Equity, Electrification, and Time of Use (TOU) rates: Coupling Thermal Energy Storage with Heat Pumps for Improved Operational Efficiency

Sara Sultan, Oak Ridge National Laboratory
Kyle R. Gluesenkamp, Oak Ridge National Laboratory
Borui Cui, Oak Ridge National Laboratory
Zhenning Li, Oak Ridge National Laboratory
Samuel Ross, Optimal Energy at NV5

ABSTRACT

Heat pumps (HPs) performance is often limited by extreme outdoor temperatures during high demand periods, when utility costs are high. Time-of-use (TOU) utility rates are designed to reduce energy consumption during periods of high demand for a utility territory. An integrated storage system can enable HPs to operate efficiently during high price periods.

This paper presents an integrated thermal energy storage (TES) system coupled to a residential HP for demand management. A Phase Change Material (PCM) based TES is coupled to the vapor compression cycle of an air-source heat pump (ASHP). The TES acts as heat source or heat sink, increasing the HP capacity up to 50%, depending on the temperature difference between the TES and HP, and outdoor temperature.

A simulation analysis is performed for Sacramento, CA using TOU utility rates from SMUD. A model of a smart thermostat continuously monitors and responds to indoor temperature fluctuations, utility price signals, and TES state of charge. TES stores energy during off-peak times to be discharged later at peak times, hence improving the ability to respond to price signals and benefiting the operational cost for HP owners.

An HP with TES aligns with broader energy efficiency goals and fosters equity by enabling residential customers to respond to TOU rate designs more effectively. Increased operational costs contribute to challenging HP customer economics and are typically not offset by incentive programs that focus on up-front costs. Pairing TES with HPs can help overcome this operational cost barrier and increase access to HPs for all residential customers.

Introduction and Background

Buildings contribute significantly to global warming and energy consumption, accounting for approximately 40% of the U.S. energy consumption (U.S. EIA 2020), 75% of the total electricity consumption and 78% of the 2:00–8:00 p.m. peak electric usage periods (Goetzler, Guernsey, and Kassuga 2019b; Center for Sustainable Systems 2021). According to the U.S. Department of Energy, the electricity consumption during peak periods is even more pronounced in the residential sector, where heating and cooling applications consume nearly half of the total energy. This highlights the criticality of addressing this energy demand, both from an economic and environmental standpoint (Goetzler, Guernsey, and Kassuga 2019a).

In the United States, 90% of the homes are air conditioned (U.S. Energy Information Administration - EIA, n.d.). Since as much as 50% of the electricity demand for the grid comes from residential buildings, it is critical to reduce AC energy use during peak periods. ((Cui et al. 2017; Arteconi, Mugnini, and Polonara 2019; Chen et al. 2018; Jensen et al. 2017; Junker et al. 2018).

More than 44% of the houses in U.S. were built before 1970, as reported by the U.S. Census Bureau. Majority of these houses were constructed according to outdated standards (Sarkar 2011). As a result, Heat Pumps (HP) are essential for regulating humidity and temperature inside these houses. Although renovating the house or fully upgrading the conventional HVAC equipment is a large expense, HP are adaptable to respond smartly to changes in peak demand.

Time-based utility rate structures, including time-of-use (TOU) and real-time pricing (RTP), are increasingly accessible to residential customers. These structures adjust electricity prices throughout the day based on factors such as climate, seasonal demand, the utility's energy generation mix, and expected demand in a time window. On-peak hours have the highest electricity prices and typically occur in the mid-to-late afternoon during summer in warmer climates and in the early-to-mid morning during winter in colder climates. TOU rates vary significantly across the United States, and they typically remain fixed during the contract period.

Previous studies highlight the potential for reducing HVAC loads and associated costs through controls based on time-based utility pricing, without incorporating storage systems. A variety of factors including utility rate structure, weather conditions, occupancy, and thermal capacity of buildings can reduce electrical utility costs and peak energy demands associated with air conditioning (Newsham and Bowker 2010). Yoon et al. (Yoon, Baldick, and Novoselac 2016) found that controls could reduce HVAC loads by up to 24.7% and save up to 10.8% in costs, maintaining thermal comfort. Similarly, Schibuola et al. (Schibuola, Scarpa, and Tambani 2015) demonstrated that heat pump control based on real-time pricing (RTP) could achieve up to 30% savings on electricity consumption costs.

Recent advancements suggest that the combination of HP with TES, employing Phase Change Materials (PCMs) in various configurations, can optimize energy storage and reduce operational costs. Active TES systems, which are directly coupled to HVAC systems to respond to control signals, are particularly promising for peak demand reduction due to their ability to control the charge and discharge cycles in response to energy pricing and thermal demands. These systems can be integrated into existing buildings with minimal additional infrastructure, highlighting their flexibility and efficiency (Sara Sultan, Gluesenkamp, and States 2021). The US Department of Energy’s *Grid-interactive Efficient Buildings* report (Goetzler, Guernsey, and Kassuga 2019b), emphasizes that consumers facing demand charges or time-of-use rates could benefit the most from adopting TES technology.

PCM-TES systems can be implemented in various configurations, categorized into passive and active systems. Passive TES systems, which operate without direct interaction with HVAC systems or control schemes, can still contribute to reduced building energy consumption despite facing challenges like complex installation, material encapsulation, and spatial constraints (Soares et al. 2013; De Gracia and Cabeza 2015; Akeiber et al. 2016; Sonnick et al. 2020; Arivazhagan et al. 2020). Such systems lack the ability to actively manage energy for peak demand reduction due to their non-interactive nature (Sara Sultan et al. 2022; Chavan, Rudrapati, and Manickam 2022; Kurdi et al. 2021; Amberkar and Mahanwar 2023; Rahman and Habib 2022; Sepehri 2022).

