chiller's coefficient of performance (COP) which trends upward as the chiller is modulated down. This is a desirable feature when in hybrid mode to save electricity and maximize the kWh of electric load shaving per kWh thermal load shifting. However, the limits of modulation for this particular chiller need further investigation to determine if speeds lower than 60% can be more readily used. In Figure 5(b), the thermal cooling delivered by the chiller plant and the split between the chiller and thermal storage is shown. The chiller plant maintains the desired chilled water temperature by modulating the ice mixing valve (described earlier).

Figure 6 shows the resulting electric load profile of the experiment. The electric power (EPWR) of the building is shown with and without the use of storage (battery and thermal). The data shows the system shaved 20 kW_e of electric power with the supervisory control scheme developed during this experimental phase. Integration of power shows 35.3 kWh_e of total shaved electric energy (25.0$_e$ kWh from thermal storage and 10.3 kWh_e from the battery).

Also shown is the electric load profile of the chiller plant and battery storage. These loads, measured at the electric panel, show the chiller modulating from 23 kW_e down to 6.8$_e$ kW before rising back up to 12.3$_e$ kW after 18:30 (due to the chiller modulation increasing up to 60%). Despite this unpredictable behavior, the battery was quickly modulated to compensate. The battery discharged at about 9.8 kW_e to 10.8 kW_e, which is in line with the expectations (Figure 1).

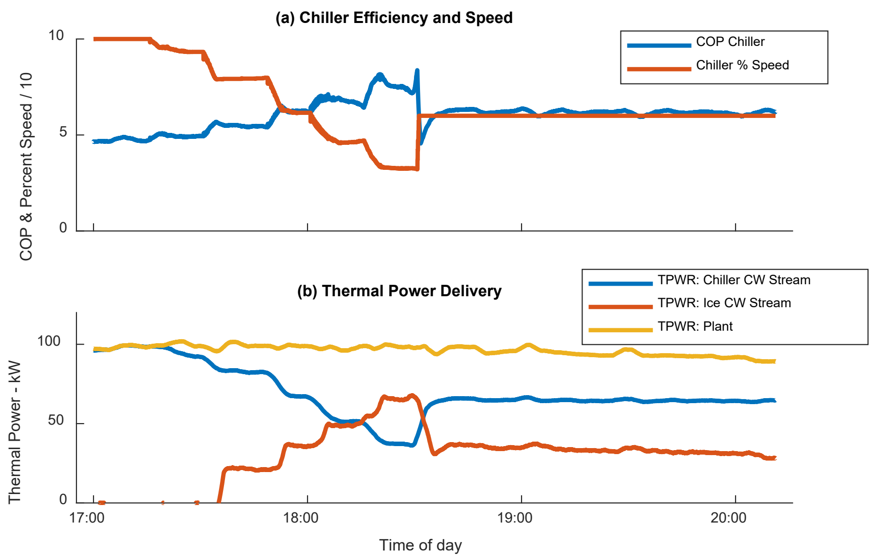

Figure 1: (a) Chiller speed and efficiency, and (b) the chiller plant's thermal load split.

Because the chiller cannot modulate below ~50-60% capacity, this limits how the chiller can respond to a load reduction signal. One option is to switch to Mode 3 (ice discharge), which shuts off the chiller. The second option is to maintain the partial capacity for the chiller and have the battery shave the remaining electrical load. The latter allows precise following of the desired electric load profile, such that the ice tank is not emptied prematurely. It also allows the chiller to operate at partial capacity, improving chiller efficiency. Finally, it enhances the ability of the chiller to respond up or down to changes in building load, since on/off cycling of large equipment is limited by manufacturer controls to ensure vapor always enters the compressor, and to extend compressor life. The next section describes further the advantages of chiller modulation during thermal storage discharge.

