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Quantification of Energy Savings and Demand Reduction for A Heat Pump Integrated with Thermal Energy Storage - Final Report

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August 2022

OAK RIDGE National Laboratory

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Building and Transportation Science Division

QUANTIFICATION OF ENERGY SAVINGS AND DEMAND REDUCTION FOR A HEAT PUMP INTEGRATED WITH THERMAL ENERGY STORAGE - FINAL REPORT

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. ABSTRACT

To mitigate the variation in demand on the electric grid, thermal energy storage (TES) is an alternative to electric batteries or installing new peaking power plants. Stakeholders and policy makers across the United States have expressed interests in promoting TES, as demonstrated by the US Department of Energy's Grid-Interactive Efficient Buildings program and the efforts of various state legislatures. However, the cost value provided by TES are unclear. If reliable cost benefits were determined, stakeholders would have a clearer picture of the financial returns that can be gained from their investment in TES. The study in this report is conducted by ORNL with collaboration with Emerson the Helix Innovation Center.

In the first part of this report, EnergyPlus was used to perform whole-building simulations for two residential buildings in Indianapolis and Atlanta. The HVAC system in both buildings were equipped with phase change material TES. The TES tank was charged in off-peak hours and discharged in peak hours to perform load shifting. First, the economic value implied by existing time-of-use (TOU) rates offered by utility companies was analyzed via whole-building simulation. Second, existing demand reduction (DR) incentives sourced from 3 different electrical grid administrators (i.e., California, Texas, and New England region) were surveyed to determine their implied value.

The study suggests that the traditional value analysis that focuses on ROI for the building owner significantly undervalues TES technology making economic viability difficult. A more comprehensive value analysis that includes peak demand management and deferred capital for peaking power plants shows that TES should be economically viable but here the value is greater for the utility and requires large market penetration and aggregation to fully realize the benefits. Therefore, to facilitate commercialization, new business models are needed that include a broader range of stakeholders and distribute the value of TES proportionally.

In the 2nd part of this project, the benefits of a novel phase change material (PCM) integrated heat pump configuration were evaluated via detailed component based simulation. A one-dimensional PCM heat exchanger model which discretizes the PCM tank and refrigerant tubes into small control volumes is developed. Each control volume can have different PCM temperatures, PCM properties, and heat transfer coefficients. The PCM tank is charged by a wrapped tank condenser and discharged by an internal refrigerant coil. The PCM heat exchanger model is integrated into DOE/ORNL Heat Pump Design Model for heat pump system simulation.

To demonstrate the performance of the PCM integrated heat pump, a case study in Chicago was performed. A Time-of-Use utility structure-based control strategy is implemented to schedule the PCM tank charging and discharging mode switching. Compared with a conventional electric heat pump, the PCM integrated heat pump shows superior performance on load shifting and utility cost reduction. As a result, the proposed system demonstrates 24.6% utility saving for cooling application and 25.8% utility saving for heating application.

2. STATEMENT OF OBJECTIVES

This project evaluated, via modelling the benefits of the novel technology of phase change material (PCM) with heat pump to enable peak demand reduction while also boasting efficiency year-round by favorably exploiting the diurnal ambient temperature swings to optimize heating and cooling efficiency with a single PCM. Furthermore, it provided a detailed market and economic analysis for the technology.

2.1 MARKET AND ECONOMIC ANALYSIS

This project conducted a market and economic analysis to develop the business case for the PCM-integrated heat pump. This assessment identified consumer benefits, as well as the thermal performance requirements and key factors required for successful commercialization. an initial proxy of the value of TES is made by assuming the deferred capital cost of power plant is the full value to reduce peak demand. Three levels of financial value of TES systems were assessed. Two are currently available to some residential customers: (1) the benefit from TOU pricing alone and (2) the benefit from TOU pricing in combination with DR incentive programs. The third level was computed as the full cost of deferred capital cost of peaking power plants. This represents the potential value that could be gained by the utilities or conceivably be offered to consumers.

2.2 PCM-INTEGRATED HEAT PUMP DESIGN, SYSTEM MODEL DEVELOPMENT AND PERFORMANCE EVALUATION

This project developed a detailed design for a PCM integrated heat pump system that meets the requirements for the targeted demand response capability. A comprehensive thermodynamic and heat transfer model was created using DOE/ORNL Heat Pump Design Model. The model was used to evaluate the performance of the system under different operating conditions. Furthermore, detailed simulation results using validated heat pump performance tools was obtained for a range of realistic heat pump operating conditions, and the performance was compared to other TES systems to demonstrate the superior performance of this system for both heating and cooling.