This paper focuses on active TES systems that integrate with HVAC systems to dynamically respond to energy pricing and thermal demands. These systems offer enhanced control over energy storage efficiency by allowing precise management of charging and discharging cycles through dedicated controller hardware. Active TES systems are characterized by their adaptability, enabling installation within existing building infrastructures without substantial modifications. These systems are designed to be programmable via the thermostat, facilitating user control over the thermal energy exchange process in response to specific cooling or heating needs.

The integration of active TES with HP represents a significant advancement, offering a programmable solution that optimizes energy use and efficiency. The ability to seamlessly integrate TES into existing HP equipment, without extensive construction, positions active HP-integrated TES (HP-TES) configurations as a flexible and efficient approach to improving building energy performance and management (Sara Sultan, Gluesenkamp, and States 2021).

Zhu et al. (Zhu et al. 2011) explored how demand-limiting control strategies with Phase Change Materials (PCM) in time and demand-based pricing affect energy consumption and costs in air-conditioned buildings, finding an 11% cost reduction and 20% peak load decrease through load shifting.

Bruno et al. (Bruno, Tay, and Belusko 2014) saved energy by using PCM for off-peak domestic cooling. They argued that while about 85% of the cooling energy could be off-set using ice-based system, the overall energy demand can be increased by 7.6% due to the exergy loss for using TES. PCM with melting point above 4°C proved to be effective but with an increased energy usage for efficient TES. They suggested to optimize the charging time and duration depending on the outside temperature, to minimize the energy usage.

Tyagi et al. (Tyagi et al. 2016) assessed the thermal performance and economic evaluation of PCM encapsulated thermal management system equipped with air conditioning, to reduce the cooling peak demand by offsetting the peak time cool energy. The proposed system was tested for the hot climate of India by discharging 3 different heat loads, and authors suggest that the system can proved to be economical and efficient in hot and humid areas around the World.

Chaiyat (Chaiyat 2015) and Chaiyat and Kiatsiriroat (Chaiyat and Kiatsiriroat 2014) improved HVAC cooling efficiency with PCM storage under Thailand's climatic conditions, achieving a 3.09 kWh/day reduction in electricity use and a 9.1% cost saving, with a payback period of 4.15 years. The PCM was solidified during nighttime by the cold air from the evaporator outlet, while during the daytime, return air from the room was passed through the PCM, liquifying it and reducing the cooling load at the evaporator.

Real et al. (Real et al. 2014) enhanced heat pump performance using PCM in two thermal tanks for hot and cold storage, demonstrating an 18.97% energy savings, though the need for real-world validation was noted.

The literature collectively affirms the effectiveness of integrated PCM-based active TES systems in shifting energy demand to off-peak times and their financial viability in regions with high on-peak electricity prices and significant cooling demands (Liu, Saman, and Bruno 2012; Waqas et al. 2018).

This research aims to bridge the gap by integrating TES systems with residential HP for efficiency improvement, cost savings, and equitable access by leveraging state energy efficiency programs. We use a novel configuration where PCM-TES does not directly control the building’s temperature or provides direct heating or cooling. Instead it helps the HP as a heat source or sink. This makes it easy to integrate with existing heat pump systems and is especially useful for homes, where even small TES units can significantly reduce peak energy usage.

The objective of this study is to investigate the impact of integrating a thermal energy storage (TES) system with a residential heat pump (HP) on improving energy efficiency and reducing utility costs in residential buildings. Analyze the potential for utility cost savings and grid resilience benefits by employing real-time data controls and leveraging off-peak electricity rates. Assess the role of state and utility rebate programs in facilitating the adoption of HP systems, particularly among low-income communities.

This work aligns with DOE's goals to decarbonize and reduce demand by 2030. Commercialized HP-TES are expected to have a much broader impact on the research community as well as consumers. Residential homeowners will benefit from HP-TES' flexible installation, enabling them to use existing HP equipment for controls with a minimal footprint, while reducing installation and consumer costs.

This study models the heating and cooling load of a residential building in Northern California during a week of extreme temperatures, comparing scenarios with and without an active TES system. The TES, integrated with a vapor compression system (VCS), functions as the VCS condensing unit during peak hours, replacing the ambient air. A Time-of-Use (TOU) utility rate from Sacramento, California, is utilized to evaluate potential customer savings.

Methodology

This research employs a model integrating various components, including a building and an R-410a vapor compression system (VCS), with a PCM heat exchanger embedded in the heat pump to enhance the vapor compression process by facilitating energy transfer with the ambient environment. Indoor temperatures are regulated by thermostat controls, while an electric utility schedule manages the operation of the heat pump for heating or cooling and the charging or discharging of the TES based on TOU pricing. The study utilizes Typical Meteorological Year (TMY 3) weather data relevant to the building's ASHRAE climate zone in 3B.

The comprehensive system model, executed in MATLAB, includes a building model, a vapor compression heat pump model, and a TES system featuring PCM as a heat exchanger, alongside a thermostat model that employs rule-based controls determined by fixed TOU pricing. The details of each model are in the following sections. The PCM within the TES, not specific to any particular material, interacts exclusively with the heat pump, facilitating heat absorption from the condenser during summer peak hours and supplying heat to the evaporator in winter peak hours. The properties of PCM are described in the PCM-TES model in the upcoming section.

The study aims to assess the impact of integrating PCM-TES with heat pumps on peak and total energy consumption and overall energy costs, utilizing straightforward, rule-based controls against predetermined utility rates.

System Overview

This study contrasts two scenarios using TOU rates: a baseline without TES and a TES-enhanced case. The baseline employs an air source HP operating through a vapor compression refrigeration system for heating or cooling. In contrast, the TES modifies this system by integrating PCM-TES to improve performance, assuming an ideal infinite heat transfer coefficient for TES, which maintains a constant temperature throughout operation. The TES adapts its role as either an evaporator or condenser based on the HP's operational mode.

A simplified schematic is shown below in Figure 1. HP mediates the heat transfer and TES assists the operation without controlling the building’s temperature directly.