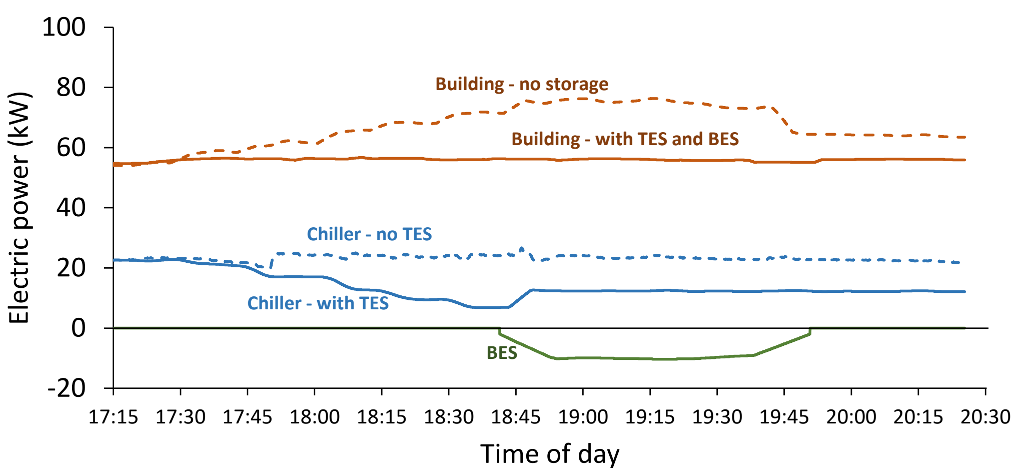

Figure 6: Electric power of the building without storage (dashed lines) and with storage (solid lines). The orange lines show the total building electric power, the blue lines show the chiller electric power, and the green line shows the battery power (negative = discharge). TES = thermal energy storage; BES = battery energy storage

4. DISUCSSION

In this section, we explore possible alternatives to the hybrid battery + thermal storage system that was tested, and discuss pros and cons of the different approaches. The options include: (1) No behind the meter storage, (2) Behind-the-meter electric batteries only, (3) Behind-the-meter thermal energy storage only, (4) Hybrid system with thermal storage and electric batteries.

The first option would require additional storage in front of the meter (i.e., on the electric grid). This type of storage is in use today, and has the advantage of not requiring distributed storage at multiple buildings. For example, grid-scale battery storage typically has a capacity of at least 1 MWh, meaning it is, in general, less expensive than behind-the-meter battery storage. However, these batteries are still more costly than behind-the-meter thermal storage, and also use expensive and rare metals such as lithium and, in some cases, cobalt. A second disadvantage is that grid-side storage does not allow for any resilience at the building, such as using batteries for backup power.

The other three options include the use of storage located at buildings (i.e., behind the electric meter). This has the potential to provide resiliency for buildings, and also to limit the electrical upgrades required due to increased load from electric vehicle charging and heating electrification.

If selecting behind the meter storage, there are many considerations between using electric batteries or thermal storage, or a combination:

- Coincidence of thermal load with peak electric load
- Costs (upfront cost and/or levelized cost)
- Overall weight and volume
- Environmental concerns from material sourcing or disposal

The first consideration is because thermal storage requires a thermal load. In the use case explored here, this is a cooling load, but it could also be a thermal load for space heating, water heating, or refrigeration. In many climates in the US, the peak is caused by electricity for space cooling, making the ice storage used here a good option. Water heating and refrigeration are year-round loads that often coincide with the electric peak. Space heating may cause the peak in the future due to heating electrification, particularly in colder climates (Waite and Modi, 2020).

In this paper, we primarily investigate the second consideration: the upfront cost for battery and thermal storage. The upfront cost (or price) to install behind-the-meter thermal or battery storage depends on many factors. Behind-the-meter battery storage costs are expected to fall as battery production increases, but by how much and when is unclear. As of 2023, the costs of utility-scale storage are ~\$480/kWh_e (Cole and Karmakar, 2023). For behind-the-meter storage, there is less data. As an example, we looked into installing two Tesla Powerwalls, with total capacity of 27 kWh_e. The listed price, including installation, is \$833/kWh_e (Tesla, 2024). Installations for commercial buildings are likely less expensive, due to lower balance-of-system costs per kWh_e. Recently advertised prices for a 232-kWh_e Tesla Powerpack came to \$538/kWh_e (Klender, 2020), which likely does not include installation.

