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Khaled Ibrahim Alghamdi

Christian K. Bach

Jeffrey D. Spitler

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Water-Based Thermal Energy Storage for Heating and Air-Conditioning Applications in Residential Buildings: Review and Preliminary Study

Khaled I. ALGHAMDI[1*], Christian K. BACH[2], Jeffrey D. SPITLER[3]

[1,2,3] Oklahoma State University, Mechanical and Aerospace Engineering School,
Stillwater, OK 74074, USA

[1] Contact Information: khaled.alghamdi@okstate.edu
[2] Contact Information: cbach@okstate.edu
[3] Contact Information: spitler@okstate.edu

* Corresponding Author

ABSTRACT

Solar photovoltaic (PV) and wind power, the two most popular renewable energy sources, cause temporal imbalances between energy demand and supply, requiring fossil fuel reserve power or costly electric energy storage to prevent grid blackouts. Alternatively, using heating, ventilating, and air- conditioning systems (HVAC) for converting electric energy and storing it in thermal form when the electricity supply is high while the demand is low can change the end-user demand profile, reducing the required reserve power and/or storage. This paper reviews technology for water-based thermal energy storage (TES) for vapor-compression systems for heating and air conditioning (AC) applications at the residential scale. Also, we screen the potential of water-based TES in shifting HVAC loads for residential buildings. The presented work informs future research needs by providing an overview of available thermal energy storage options and their applications in residential buildings. In addition, the findings of the preliminary study show the potential of water-based TES in shifting loads with a reasonable size compared to the building footprint.

1. INTRODUCTION

Penetration of renewable resources has been used to address energy generation emission and their impact on climate change. Wind and solar PV generated 9.2% and 2.8%, respectively, of the total electricity generation in the United States in 2021 (EIA, 2022b). However, this penetration of renewable resources causes issues, such as an imbalance between supply and demand, because the resources are intermittent. As an example, the "duck curve" phenomenon in California presents a challenge for utility companies due to the necessity of those companies to generate electricity in an unstable way, causing reliability and efficiency issues for them (Liu et al., 2019). For example, renewable resources often reach their production peak while the demand is low around noon, so conventional energy production must be reduced. The renewable production may, on some days, exceed the demand. Additionally, solar PV rapidly decreases in output late in the day, just as residential electricity consumption is rapidly increasing, so the utility company must increase the energy production to the maximum in a short period. These rapid changes require more highly dispatchable forms of electricity generation, and base load generation capacity may be sidelined. In general, if a utility company generates energy from intermittent renewable resources, it will often generate surplus energy while the demand is low and vice versa.

Storing energy generated from intermittent renewable resources may solve the supply-demand imbalance. The surplus energy produced during the peak generation period can be stored for later use when demand is high while the renewable resource generation is low. Therefore, through demand-response management, utility companies could offer incentives for end-users to use the electricity when the renewable-source production is high by reducing the utility rates and increasing the rates when the production is low (Arteconi et al., 2012, 2013; Renaldi et al., 2017; Tam et al., 2019).

Residential buildings, which are the scope of this study, are responsible for 21% of the energy consumption in the United States in 2015 (EIA, 2022a). Out of the 21% consumed by the residential buildings, space heating, AC, and water heating were responsible for 43%, 8%, and 19% of energy consumption, respectively (EIA, 2015). Hence, the integration of energy storage for heating and AC has a high potential for shifting residential building loads. For heating and AC applications, thermal energy storage (TES) can store energy in the form of heat by heating or cooling the medium in the storage. In our review of the literature, we observed that water-based TES systems are not studied as intensely as TES systems integrating phase change materials (PCMs), as can be observed from Table 1 in Hirmiz et al. (2019) and Table 3.1 in Heier et al. (2015). The limited consideration of water-based TES might be due to the lower energy density of water compared to PCMs. For example, 300 kWh of energy stored at 15 °C (59 °F) ΔT requires 16 m^3 (565 $ft.^3$) storage volume of water, while it requires 6.6 m^3 (233 $ft.^3$) storage volume of organic PCMs (Hasnain, 1998). However, unlike PCMs, water can be used as a storage or distribution medium over a wide range of temperatures. Therefore, this paper aims to review the literature to identify future directions for research on water-based TES in heating and AC applications. We review the literature considering only studies that investigated water-based TES integration, either in liquid or iced form, for vapor-compression systems for heating and AC applications in residential buildings. Also, we aim to investigate the potential of water-based TES in shifting heating and cooling loads for residential buildings.

We organize this paper as follows: the review of the existing studies of the water-based TES integration is reported in Section 2, the preliminary study investigating the potential of water-based TES integration for heating and AC applications is shown in Section 3, and the conclusion of our review and study is presented in Section 4.