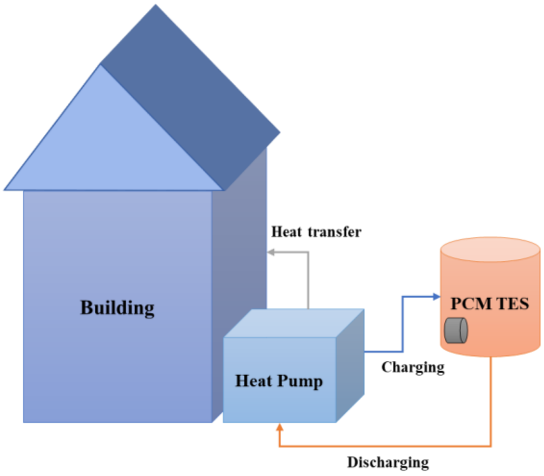
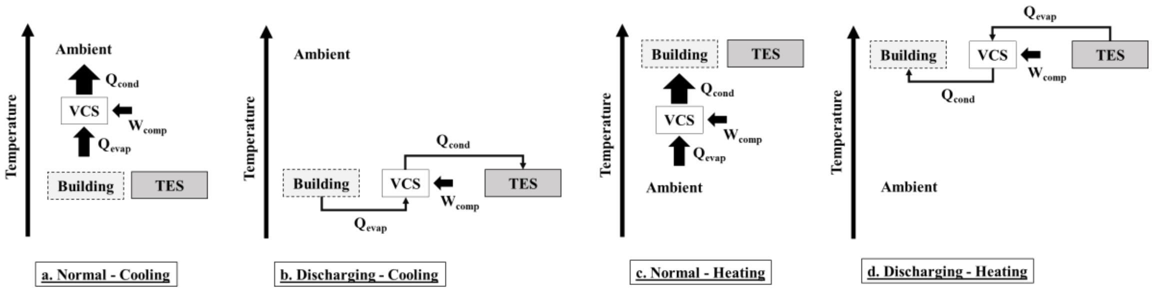


Figure 1: HP-TES in building

A illustrative representation of temperature gradients under normal VCS operations (baseline) versus TES-assisted operations for both cooling and heating modes is illustrated in Figure 2. For the baseline cooling mode (Figure 2A), the building is cooled using a conventional VCS, with the evaporator lowering indoor air temperature and the condenser releasing heat outdoors.

TES introduces an improved temperature gradient, enabling more efficient VCS operation through a negative temperature lift. In the TES-assisted cooling mode (Figure 2B), the VCS's condenser is linked to the TES's cooler temperature, creating a negative temperature gradient for removing the building's cooling load. Similarly, TES-assisted heating involves coupling the evaporator to the warmer temperature of the PCM, employing a negative gradient to transfer the heating load. This approach significantly enhances the VCS's performance over the baseline scenario (S Sultan et al. 2021).



a. Normal - Cooling

b. Discharging - Cooling

c. Normal - Heating

d. Discharging - Heating

Figure 2: Baseline and TES systems.

Operating Modes and Controls

The system operates in two primary modes: cooling and heating, each with four operational modes: normal, charging, discharging, and standby. Standby and normal modes do not involve TES. The baseline system does not use TES.

In normal mode, the building's temperature is regulated solely by the conventional operation of the HP. During cooling, the vapor compression cycle expels heat from the building to the ambient (Q_{cond}) while absorbing indoor heat (Q_{evap}) into the HP. In heating mode, this cycle reverses, capturing ambient heat for the HP and distributing warmth indoors.

Standby mode occurs when the HP and TES are inactive, and no thermal adjustment is necessary, with ambient thermal loads and solar heat gains occurring passively.

TES enhances cooling or heating in the charging and discharging modes. In the cooling discharging mode, the evaporator connects to the building for cooling, with the condenser linking to the TES, absorbing heat (Q_{cond}) via the latent heat of melting, resulting in a higher Coefficient of Performance (COP) than normal operation. During cooling charging mode, TES acts as the evaporator, shedding the latent heat of freezing, and expelling condenser heat to the ambient.

Operational mode selection is governed by a control decision tree (Figure 3), considering peak times, cooling needs, and the PCM state of charge (SOC). During off-peak times, normal mode operates conventionally. Charging mode, occurring in off-peak periods without cooling demand, replenishes TES by refreezing melted PCM, exploiting lower electricity costs and ambient temperatures. This mode can shift to normal if cooling is needed, ensuring indoor comfort. Discharging mode, activated during peak times for cooling, utilizes TES's latent heat from melting PCM to maintain a constant cold temperature. TES functionality ceases once all PCM is melted, necessitating a switch to normal mode for further cooling. Outside these operations, the system remains in standby.