The cost of thermal energy storage also depends strongly on the application, the specific building, and the HVAC system type. The theoretical cost of ice storage is low since the primary storage material is water. But there are other costs for integrating the storage, including valves and extra piping, as well as the storage container, insulation, heat exchanger, and the installation cost. The ASHRAE Design Guide for Cool Thermal Storage indicates a cost of \$43-57/kWh_{th} for the storage tank. Discussions with representatives from ice storage and chilled-water storage companies indicated a similar price. However, the total system cost is higher when including the balance of system components mentioned above. Multipliers of 1.5-2x higher than the storage only cost were mentioned in discussions with thermal storage companies. Here we use a cost of \$100/kWh_{th}, which is the same as that used by (Brandt *et al.*, 2022).

We must distinguish between costs on a kWh_{th} and kWh_e basis. This makes the efficiency of the chiller (or other HVAC&R equipment) that connects with the thermal storage critical to evaluating the different storage options. Electric resistance heating, with a COP of 1.0, means the thermal cost (\$/kWh_{th}) and electric cost (\$/kWh_e) are equivalent. A high efficiency application, such as cooling in a mild climate, may result in a COP of 4.5, which would mean the \$100/kWh_{th} thermal cost would be equivalent to \$450/kWh_e electric cost. This is because every 1 kWh_{th} of thermal energy that is met with the ice tank, reduces the thermal capacity met by the chiller by 1 kWh_{th}, which is equivalent to 0.2 kWh_e (for a COP of 5).

Based on the performance of the 30-ton chiller, we can estimate the upfront cost of the thermal storage, in \$/kWh_e, and compare it to the cost of an electric battery. Because the chiller operating at part load is more efficient than operating at full load, the equivalent cost must consider both the COP of the *baseline operation*, which is the efficiency of the chiller if it would have operated for the full load, and the COP of the chiller operating at part load as the ice tank meets the remainder of the cooling load.

$$\frac{\$}{kWh_{e,eq}} = \frac{\$}{kWh_{th}} \frac{Q_{TES}}{\left(\frac{Q_{load}}{COP_{baseline}}\right) - \left(\frac{Q_{chiller}}{COP_{part-load}}\right)} \tag{1}$$

where the total thermal load is split between that still met by the chiller, and that met by the thermal storage:

$$Q_{load} = Q_{chiller} + Q_{TES} \tag{2}$$

Here, Q_{TES} is also the capacity of the thermal storage.

Figure 7(a) shows the thermal storage first cost, based on an equivalent electrical capacity, compared to battery storage. We've shown two battery first cost estimates. One is based on an estimate of today's battery costs for behind the meter storage ($600/kWh$_e$), while the other assumes a first cost that is 33% lower ($400/kWh$_e$). Based on cost projections for utility-scale batteries, this cost reduction is projected to take about 10 years (Cole and Karmakar, 2023). The thermal storage cost for a system that is only thermal storage ($Q_{TES}/Q_{total} = 1$) is $440/kWh$_e$, which is simply the $100/kWh$_{th}$ times the baseline COP ($COP_{baseline} = 4.4$).

A hybrid system, which allows the chiller to operate at partial load and with a higher evaporator temperature, improves the chiller efficiency. This increases the effective electrical capacity of the ice tank and lowers the electrical equivalent first cost. Operating at 60% chiller capacity, with 40% thermal storage (as in the example above), the electric equivalent first cost for the thermal storage drops by 25% from $440/kWh$_e$ to $338/kWh$_e$.