2. WATER-BASED TES IN HEATING AND AC APPLICATIONS: REVIEW

In general, three main types of vapor-compression systems for heating and AC applications integrating water-based TES have been found in the literature: an entire system for heating and AC, a system for heating only (Subsection 2.1), or a system for cooling only (Subsection 2.2). A study of TES integrated into a ground-source heat pump (GSHP) system that provided both heating and cooling was described by Heng (2017). Heng used Modelica to model the system, which integrated hot and cold TES tanks, the water-to-water GSHP, and a fan-coil unit (FCU). The GSHP serves to charge the tanks based on the operational mode. The operational modes are Dual Charging (DC), Cold Charging (CC), and Hot Charging (HC). The GSHP absorbs heat from the cold tank in the DC mode and rejects it to the hot tank. In the CC mode, the GSHP absorbs heat from the cold tank and rejects it through the ground heat exchangers, while the GSHP absorbs heat through the ground heat exchangers and rejects it to the hot tank for the HC mode. The building's heating or cooling demand is met using water from the tanks and a fan-coil unit. The system serves a house modeled as a single space having dimensions of 10 m (33 ft.) wide, 20 m (66 ft.) long, and 6 m (20 ft.) height in Stillwater, Oklahoma. The sixteen one-year simulations considering different compressor and tank sizes show that the system works efficiently with larger compressors and smaller tanks. However, reducing the tank size results in increased cycling of the GSHP.

For an entire system using renewable-energy resources and integrating water-based TES, Li et al. (2021) modeled and simulated a single-family single-level house integrating a solar-powered heat pump with TES for space heating and cooling in Brisbane, Australia. The system consists of rooftop PV panels, TES hot and cold-water tanks, an air-source heat pump (HP), and an FCU. The PV or the grid can power the HP to charge either the cold or hot TES tank; then, the TES supplies heating or cooling to the building. The proposed system is compared to two other systems: a baseline system with conventional AC and domestic hot water (DHW) and a system identical to the proposed system but without the TES tanks. The results showed that the proposed system with 5-kW panels reduced the grid energy demand by 76% with shifting load during the grid demand peak, which reduced the peak load by 45% compared to the baseline system.

2.1 Water-Based TES for Heating

Arteconi et al. (2013) investigated the impact of using TES with an HP system on the performance of the system and occupant comfort in a simulation study. TRNSYS is used as a simulation tool with the building model of a detached house in Northern Ireland. The baseline heating system consists of an air-to-water HP with a hydronic distribution system utilizing radiant underfloor heating or panel radiators. TES is integrated into the heating system to provide heat directly to the building, while the coupled HP provides heat to the TES. Three electricity rate structures are considered to calculate the energy cost: a flat rate, a two-tier structure with a 7-hour reduced rate period and 17 hours at the flat rate, and a rate structure with three levels of cost based on electricity generation cost. The results showed the necessity of integrating TES with a system with low thermal mass, such as radiators, to avoid excessive HP cycling while maintaining thermal comfort. Also, TES integration reduces the energy cost with utility rates varied throughout the day but does not reduce the energy consumption.

In terms of design and optimization, Renaldi et al. (2017) developed a framework for designing and optimizing a heating system that integrates an HP with TES to reduce the total cost, including initial cost, operational cost, and revenue from subsidy in the United Kingdom. The framework includes models of heat demand, an air-source HP, TES, and electricity tariff. The heat demand model considers external temperature, occupancy profile, and annual energy demand. The HP model is represented by a function of the temperature difference between supply temperature and external temperature with the use of the manufacturer's data to produce a linear regression fit for the HP performance. The TES is considered to be charged through the HP and a resistive heater, and it is represented by a set of equations. Three electricity tariffs are considered: Standard, where the rate is flat, and Economy 7 and 10 (E7 and E10), where 7-hour and 10-hour off-peak rate occurs, respectively. The optimization problem is formulated by Pyomo 4.0 and solved with CPLEX, and the results are compared to results obtained with TRNSYS. Compared to a boiler-based system, a heating system with HP has a higher total cost. However, adding TES to the system and time-of-use electricity rate and a governmental subsidy can make the HP-based system as competitive as the conventional system.

For studying the impact of sizing TES and HP on the cost and heating load shifting under variable electricity rates, Bechtel et al. (2020) simulated a Nearly-Zero-Energy-Building house in Luxembourg. The system consists of air-to-water HP coupled with TES and a tank for DHW. The building is heated by hot water stored in the TES through a heating-floor system. The building and the system are modeled in TRANSYS and coupled with a MATLAB model for a model-predictive controller. A parametric study is conducted using two HP sizes with identical COP and four TES sizes. The results show that increasing TES size can improve the flexibility of the HP in shifting the load and the efficiency of the whole system. Also, including DHW for shifting the load alongside the heating system might not improve the flexibility due to limited capacity and working within a tight temperature band.

2.2 Water-Based TES for AC

Zhang et al. (2020) modeled an ice storage system based on super-cooled ice production for charging/discharging TES. The model was developed within MATLAB SIMULINK with inputs of hourly temperatures and electricity rates for calculating energy use and cost over the cooling season of an average home in two U.S. cities: Las Vegas and Phoenix. The system has three subsystems for refrigerant, water, and air. The refrigerant subsystem is an HP with an evaporator that can be refrigerant-to-water or refrigerant-to-air. The water subsystem consists of TES and a water pump, and it can use the evaporator in the refrigerant subsystem to produce super-cooled water. The system has four modes of operation: charging, discharging, cooling, and standby. A controller determines the mode of the operation based on T_{indoor}, T_{set}, electricity rate, TES state of charge, and the capability of the super-cooling system. Compared to the result of a conventional AC system with identical operational conditions, the proposed system can reduce the energy cost by up to 75%. In contrast, the system causes a minor reduction in energy use - no number has been reported in the study.