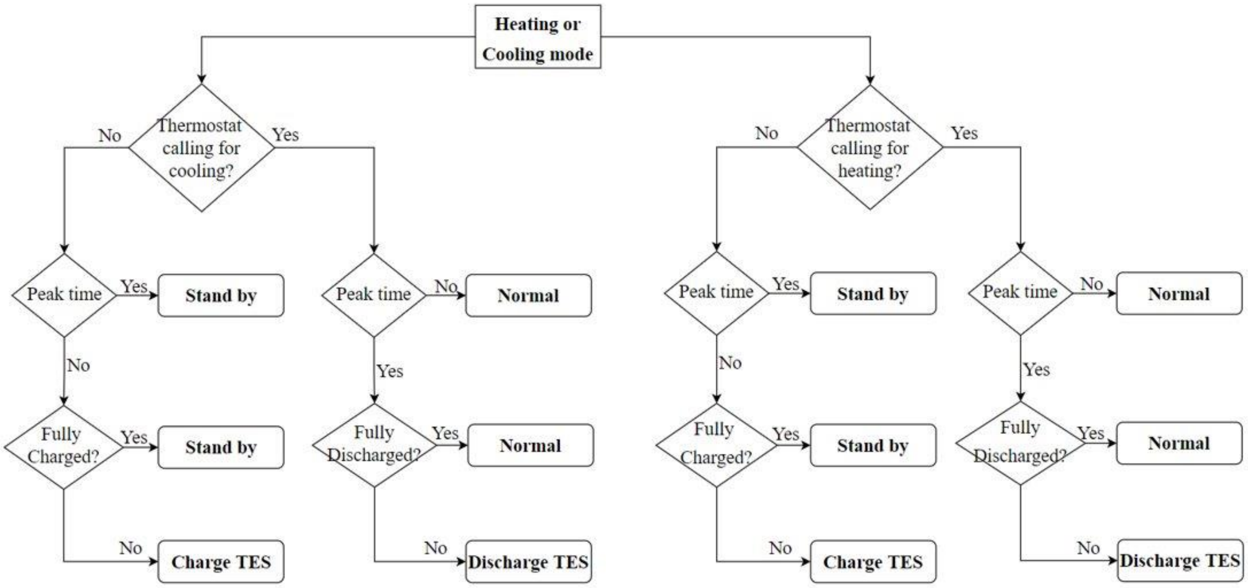


Figure 3: Controls Decision Tree

Weather Data and Utility Rate Analysis

Figure 4 shows dry bulb temperature versus utility rate on a hottest day in Sacramento, CA. The TOU utility schedule has two peaks for summer, mid peak and peak. Mid peak occurs between noon and 4 PM, the ambient temperature peak is within that timeframe. After 4 PM, the temperature begins to drop, which means the ambient temperature peak does not align with the utility peak.

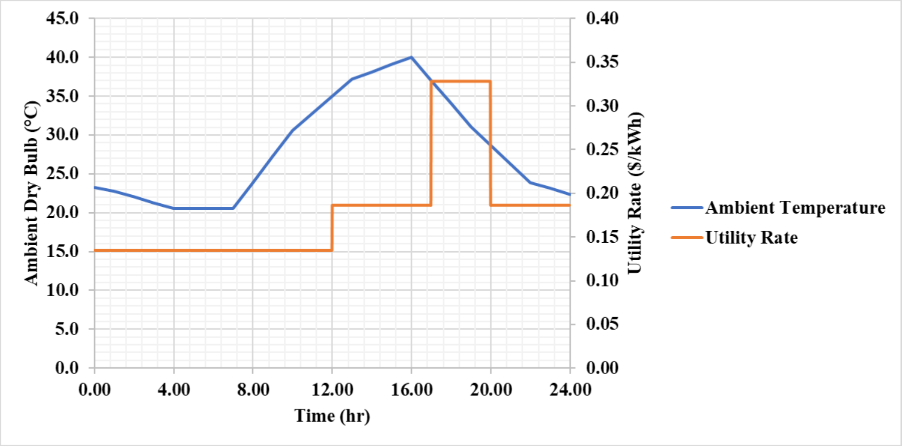


Figure 4: Ambient Weather and Utility Rate on the hottest day in Sacramento

Table 1 shows the utility tariff from Sacramento Municipal Utility District (SMUD) for Sacramento, CA.

Table 1: TOU Utility Schedule

Utility	TOU tariff			
	Tariff name	Mid-peak rate (¢/kWh)	On-peak rate (¢/kWh)	Off-peak rate (¢/kWh)
Sacramento Municipal Utility District	Time-of-Day (5-8 p.m.) Rate	19.67 (summer[1])	32.79 (summer[1]) 15.47 (Non-summer[2])	13.50 (summer[1]) 11.20 (Non-summer[2])

[1] June 1 – Sep 30
[2] Rest of the year

Thermostat Model

The thermostat regulates indoor temperature and signals VCS when heating or cooling is needed. TES control strategy decides whether to fulfill this demand through TES or conventional VCS operation linked to the ambient environment, considering the time of day and utility electricity rates. This strategy also guides the recharging of the TES, engaging the VCS to connect the TES with the ambient environment when conditions are favorable.

Building Model

An existing validated building model provided by Cui et al. (Cui et al. 2018; 2012; 2019) as a python code was integrated into the developed model as a MATLAB function. The model used equations from a validated RC building model by Cui et al. (Cui et al. 2018; 2012; 2019) and implemented in MATLAB. The model was trained with the field data for the smart home building at UC Davis. The properties for the PCM and building envelope were taken from Jason et al. (Hirschey 2022).

Heat Pump Model

A 2-ton HP is simulated in MATLAB using Coolprop. The basic vapor compression model calculates the COP for cooling and heating from the evaporator and condenser outputs and electric consumption by compressor. Equation 14 and 15 define cooling and heating COP, respectively.

$$COP_c = Q_{evap}/W_{comp} \tag{1}$$

$$COP_h = Q_{cond}/W_{comp} \tag{2}$$

The outputs of HP model, Q_{evap} from the evaporator and Q_{cond} from the condenser are called into the cooling and heating functions in MATLAB, where they are coupled to PCM-TES depending on the operating mode. The thermostat model is used to control the VCS and PCM state of use.

PCM-TES Model

HP vapor compression system interfaces with PCM through a Heat Exchanger (HX), utilizing an arbitrary salt hydrate PCM with a melting point of 20°C. The system's operational modes—charging, discharging, and standby—are determined by the PCM SOC, which depends on peak time periods and indoor temperature. These modes are selected through a control decision tree that dictates the system's operation.

Information Flow

Figure 5 illustrates the information flow within the model, which comprises several sub-models functioning concurrently to sustain a comfortable indoor temperature. This figure provides an overview of the total model's operational schematic and how information is exchanged among the sub-models. The entire model setup was developed in MATLAB, with a decision tree serving as the central control mechanism to coordinate the activities of all components.