If the peak power reduction in unimportant, and instead the focus is simply on shifting electric energy, then this 25% lower cost would be the cost for a thermal-storage only system. However, if the peak power reduction is also important, then the remaining load would be reduced by an electric battery. This situation is shown in Figure 7(b), which plots the total hybrid system storage cost for two battery first cost estimates. Based on today's cost estimates, it appears that the thermal storage only system ($Q_{TES}/Q_{total} = 1$) is still the least expensive option. However, if electric battery costs drop to $400/kWh$_e$, then the hybrid system becomes the lowest first cost option. Specifically, reducing chiller capacity to 60% with thermal storage like the example above results in a first cost of $375/kWh$_e$ versus $440/kWh$_e$ for thermal storage only or $400/kWh$_e$ for electric battery only.

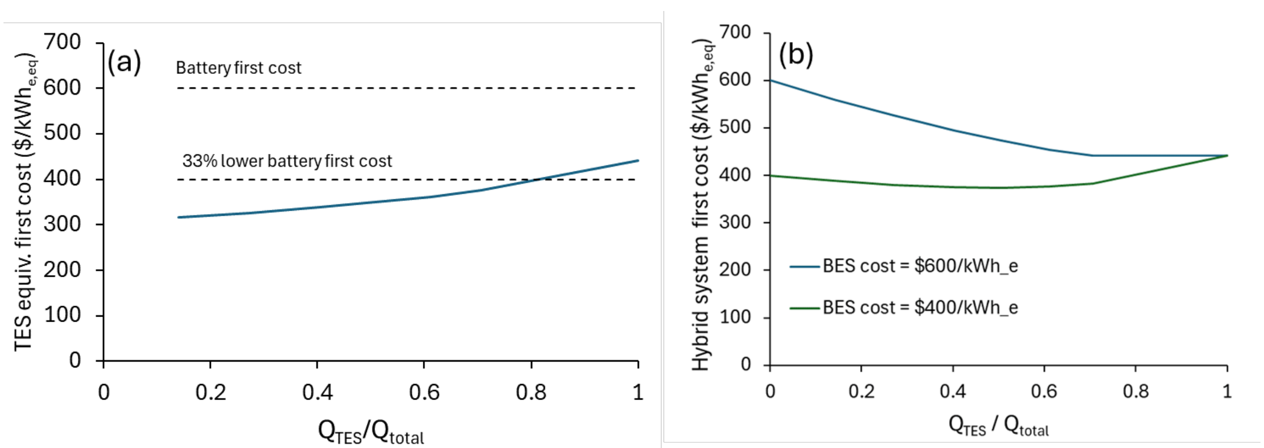

Figure 7: (a) Thermal storage first cost per kWh of electricity equivalent capacity, (b) Total hybrid system first cost per kWh of electricity equivalent capacity

Note that this analysis is different than the effective round-trip efficiency being above 1, due to efficient charging of the thermal storage. Effective roundtrip efficiencies above 1 are possible by offsetting a low COP during hot ambient conditions with a high COP during charging. Although freezing ice requires low evaporator temperatures, charging while the ambient temperatures are low at night can lead to less energy use than running the chiller during the hot afternoon.

Finally, we explore how other applications may be similarly compared to battery storage. The effective COP of the baseline equipment can drastically change the equivalent electric storage cost. This is shown in Figure 8, which looks at different applications. However, note that we've continued to use the $100/kWh$_{th}$ first cost for the thermal storage, which may not make sense for some applications (e.g., heating may be better suited to a different transition temperature than the T_t = 0 °C of water).

Figure 8 shows that cooling applications, with their relatively high baseline COPs, have higher electric equivalent first costs compared to other applications. Heating in cold climates and refrigeration in hot climates have baseline COPs that are roughly half that of cooling, and therefore the electric equivalent first cost is also about half that of cooling applications. Electric resistance heating is in general an inefficient option for space heating, with high operating costs, but it is used today as backup heat for some heat pumps. Therefore, thermal storage that avoids backup electric resistance heating in a heat pump system has the potential for a low electric equivalent first cost.