The system briefly described in Zhang et al. (2020) is described in detail by Mokarram & Wang (2022). Mokarram & Wang (2022) modeled a residential AC system integrating an ice TES with a two-fluid micro-channel condenser and a three-fluid micro-channel evaporator. The system has three loops: refrigerant loop, water loop, and air loop. The key component arranging the loops is the evaporator with a tube with refrigerant adjacent to another tube with super-cooled water while air flows over the tubes. The system has three modes of operation: ice-charging, where heat transfers from the water loop to the refrigerant loop in the evaporator; regular home-cooling mode, where heat transfers from the air loop to the refrigerant loop in the evaporator; and ice home-cooling mode, where heat transfers from the air loop to the water loop in the evaporator. The system was modeled using SIMULINK of MATLAB, and the results of heat transfer coefficients obtained with the model were verified with results in the literature.

In terms of improving a system performance by integrating TES, Sultan et al. (2021) modeled a vapor compression system (VCS) integrating water/ice TES for a residential building in ASHRAE Climate Zone 3-B using a time-of-use utility rate scheme for a week of extreme heat to study the economic and energy saving of the proposed system. The baseline HVAC system of the studied building is a conventional air-source VCS without integrating TES to be compared to an identical system integrating TES. The TES is an 80-gallon (303 liters) ice/water tank used mainly as a heat sink to improve the performance of the VCS. The system has four operational modes: Standby, where the system is off; Normal, where the system works as conventional VCS; Charging, where the VCS moves heat from the TES to the ambient; and Discharging, where the VCS moves heat from the building to the TES to improve the VCS performance. The system is controlled based on the off-peak and on-peak periods of the utility rates. The system is modeled in Engineering Equation Solver (EES) with a simple building model represented by an overall U-factor and thermal capacitance. The proposed system with TES reduced the energy use by 14.5%, on-peak energy use by 87.5%, and the utility cost by 20% for the simulated period.

Investigating the effectiveness of integrating TES and precooling using a simulation tool, Nelson et al. (2019) implemented and optimized precooling and TES strategies for single-family homes in three U.S. cities, Los Angeles, CA, Phoenix, AZ, and Kona, HI, to study the strategies' impacts on energy use and cost. EnergyPlus is used as a simulation tool with a model house designed to Building America B10 Benchmark specifications (Wilson et al., 2014). The HVAC system consists of an air-source HP only as the considered location are cooling-dominated locations. The sizing of the HVAC system is optimized among a set of sizes considering the unmet loads and electricity cost and use. The cooling strategies are:

- Baseline: the thermostat set point is adjusted at 24.4°C (75.9°F).
- Precooling: the thermostat set point is adjusted based on the outdoor temperature and on-peak time with and without considering the setback point.
- TES : a single-speed cooling coil in EnergyPlus is paired with TES.
- Combined: combine the Precooling and TES strategies with and without the setback option.

The Combined strategy with the setback option provides the most significant reduction in energy use for the simulation period, which is the hottest week of July. The TES strategy reduces the on-peak demand by percentages varied from 11.5-54.6%. However, the payback period of the TES and Combined strategies exceed ten years.

In terms of the economic impact of integrating TES, Tam et al. (2018) evaluated, with modeling, the overall economics of an AC with an ice storage for residential cooling applications considering system performance and operation cost in various locations with the consideration of the advantage the storage might provide in terms of reducing the operational cost (utility rate incentive) and the initial cost (equipment sizing). The evaluation considers the trade-off between the system capacity, efficiency, and storage size to obtain the least payback period. The proposed HVAC system consists of an air-source AC system coupled with a secondary water-glycol secondary loop connected with ice storage. For assessing the economic feasibility, the system sizing has been obtained using two approaches: design day analysis considering the AC system operates in full capacity with the storage running at 0-80% of its capacity, and sizing the equipment based on that gives the least payback period. The system cost model is developed based on data from the U.S. Department of Energy and the Department of the Army (DOE (2016) and Chang (1995) in Tam et al. (2018)). The optimal payback period is calculated compared to a conventional AC system by optimizing the objective function using a nonlinear programming solver - 'fmincon' function of MATLAB. The proposed system is compared with a 3-ton split AC system rated at 35°C (95°F) with 3 COP; it is represented for various T_{amb} by equations developed using the ACHP tool (see: Bell (2012)). The system is evaluated based on utility rates and climate conditions of Miami, California, Alabama, South Carolina, and North Carolina. The system with ice storage with a high SEER has a short payback period, and the payback periods are ranged from 12 to 117 years, with the lowest for locations with a hot climate and favorable utility rates.