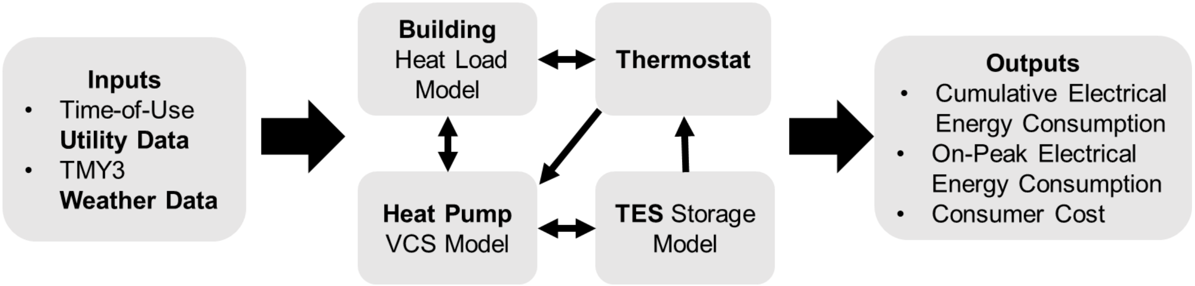


Figure 5: Information flow chart showing the submodels and direction of information flow.

Results and Discussion

Sacramento is a hot climate zone and analysis is performed for extreme temperatures. The graphs below show peak electric consumption and utility cost for an extreme week of summer. Due to space restrictions, winter extreme graphs are not shown here.

Energy Consumption

The Figure 6 compares baseline and TES electric consumption for peak hours and total (peak and non-peak) hours for the whole week. The y-axis shows the cumulative electric consumption in kWh against time on the x-axis. The on-peak consumption is represented by the dotted lines for both TES and baseline system, while the total represents both on-peak and off-peak hours during the day. The baseline system does not use TES but uses a TOU utility rate schedule for peak and off-peak hours, while the TES system uses a PCM-TES to provide necessary space conditioning during peak hours, essentially shifting the peak load.

TES is able to save peak demand by more than 50% but the total energy consumption is higher in TES case. This could be because of sub optimal control strategy that only depends on TOU rate rather than ambient temperature, resulting in energy losses due to frequent charging and discharging cycles. As shown in Figure 4 in previous section, the utility peak and ambient temperature peak are not aligned. This causes TES to operate even when ambient conditions are extreme and not favorable, hence more energy consumption. For instance, during summer, if the TES is hotter than the ambient air, using it for cooling will use more electricity than simply using the colder outside air to cool the home through heat pump (explained in Figure 2). For climate locations where TOU schedule aligns with ambient extreme temperatures, the savings are much more significant.

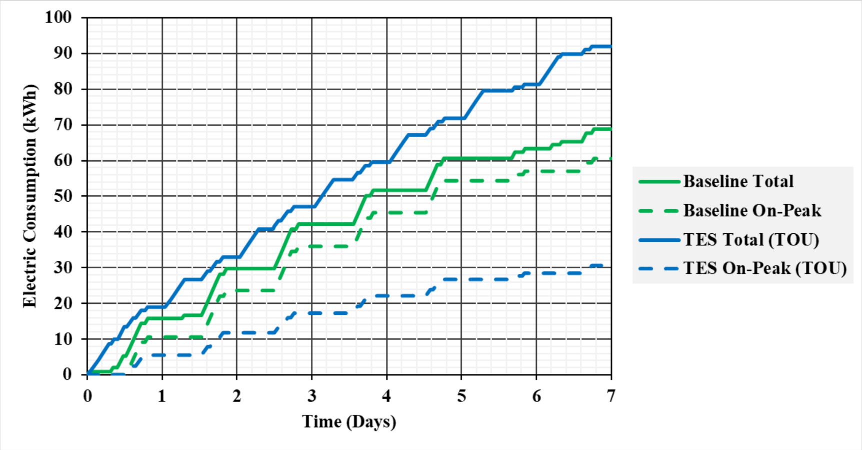


Figure 6: Electric Consumption

Cost Savings

The Figure 7 compares baseline and TES cumulative utility cost for both peak hours and non-peak hours for the whole week, during an week of summer with extreme temperatures in Sacramento. The y-axis shows utility cost in $ against time on x-axis. The on-peak cost is represented by dotted lines for both TES and baseline system, while the total represents both on-peak and off-peak hours during the day. The baseline does not use TES.

TES saved the cost associated with peak demand as compared to baseline. The on-peak cost in the TES case is 50% lower than that of baseline. However, the the total cost is a little higher than baseline because of increased energy consumption. Future study will include weather forecast in the controls logic, which can prevent that higher TES energy consumption.

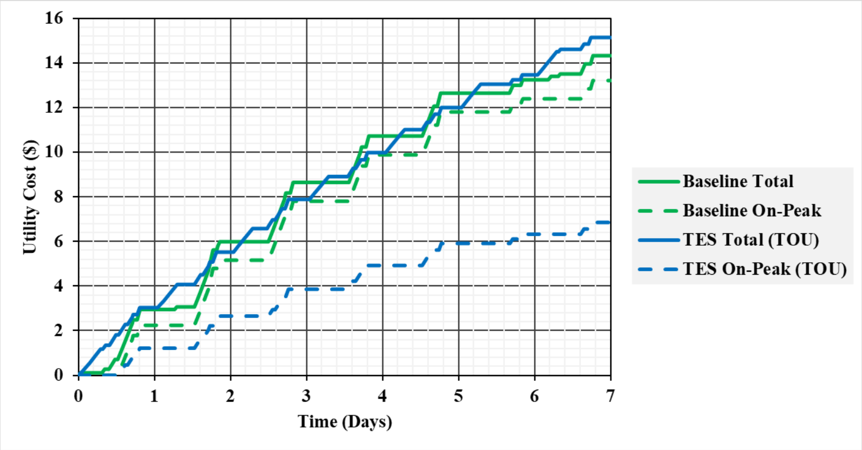


Figure 7: Utility Cost

Heat Pump COP

Figure 8 shows cooling COP values throughout the extreme summer week for baseline and TES. The system with TES has better COP as compared to baseline even in this worst-case scenario. This is because of the lower temperature difference since TES behaves as heat source or heat sink for HP. As explained in Figure 2, the integration of TES with HP reduces the temperature difference between the heat source and indoor space. The HP normally extracts heat from the outdoor, but extracting heat from the TES if it's warmer than the ambient, will require less energy. Hence, HP will have much better COP.