Thermal storage for cooling applications are one of the most mature thermal storage technologies and therefore may still compare favorably with battery storage or other applications, until the first cost of the thermal storage for these other applications becomes lower as it matures.

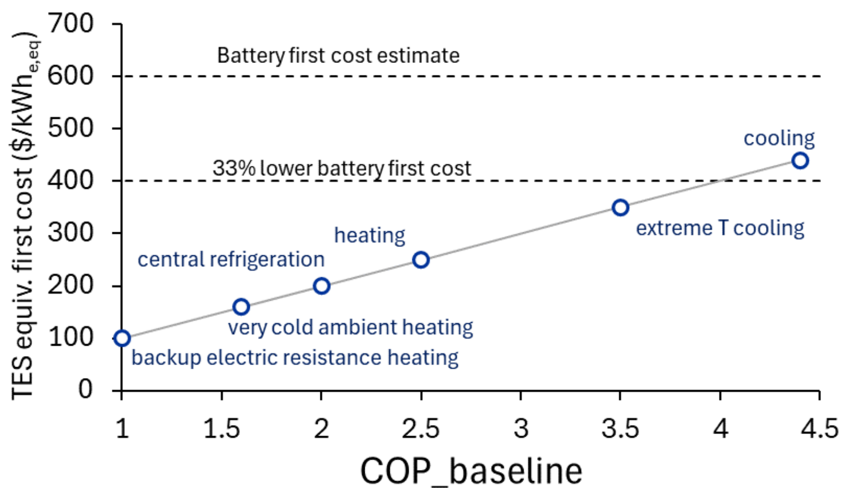

Figure 8: Thermal storage electrical-equivalent first cost as a function of COP for the baseline equipment. Approximate location for certain HVAC&R applications are shown with the blue circles.

6. CONCLUSIONS

In this paper, we explored combining battery and thermal storage through an experimental demonstration, as well as a theoretical analysis.

- Thermal energy storage with variable speed chillers are well suited to load-leveling applications with relatively slowly changing discharge rates.
- Because of internal controls in some chiller equipment, electric batteries are better suited to follow quickly changing discharge rates.
- Combining battery and thermal energy storage has been shown to have several benefits. One benefit demonstrated here is the improvement of chiller efficiency during discharge (~25% improvement is shown here).
- Because it is always still on, the chiller's ability to respond to ramp up or ramp down signals is enhanced, since on/off cycling of large equipment is difficult.
- Thermal energy storage is likely less costly than electric batteries today, and the above efficiency improvement reduces further the electric equivalent first cost of thermal storage relative to batteries.
- The COP of the HVAC&R equipment that thermal storage replaces is an important factor in determining the storage's electric equivalent cost. Applications that use heat pumps with larger lifts, and therefore lower COPs (e.g., space heating in cold climates), are better suited to thermal storage. The material and heat

exchanger costs for non-cooling applications is less clear though since some may require more expensive phase change materials.

- We have ignored the charging cost in the levelized cost of storage (Odukomaiya *et al.*, 2021), and focused instead on the capital cost. In general, the capital cost is more dominant than the charging cost. Future studies should include an investigation of the charging cost, O&M costs, as well as time value of money to estimate the full levelized cost of storage.

NOMENCLATURE

COP	coefficient of performance	(-)
HVAC&R	heating, ventilation, air conditioning, and refrigeration	
kWh_e	electric energy	(kWh)
kWh_{th}	thermal energy	(kWh)
Q	thermal load	(kWh)

Subscript

baseline	chiller operating in cooling only mode
chiller	load addressed by chiller
e	electric
e,eq	electric equivalent
part-load	chiller operating in part load mode while discharging TES
TES	load addressed by thermal storage
th	thermal

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