Lee & Jones (1996) experimentally tested a cooling system integrating an ice-on-coil TES aiming to develop testing and rating procedures for such a system for residential and light commercial buildings. The authors proposed a system consisting of a compressor, DHW tank, TES with a coil, an outdoor air-to-refrigerant coil, an air-to-water indoor heat exchanger, and two circulating pumps. The system absorbs heat from the TES and rejects it to the DHW and the outdoor coil, while heat is absorbed from the indoor heat exchanger and rejected to the TES. The proposed system is tested using a dual-air-loop lab facility considering the outdoor air coil, the indoor air coil, and the TES with a coil. The system is tested for the charging and discharging operational modes. In the charging test, the water is cooled from 40°F to the formation of ice until 65% of the TES is transformed to ice under sink temperatures of 60, 70, and 95°F. In the discharging test, a test lasts until ice is depleted from under source temperature of 75, 80, and 85°F. In the charging test, results show that ice formation rate is linear although the temperature difference decreases in the heat source. Also, the ice formation rate increases as the heat sink temperature decreases at any given charging time. For the discharging test, the ice's melting rate increases as the discharging process period increases, and the melting rate increases as the heat source temperature increases.

3. PRELIMINARY STUDY

Due to its high capacitance and availability, water can be an effective medium for storing thermal energy. However, the energy density of water-based TES can be significantly less than TES integrating PCM (Hasnain, 1998). As the application is important in determining the suitability of water as a storage medium, we conducted a study to investigate the volume of water-based TES required to shift heating or/and cooling loads in residential buildings. The study considers five U.S. locations representing the main U.S. climates. For each location, load profiles and time-of-use utility rates are obtained from OpenEI.org (NREL, 2022b,a). The selected locations are Arcata, CA (Marine), El Paso, TX (Mixed-Dry/Hot-Dry), Madison, WI (Cold/Very- Cold), Memphis, TN (Mixed-Humid), and Tampa, FL (Hot-Humid). The locations are the representative cities in the Ong & Clark (2014) study, which is the source of the load profiles (NREL, 2022a), except Madison, WI. Madison, WI is considered for a Cold/Very-Cold climate instead of Billing, MT because the utility rate database (NREL, 2022b) has only a flat-rate utility rate for the latter location. The load profiles are the BASE profiles in the Ong & Clark (2014) study, which represent Building America B10 Benchmark (Hendron & Engebrecht, 2010). The load profiles are reported as end-use consumption in kWh, so the loads are converted to units of heat energy by considering a Seasonal Energy Efficiency Ratio (SEER) of 13 for electricity as an energy source and efficiency of 78% for gas as an energy source. The conversion values are based on values listed in Table 4 in Hendron & Engebrecht (2010), which documents the development of the Building America B10 Benchmark. The rate profile names of the considered locations are listed in Table 1, and their profile is graphically shown in Figure 1. In Figure 1, the x-axis represents the date (day of the year), the y-axis represents the time of day, and the main plot area color indicates the electricity rate represented by the side color bar.

Table 1: General information of the rates of considered locations (NREL, 2022b).

City	Utility Name	Rate Name	Zip Area
Arcata, CA	Pacific Gas & Electric Co.	E-TOU-B - Residential Time of Use	95521
El Paso, TX	El Paso Electric Co.	Residential Service - TOU	79901
Madison, WI	Madison Gas & Electric Co.	TOD Residential Time of Day	53701
Memphis, TN	City of Memphis, Tennessee	RS Time-of-Use Residential Rate	38105
Tampa, FL	Tampa Electric Co.	RSVP-1 Residential Service Variable Pricing Program	33606

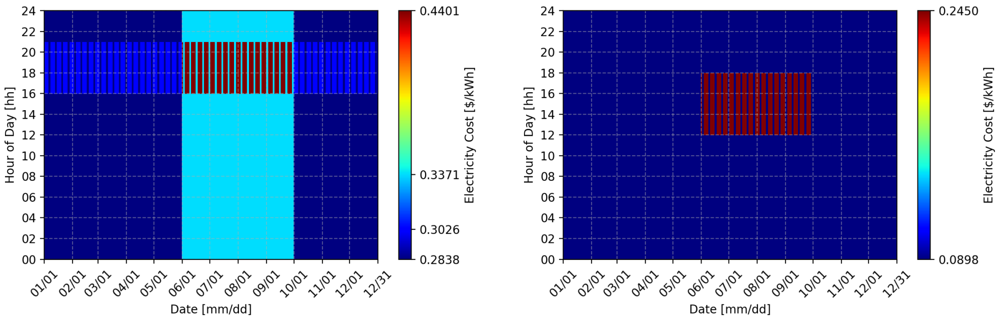
3.1 Methodology for the Preliminary Study

To determine the size of the TES, we found the loads occurring when the daily electricity rate was the maximum, as shown in Figure 2. In Figure 2, the x-axis represents the date (day of the year), the y-axis represents the time of day, and the primary plot area color indicates the load where the blue (-) is cooling, and the red (+) is heating represented by the side color bar. We only considered the electricity cost per kWh plus any kWh adjustments shown under the “Energy” tab of NREL (2022b). Then, we calculated the daily load occurring at the daily maximum rate to determine the annual cumulative frequency of occurrence (CFO) below the maximum load, e.g., how often the maximum load is below the indicated percentage considering only loads occurring when the rate is the maximum. After that, we assumed a range of ΔT for water in TES considering water heat capacity of 4.182 [kJ/kg-K] and density of 1,000 [kg/m^3] and CFO of 90, 95, and 100% to size the TES for shifting heating or/and cooling loads. The sizing of the TES does not consider the heat loss of the TES.