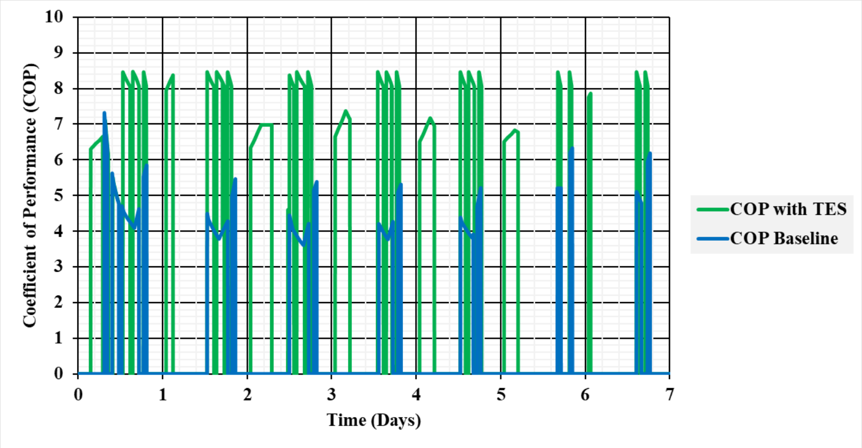


Figure 8: Heat Pump COP

For the configuration we chose for this study, PCM-TES does not directly regulate the building's temperature but is coupled to the HP as a thermal reservoir (heat sink/source). This configuration allows for easy integration with existing HP systems and offers significant benefits for residential applications, where even small TES units can provide notable peak reductions.

A previous study (S Sultan et al. 2021) documented 20% energy savings with a similar approach using an ice storage system in Fresno, California—a location characterized by large diurnal temperature fluctuations even during extreme hot week—TES systems are particularly effective in climates with significant daily temperature swings, reducing the temperature differential between the indoors and TES. The extent of cost savings and the shift in peak load depends largely on the timing of peak energy rates, ambient temperature and the specific heating or cooling needs of the building.

State Energy Efficiency Programs

In the state of California, residential rebates for heat pump installation represent a critical tool in the push for energy efficiency and decarbonization of heating solutions within residential sectors. These rebates, offered through various utility and government programs, are designed to lower the financial barrier associated with the upfront costs of heat pump systems, which are renowned for their efficiency and lower operating costs compared to traditional heating methods. Specifically, income-eligible households are positioned to significantly benefit from these incentives.

To encourage home energy retrofits, the Inflation Reduction Act of 2022 created two programs: Home Efficiency Rebates (HOMES), which help low-income households go electric with qualified appliance rebates, and Home Electrification and Appliance Rebates (HEEHRA), which help low-moderate income households go electric with whole-house energy efficiency retrofits. The strategic targeting of rebates towards income-eligible households facilitates the access to energy-efficient technologies but the increasing cost of utilities remains a challenge for the income eligible households. The need for innovative solutions is even more vital given the record breaking temperatures in 2024 have increased the energy demand. A 2% increase in electric demand has been forecasted by EIA in the second half of 2024 compared to same period in 2023. The expected climate change and economic conditions will further increase the demand and costs, putting the most vulnerable communities at more risk,

This study aims to conclude that HP-TES can play a crucial role in combatting economic challenges by reducing the energy demand and utility cost. State energy efficiency programs can propose initiatives that address the demand reduction scenarios in addition to heat pump rebates. This work aligns with broader equity goals, ensuring that the transition towards greener technologies is inclusive, enabling lower-income households to partake in the benefits of energy efficiency.

Conclusions

This research highlights the integration of Thermal Energy Storage (TES) systems, utilizing Phase Change Materials (PCMs), with residential heat pumps (HPs) to enhance energy efficiency and reduce utility costs, particularly during peak demand periods. The implementation of a smart thermostat and Time-of-Use (TOU) rates in a Sacramento, CA, residential scenario demonstrates the system's ability to store energy during off-peak hours for use during peak times, resulting in significant operational cost savings while also improving the system's overall performance and efficiency. Future research will focus on optimizing control strategies and incorporating weather forecasts to further enhance energy savings and operational efficiency.

The integration of HPs with TES not only aligns with energy efficiency initiatives but also enhances affordability and accessibility to efficient heating and cooling, overcoming the economic barriers often presented by higher operational costs and insufficient incentives. This approach broadens the reach of HP technology, making it a more viable option for diverse households.

Acknowledgements

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

References

Akeiber, Hussein, Payam Nejat, Muhd Zaimi Abd Majid, Mazlan A. Wahid, Fatemeh Jomehzadeh, Iman Zeynali Famileh, John Kaiser Calautit, Ben Richard Hughes, and Sheikh Ahmad Zaki. 2016. "A Review on Phase Change Material (PCM) for Sustainable Passive Cooling in Building Envelopes." *Renewable and Sustainable Energy Reviews* 60: 1470–97. https://doi.org/10.1016/j.rser.2016.03.036.

Amberkar, Tejashree, and Prakash Mahanwar. 2023. "Thermal Energy Management in Buildings and Constructions with Phase Change Material-Epoxy Composites: A Review." *Https://Doi.Org/10.1080/15567036.2023.2171514* 45 (1): 727–61. https://doi.org/10.1080/15567036.2023.2171514.

Arivazhagan, R., N.B. Geetha, P. Sivasamy, P. Kumaran, M. Kumara Gnanamithra, S. Sankar, Ganesh Babu Loganathan, and A. Arivarasan. 2020. "Review on Performance Assessment of Phase Change Materials in Buildings for Thermal Management through Passive Approach." *Materials Today: Proceedings* 22 (January): 419–31. https://doi.org/10.1016/j.matpr.2019.07.616.

Arteconi, Alessia, Alice Mugnini, and Fabio Polonara. 2019. "Energy Flexible Buildings: A Methodology for Rating the Flexibility Performance of Buildings with Electric Heating and Cooling Systems." *Applied Energy* 251 (May): 113387. https://doi.org/10.1016/j.apenergy.2019.113387.

Bruno, F., N. H S Tay, and M. Belusko. 2014. "Minimising Energy Usage for Domestic Cooling with Off-Peak PCM Storage." *Energy and Buildings* 76 (June): 347–53. https://doi.org/10.1016/j.enbuild.2014.02.069.

Center for Sustainable Systems. 2021. "Residential Buildings Factsheet." https://css.umich.edu/publications/factsheets/built-environment/residential-buildings-factsheet.

Chaiyat, Nattaporn. 2015. "Energy and Economic Analysis of a Building Air-Conditioner with a Phase Change Material (PCM)." *Energy Conversion and Management* 94: 150–58. https://doi.org/10.1016/j.enconman.2015.01.068.

Chaiyat, Nattaporn, and Tanongkiat Kiatsiriroat. 2014. "Energy Reduction of Building Air-Conditioner with Phase Change Material in Thailand." *Case Studies in Thermal Engineering* 4: 175–86. https://doi.org/10.1016/j.csite.2014.09.006.

Chavan, Santosh, Ramesh Rudrapati, and Selvaraj Manickam. 2022. "A Comprehensive Review on Current Advances of Thermal Energy Storage and Its Applications." *Alexandria Engineering Journal* 61 (7): 5455–63. https://doi.org/10.1016/J.AEJ.2021.11.003.

Chen, Yongbao, Peng Xu, Jiefan Gu, Ferdinand Schmidt, and Weilin Li. 2018. "Measures to Improve Energy Demand Flexibility in Buildings for Demand Response (DR): A Review." *Energy and Buildings* 177 (October): 125–39. https://doi.org/10.1016/J.ENBUILD.2018.08.003.

Cui, Borui, Jin Dong, Jeffrey Munk, Ning Mao, Teja Kuruganti, Herrick / Cui, Borui ; Dong, Jin ; Munk, Jeffrey ; Mao, and Ning ; Kuruganti. 2018. "A Simplified Regression Building Thermal Modelling Method for Detached Two- Floor House in U.S." In *International High Performance Buildings Conference*. https://docs.lib.purdue.edu/ihpbc/284.

Cui, Borui, Cheng Fan, Jeffrey Munk, Ning Mao, Fu Xiao, Jin Dong, and Teja Kuruganti. 2019. "A Hybrid Building Thermal Modeling Approach for Predicting Temperatures in Typical, Detached, Two-Story Houses." *Applied Energy* 236 (February): 101–16. https://doi.org/10.1016/J.APENERGY.2018.11.077.

Cui, Borui, Jeffrey Munk, Roderick Jackson, David Fugate, and Michael Starke. 2012. "Building Thermal Model Development of Typical House in U.S. for Virtual Storage Control of Aggregated Building Loads Based on Limited Available Information." In *PROCEEDINGS OF ECOS 2017 - THE 30TH INTERNATIONAL CONFERENCE ON EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS*. http://energy.gov/downloads/doe-public-access-plan.

———. 2017. "Building Thermal Model Development of Typical House in U.S. for Virtual Storage Control of Aggregated Building Loads Based on Limited Available Information." In *30th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2017*.

Dong, Jin, Bo Shen, Jeffrey Munk, Kyle R. Gluesenkamp, Tim Laclair, and Teja Kuruganti. 2019. "Novel PCM Integration with Electrical Heat Pump for Demand Response." In *IEEE Power and Energy Society General Meeting*. https://doi.org/10.1109/PESGM40551.2019.8973936.

Goetzler, Bill, Matt Guernsey, and Theo Kassuga. 2019a. "Grid-Interactive Efficient Buildings Technical Report Series: Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration."

———. 2019b. "Grid-Interactive Efficient Buildings Technical Report Series: HVAC; Water Heating; Appliances; and Refrigeration." http://www.osti.gov/servlets/purl/1577966/%0Ahttp://files/87/Neukomm et al. - 2019 - Grid-Interactive Efficient Buildings Technical Rep.pdf.

Gracia, Alvaro De, and Luisa F. Cabeza. 2015. "Phase Change Materials and Thermal Energy Storage for Buildings." *Energy and Buildings* 103: 414–19. https://doi.org/10.1016/j.enbuild.2015.06.007.

Hirschey, Jason. 2022. "Investigation of Inorganic Salt Hydrate Phase Change Materials for Thermal Energy Storage Integrated into Heat Pump Systems." https://smartech.gatech.edu/handle/1853/70179.

Jensen, Søren Østergaard, Anna Marszal-Pomianowska, Roberto Lollini, Wilmer Pasut, Armin Knotzer, Peter Engelmann, Anne Stafford, and Glenn Reynders. 2017. "IEA EBC Annex 67 Energy Flexible Buildings." *Energy and Buildings* 155 (November): 25–34. https://doi.org/10.1016/j.enbuild.2017.08.044.

Junker, Rune Grønborg, Armin Ghasem Azar, Rui Amaral Lopes, Karen Byskov Lindberg, Glenn Reynders, Rishi Relan, and Henrik Madsen. 2018. "Characterizing the Energy

Flexibility of Buildings and Districts.” *Applied Energy* 225 (April): 175–82. https://doi.org/10.1016/j.apenergy.2018.05.037.