3.2 Results of the Preliminary Study

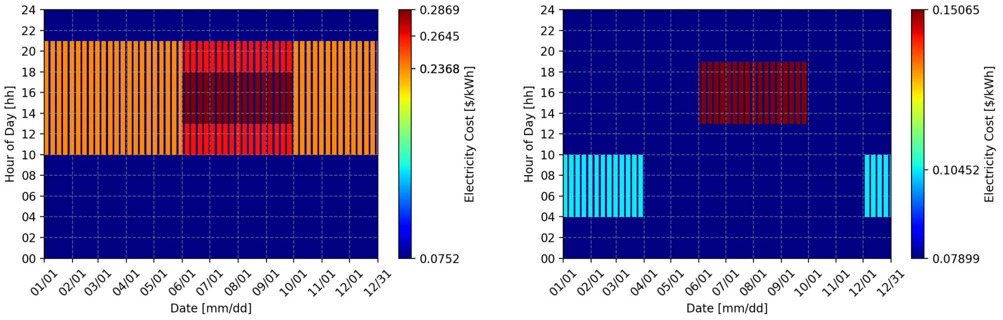
The ratio of the yearly loads occurring when the daily rate is the maximum to the yearly total load is shown in Figure 3. The ratio is minimum in the Marine climate zone (Arcata, CA) at around 7%, and it is a maximum of 45% in the Hot-Humid climate zone (Tampa, FL). Hence, considering TES for locations with a lower ratio might cause minor load shifting, while it can cause significant load shifting when the ratio is high.

Results of the TES size are shown in Figure 5. In Figure 5, the x-axis represents ΔT of TES, the y-axis represents the size of TES, the marker shape represents the locations, and the marker color indicates the CFO represented by the side color bar. The size of the TES storage is more sensitive to the temperature change ΔT of the stored water than the CFO of the maximum load. For example, the TES for shifting heating loads in a Cold/Very-Cold climate zone (Madison, WI) can be 300% more extensive for ΔT of 5°C (41°F) as compared to 25°C (77°F), while it is around 60% larger with a load CFO at 90% as compared to a CFO of 100%. Additionally, although a larger ΔT reduces the size of the TES, the large ΔT requires increased equipment size due to reduced heat pump capacities at larger temperature lifts to charge the TES within the availability time. Hence, the trade-off between the size of the TES and the equipment should be optimized. Note that the footprint of the maximum size with the extreme case, e.g., lower ΔT and higher CFO with the highest load, is not extremely large compared to the building footprint. For example, the maximum TES size of around 20 m^3 occurring in the Cold/Very-Cold climate can fit into 4.5% (11 m^2 (121 ft.^{2})) of the building footprint with a total area of 250 m^2 (2,696 ft.^{2}) if the TES is 1.8 m (6 ft.) tall with a radius of 1.9 m (6.2 ft).



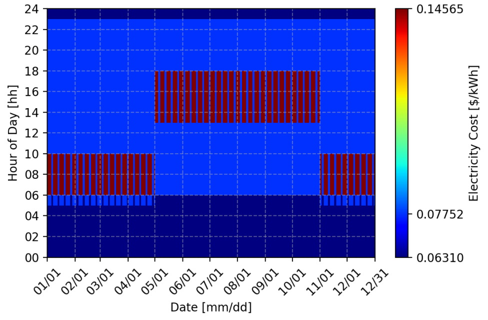
(a) Arcata, CA (Marine).

(b) El Paso, TX (Mixed-Dry/Hot-Dry).



(c) Madison, WI (Cold/Very-Cold).

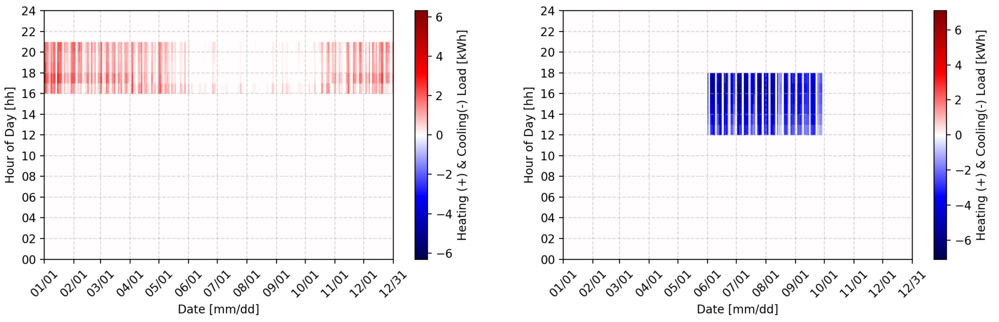
(d) Memphis, TN (Mixed-Humid).



(e) Tampa, FL (Hot-Humid).