Kurdi, Abdulaziz, Nasser Almoatham, Mark Mirza, Thomas Ballweg, and Bandar Alkahlan. 2021. “Potential Phase Change Materials in Building Wall Construction—A Review.” *Materials 2021, Vol. 14, Page 5328* 14 (18): 5328. https://doi.org/10.3390/MA14185328.

Liu, Ming, Wasim Saman, and Frank Bruno. 2012. “Review on Storage Materials and Thermal Performance Enhancement Techniques for High Temperature Phase Change Thermal Storage Systems.” *Renewable and Sustainable Energy Reviews*. Pergamon. https://doi.org/10.1016/j.rser.2012.01.020.

Newsham, Guy R., and Brent G. Bowker. 2010. “The Effect of Utility Time-Varying Pricing and Load Control Strategies on Residential Summer Peak Electricity Use: A Review.” *Energy Policy* 38 (7): 3289–96. https://doi.org/10.1016/j.enpol.2010.01.027.

Rahman, Muhammad Mustafizur, and Md Ahsan Habib. 2022. “Energy Storage Using Phase Change Materials - Challenges and Opportunities for Power Savings in Residential Buildings.” *AIP Conference Proceedings* 2681 (1): 020054. https://doi.org/10.1063/5.0117296.

Real, A., V. García, L. Domenech, J. Renau, N. Montés, and F. Sánchez. 2014. “Improvement of a Heat Pump Based HVAC System with PCM Thermal Storage for Cold Accumulation and Heat Dissipation.” *Energy and Buildings* 83: 108–16. https://doi.org/10.1016/j.enbuild.2014.04.029.

Sarkar, Mousumi. 2011. “How American Homes Vary By the Year They Were Built; How American Homes Vary By the Year They Were Built.” Washington, DC. http://www.census.gov/const/www/charindex.html.

Schibuola, Luigi, Massimiliano Scarpa, and Chiara Tambani. 2015. “Demand Response Management by Means of Heat Pumps Controlled via Real Time Pricing.” *Energy and Buildings* 90 (March): 15–28. https://doi.org/10.1016/j.enbuild.2014.12.047.

Sepehri, Amin. 2022. “Introduction and Literature Review of Building Components with Passive Thermal Energy Storage Systems.” *Green Energy and Technology*, 1–18. https://doi.org/10.1007/978-3-031-08732-5_1/FIGURES/11.

Soares, N., J. J. Costa, A. R. Gaspar, and P. Santos. 2013. “Review of Passive PCM Latent Heat Thermal Energy Storage Systems towards Buildings’ Energy Efficiency.” *Energy and Buildings* 59: 82–103. https://doi.org/10.1016/j.enbuild.2012.12.042.

Sonnick, Sebastian, Lars Erlbeck, Maximilian Gaedtke, Frederik Wunder, Christoph Mayer, Mathias J. Krause, Hermann Nirschl, and Matthias Rädle. 2020. “Passive Room Conditioning Using Phase Change Materials—Demonstration of a Long-Term Real Size Experiment.” *International Journal of Energy Research*, April. https://doi.org/10.1002/er.5406.

Sultan, S, J Hirschey, KR Gluesenkamp, and S Graham. 2021. “Analysis of Residential Time-of-Use Utility Rate Structures and Economic Implications for Thermal Energy Storage.” In , 1–10. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1369&context=ihpbc.

Sultan, Sara, Kyle R Gluesenkamp, and United States. 2021. “The State of Art of Heat-Pump Integrated Thermal Energy Storage for Demand Response.” *IEA Heat Pump Technologies Magazine*, 2021. https://doi.org/https://doi.org/10.23697/62tr-nt79.

Sultan, Sara, Tugba Turnaoglu, Damilola Akamo, Jason Hirschey, Tim Laclair, Xiaobing Liu, and Kyle R. Gluesenkamp. 2022. “PCM Material Selection For Heat Pump Integrated With

Thermal Energy Storage For Demand Response in Residential Buildings." *International High Performance Buildings Conference*, July. https://docs.lib.purdue.edu/ihpbc/427.

Tyagi, V. V., A. K. Pandey, D. Buddhi, and Richa Kothari. 2016. "Thermal Performance Assessment of Encapsulated PCM Based Thermal Management System to Reduce Peak Energy Demand in Buildings." *Energy and Buildings* 117: 44–52. https://doi.org/10.1016/j.enbuild.2016.01.042.

U.S. EIA. 2020. "Annual Energy Outlook 2020."

U.S. Energy Information Administration - EIA. n.d. "Nearly 90% of U.S. Households Used Air Conditioning in 2020." Residential Energy Consumption Survey. Accessed June 16, 2022. https://www.eia.gov/todayinenergy/detail.php?id=52558&src=%E2%80%B9%20Consumption%20%20%20%20%20%20Residential%20Energy%20Consumption%20Survey%20(RECS)-b1.

Waqas, Adeel, Jie Ji, Majid Ali, and Jahan Zeb Alvi. 2018. "Effectiveness of the Phase Change Material-Based Thermal Energy Storage Integrated with the Conventional Cooling Systems of the Buildings – A Review." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 232 (6): 735–66. https://doi.org/10.1177/0957650917754033.

Yoon, Ji Hoon, Ross Baldick, and Atila Novoselac. 2016. "Demand Response Control of Residential HVAC Loads Based on Dynamic Electricity Prices and Economic Analysis." *Science and Technology for the Built Environment* 22 (6): 705–19. https://doi.org/10.1080/23744731.2016.1195659.

Zhu, Na, Shengwei Wang, Zhenjun Ma, and Yongjun Sun. 2011. "Energy Performance and Optimal Control of Air-Conditioned Buildings with Envelopes Enhanced by Phase Change Materials." *Energy Conversion and Management* 52 (10): 3197–3205. https://doi.org/10.1016/j.enconman.2011.05.011.