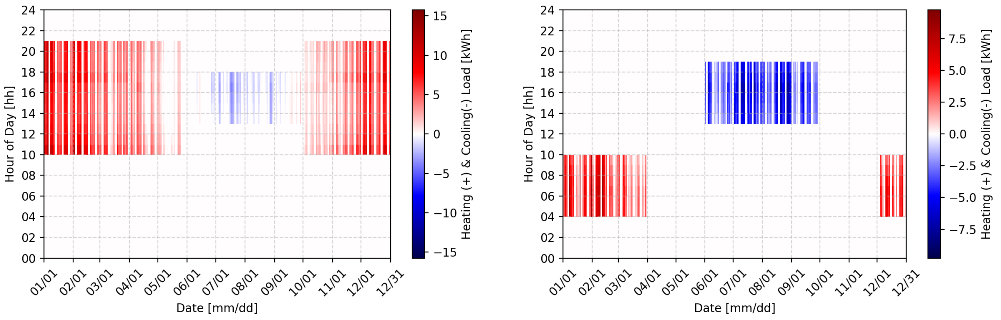
Figure 1: Electricity rates for the considered locations.

Also, the results show that load type occurring when the rate is the maximum varies from one location to another. For example, the Marine climate zone (Arcata, CA) has only heating loads throughout the year as no AC is utilized (Ong & Clark, 2014), and the Mixed-Dry/Hot-Dry climate zone (El Paso, TX) has only cooling loads when the rate is the maximum. Hence, integrating TES for daily shifting of a load can be limited to a few months of the year, as the TES will shift one load type. In addition, a significant imbalance between cooling and heating loads occurring when the rate is the maximum in the Cold/Very-Cold (Madison, WI) makes adopting one TES for both loads difficult because the imbalance results in oversizing the TES for one load type. Oversizing the TES can negatively impact the total energy consumption unless a control scheme is adopted to optimize the charging and discharging operations. An example of such an optimizing control is weekly charging the TES during a cooling season on the weekends when the rate is flat and equivalents to the minimum rate on weekdays. Nevertheless, heat loss can be an issue for relatively long-term storage if the TES heat losses are not fully recaptured within the building. For the Mixed-Humid climate zone (Memphis, TN), the heating and cooling loads occurring yearly (Figure 4) as well as when the rate is the maximum are relatively balanced and occur throughout a year (Figure 3), so the TES will have the highest utilization throughout the year. For the Hot-Humid climate zone (Tampa, FL), there is also a balance between the heating and cooling loads occurring when the rate is the maximum, yet the yearly heating load is only 10% of the yearly total load as shown in Figure 4.



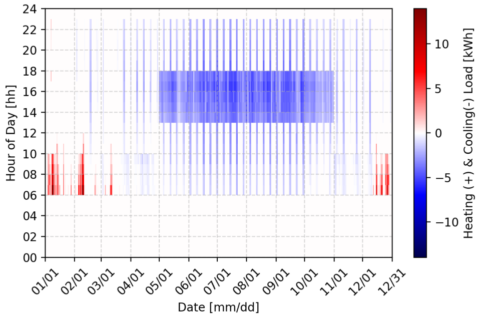
(a) Arcata, CA (Marine).

(b) El Paso, TX (Mixed-Dry/Hot-Dry).



(c) Madison, WI (Cold/Very-Cold).

(d) Memphis, TN (Mixed-Humid).



(e) Tampa, FL (Hot-Humid).

Figure 2: Heating (+ and in red) and cooling (- and in blue) loads occurring during the maximum daily rate.

4. CONCLUSIONS

This study reviewed the literature for studies on systems integrating water-based TES. The reviewed papers show various aspects of integrating TES in vapor-compression systems, such as energy consumption and cost, and system performance. TES integration with an HVAC system might help reduce on-peak energy consumption and cycling of the system compared to the case of not integrating TES. Nevertheless, the TES integration could increase the integrated system's operational hours, increasing total energy consumption. In terms of cost, TES integration increases the initial cost compared to conventional systems. However, the initial cost can be compensated by operational cost through time-of-use rates. The system can shift loads from periods of high energy cost to periods of excess renewable electricity supply. In terms of TES size, reducing the size of the TES reduces heat loss from the TES, which results in improving the system integrating TES efficiency. Nevertheless, the reduction of the TES size would cause high cycling of the coupled system. Also, integrating TES with a system powered by renewable resources and grid can significantly reduce the grid peak consumption and enhance the flexibility of such a system in shifting loads. Hence, drawing a conclusion about the TES integration with HVAC systems is difficult without considering both building-level and grid-level requirements. Moreover, the authors anticipate further penetration of intermittent renewable sources, exacerbating the supply/demand

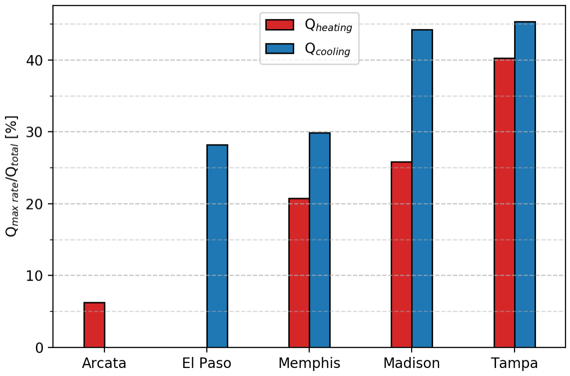


Figure 3: Ratio of a yearly load type occurring at max. daily rate to the same type total yearly load.

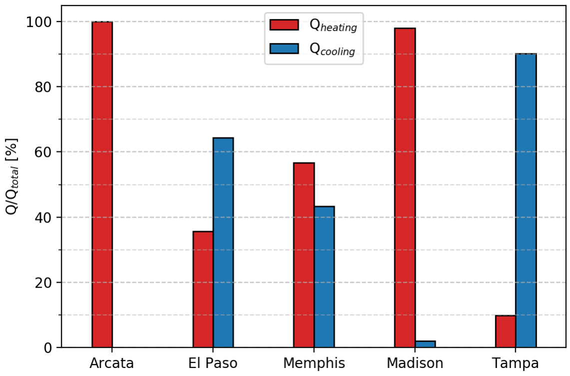
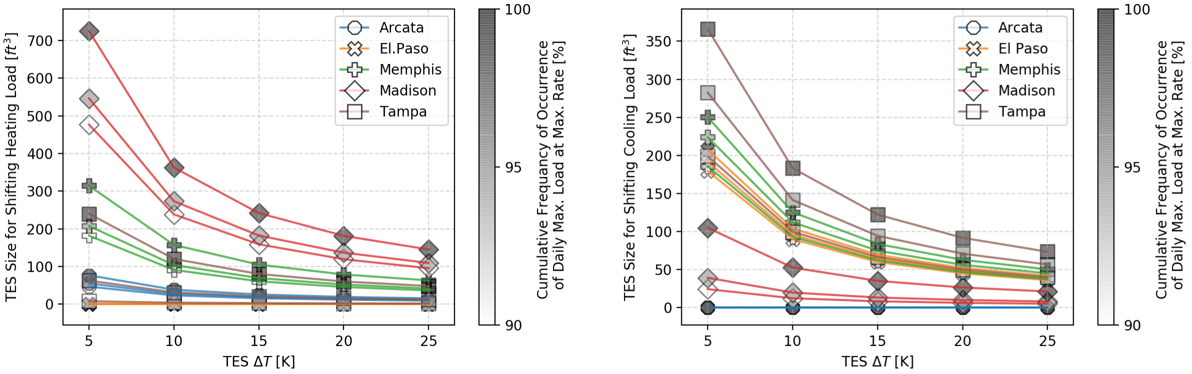


Figure 4: Ratio of a yearly load type to the the total yearly load (heating+cooling).



(a) Heating.

(b) Cooling.

Figure 5: TES size for shifting heating and cooling loads considering various cumulative frequency of occurrence of maximum load during maximum daily rate and ΔT for the TES's.

mismatch, with electrical batteries having higher environmental impact than water-based TES. Hence, the seasonal and economic analysis of an entire system handling loads throughout a year and integrating low environmental impact TES for various climate conditions should be further investigated.

Also, we investigated the potential of water-based TES for heating and AC applications. We selected five locations representing the U.S. climates with time-of-use rates found in the utility database (NREL, 2022b) for each of the locations. We found that the maximum size of the TES with the extreme operational conditions, such as small ΔT and high cumulative frequency of loads, can be as low as 4.5% of the house's footprint. Therefore, water-based TES for integration with HVAC can be competitive with the PCM-based TES in energy density. Also, the study shows that each climate has its unique sizing considerations in terms of dominating load occurring when the rate is maximum on daily bases (Figure 3), as well as the yearly dominant load type (heating or cooling) (Figure 4). Hence, attaining a conclusion regarding the sizing of the TES requires considering the coupled system, heating, and cooling mode consideration, utility rate scheme, and the systems control scheme to evaluate the optimum cost trade-off between sizing the VCS system and sizing the TES.

NOMENCLATURE

AC	Air Conditioning
CFO	Cumulative Frequency of Occurrence
DWH	Domestic Hot Water
FCU	Fan-Coil Unit
GSHP	Ground-Source Heat Pump
HP	Heat Pump
HVAC	Heating, Ventilation, and Air Conditioning
PCM	Phase Change Materials
PV	Photovoltaic Panels
SEER	Seasonal Energy Efficiency Ratio
TES	Thermal Energy Storage
UTS	Underground Thermal Storage
VCS	Vapor Compression System

REFERENCES

Arteconi, A., Hewitt, N., & Polonara, F. (2012). State of the art of thermal storage for demand-side management. *Applied Energy*, *93*, 371-389. doi: https://doi.org/10.1016/j.apenergy.2011.12.045

Arteconi, A., Hewitt, N., & Polonara, F. (2013). Domestic demand-side management (DSM): Role of heat pumps and thermal energy storage (TES) systems. *Applied Thermal Engineering*, *51*(1), 155-165. doi: https://doi.org/10.1016/j.applthermaleng.2012.09.023

Bechtel, S., Rafii-Tabrizi, S., Scholzen, F., Hadji-Minaglou, J.-R., & Maas, S. (2020). Influence of thermal energy storage and heat pump parametrization for demand-side-management in a nearly-zero-energy-building using model predictive control. *Energy and Buildings*, *226*, 110364. doi: https://doi.org/10.1016/j.enbuild.2020.110364

Bell, I. (2012). *ACHP Documentation.* Retrieved 03/10/2022, from `http://achp.sourceforge.net/index.html`

EIA. (2015). *Use of energy explained: Energy use in homes.* Retrieved 11/14/2021, from `https://www.eia.gov/energyexplained/use-of-energy/homes.php`

EIA. (2022a). *Energy Consumption by Sector.* Retrieved 03/27/2022, from `https://www.eia.gov/totalenergy/data/monthly/pdf/sec2_3.pdf`

EIA. (2022b). *What is U.S. electricity generation by energy source?* Retrieved 03/27/2022, from `https://www.eia.gov/tools/faqs/faq.php?id=427&t=3`

Hasnain, S. (1998). Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy Conversion and Management*, *39*(11), 1127-1138. doi: https://doi.org/10.1016/S0196-8904(98)00025-9

Heier, J., Bales, C., & Martin, V. (2015). Combining thermal energy storage with buildings – a review. *Renewable and Sustainable Energy Reviews*, *42*, 1305-1325. doi: https://doi.org/10.1016/j.rser.2014.11.031

Hendron, R., & Engebrecht, C. (2010). *Building america house simulation protocols.* Retrieved 03/27/2022, from `https://www.nrel.gov/docs/fy11osti/49246.pdf`

Heng, K. L. (2017). *Modeling and control strategy of geothermal heat pump water chiller-heater with dual thermal storage water tanks* (MS Creative Component Report). Stillwater, Oklahoma, United States: Oklahoma State University.

Hirmiz, R., Teamah, H., Lightstone, M., & Cotton, J. (2019). Performance of heat pump integrated phase change material thermal storage for electric load shifting in building demand side management. *Energy and Buildings*, *190*, 103-118. doi: https://doi.org/10.1016/j.enbuild.2019.02.026

Lee, A. H., & Jones, J. W. (1996). Laboratory performance of an ice-on-coil, thermal-energy storage system for residential and light commercial applications. *Energy*, *21*(2), 115-130. doi: https://doi.org/10.1016/0360-5442(95)00095-X

Li, Y., Mojiri, A., Rosengarten, G., & Stanley, C. (2021). Residential demand-side management using integrated solar-powered heat pump and thermal storage. *Energy and Buildings*, *250*, 111234. doi: https://doi.org/10.1016/j.enbuild.2021.111234

Liu, X., Shi, L., Qu, M., & Warner, J. (2019, 11). *A Preliminary Study of a Novel Heat Pump Integrated Underground Thermal Energy Storage for Shaping Electric Demand of Buildings* (Tech. Rep.). Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States). Retrieved from `https://www.osti.gov/biblio/1606946`

Mokarram, N. H., & Wang, H. (2022). Design and modeling of novel two-phase heat exchangers for a home cooling system with ice energy storage. *Applied Thermal Engineering*, *207*, 118175. doi: https://doi.org/10.1016/j.applthermaleng.2022.118175

Nelson, J., Johnson, N. G., Chinimilli, P. T., & Zhang, W. (2019). Residential cooling using separated and coupled precooling and thermal energy storage strategies. *Applied Energy*, *252*, 113414. doi: https://doi.org/10.1016/j.apenergy.2019.113414

NREL. (2022a). *Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States.* Retrieved 03/27/2022, from `https://data.openei.org/submissions/153`

NREL. (2022b). *Utility Rate Database.* Retrieved 03/27/2022, from `https://openei.org/wiki/Utility_Rate_Database`

Ong, S., & Clark, N. (2014, 11). *Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States.* Retrieved 03/27/2022, from `https://data.openei.org/submissions/153?source=post_page`

Renaldi, R., Kiprakis, A., & Friedrich, D. (2017). An optimisation framework for thermal energy storage integration in a residential heat pump heating system. *Applied Energy*, *186*, 520-529. doi: https://doi.org/10.1016/j.apenergy.2016.02.067

Sultan, S., Hirschey, J., Gluesenkamp, K. R., & Graham, S. (2021). Analysis of Residential Time-of-Use Utility Rate Structures and Economic Implications for Thermal Energy Storage. In *International High Performance Buildings Conference.* Retrieved from `https://docs.lib.purdue.edu/ihpbc/370` (Paper 370)

Tam, A., Braun, J. E., Jain, N., & Ziviani, D. (2018). An Overall Assessment of Ice Storage Systems for Residential Buildings. In *International High Performance Buildings Conference.* Retrieved from `https://docs.lib.purdue.edu/ihpbc/335` (Paper 335)

Tam, A., Ziviani, D., Braun, J. E., & Jain, N. (2019). Development and evaluation of a generalized rule-based control strategy for residential ice storage systems. *Energy and Buildings*, *197*, 99-111. doi: https://doi.org/10.1016/j.enbuild.2019.05.040

Wilson, E., Engebrecht-Metzger, C., Horowitz, S., & Hendron, R. (2014, 3). *2014 Building America house simulation protocols* (Tech. Rep.). National Renewable Energy Lab.(NREL), Golden, CO (United States). Retrieved from `https://www.osti.gov/biblio/1126820` doi: https://doi.org/10.2172/1126820

Zhang, Y., Kissick, S., & Wang, H. (2020, 04). Modeling and simulation of building cooling system with supercooling-based ice energy storage. *ASME Journal of Engineering for Sustainable Buildings and Cities*, *1*(2). (021002) doi: https://doi.org/10.1115/1.4046788