2.2.1 System design

The PCM-integrated heat pump was designed to achieve the targeted load shift capabilities. An existing high efficiency heat pump was selected as a baseline that the PCM-integrated system was based on. Sizing of the PCM heat exchanger and basic control elements for integration of the TES with the heat pump operation was developed.

2.2.2 Development of 1-dimensional discretized PCM heat exchanger model.

A segment-to-segment modelling approach was used to model the PCM heat exchanger, to represent the local temperatures, phase change ratios, and heat transfer characteristics in numerous control volumes, during charging/discharging processes.

2.2.3 Integration of 1-dimensional discretized PCM heat exchanger model to a detailed heat pump simulation model.

The segment-to-segment PCM model was integrated to a detailed heat pump design model for quasi-steady-state co-simulation. The co-simulation predicted energy consumption and energy delivery in a complete cycle including charging and discharge processes.

2.3 CONTROL STRATEGY DEVELOPMENT AND EVALUATION

The project developed the control strategies of varying complexity for maximizing the load shifting of the system while providing improved energy efficiency and cost benefits for the PCM-integrated heat pump. The performance of the system was modeled for different control strategies to assess the opportunities for performance enhancements resulting from improved controls.

3. BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

To mitigate the variation in demand on the electric grid, thermal energy storage (TES) is an alternative to electric batteries and constructing new peaking power plants. The aggressive carbon reduction goals of the United States are accelerating the electrification of building equipment. If space heating and cooling in the US were electrified using conventional heat pump technologies, the winter electric grid peak would approximately double. Integrating TES with heat pump (HP) enables electrification of space cooling and heating devices without overtaxing the grid. Stakeholders and policy makers across the United States have expressed interests in promoting TES, as demonstrated by the US Department of Energy's Grid-Interactive Efficient Buildings program and the efforts of various state legislatures. However, the cost value provided by TES are unclear. If reliable cost benefits were determined, stakeholders would have a clearer picture of the financial returns that can be gained from their investment in TES.

This project evaluated the benefits of a novel phase change material (PCM) integrated heat pump configuration via simulation. The PCM heat exchanger model is integrated into DOE/ORNL Heat Pump Design Model for heat pump system simulation. This research suggests that the traditional value analysis that focuses on ROI for the building owner significantly undervalues TES technology making economic viability difficult. A more comprehensive value analysis that includes peak demand management and deferred capital for peaking power plants shows that TES should be economically viable for the utility and requires large market penetration and aggregation to fully realize the benefits. Therefore, to facilitate commercialization, new business models are needed that include the broader range of stakeholders and distributes the value of TES proportionally.

4. TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

4.1 COST TARGETS TO ACHIEVE COMMERCIALLY VIABLE THERMAL STORAGE IN BUILDINGS

4.1.1 BACKGROUND

TES is an important way to buffer the temporal variations of renewable energy electricity generation. The intermittent availability of renewable sources can result in rapid fluctuations in power supply to the electric grid, and TES can address this issue by storing thermal energy when electricity production exceeds demand and reinjecting energy into the system when supply is short. Since periods of peak demand normally occur in extreme thermal conditions that require large cooling or heating loads on buildings, TES provides an excellent means to buffer imbalances in the supply and demand of electric power. Furthermore, TES can be more cost effective than electrical storage with batteries.

In addition, the retirement of coal-fired power plants throughout the United States could present new opportunities for TES. Although the construction of natural gas power plants will increase initially to achieve compliance with the Clean Power Plan and other emissions standards, over time, the renewable generation will gain an increasingly large share of the generation mix. Thus, load variability and the need for flexible generation will increase the need for TES.

- **Reduce emissions of greenhouse gases**. TES can help capture excess renewable energy generation from the electrical grid for later use and thus reduce or avoid the curtailment of renewable energy and displace the use of fossil fuels to generate electricity.

- **Reduce demand for peak electricity generation**. In states where a large portion of electricity is generated using fossil fuel power plants, peak demand is usually met by building more carbonemitting peak power plants because renewable resources are unavailable. TES can be used in place of peak power plants in high–electricity demand hours. It can be an effective alternative to adding generation capacity, thereby reducing demand for peak generation.

- **Defer or substitute for an investment in electricity generation**. By absorbing and compensating for fluctuating demand on the electrical grid, energy storage can complement existing power plants to meet energy system needs and save the capital costs to build new power plants.

Adding TES to buildings' HVAC systems usually involves integrating the heat pump system with a TES component to shift most of the electricity used for space cooling and/or heating from peak to off-peak periods. Taking space cooling as an example, TES systems produce ice, chilled water, or another solidified phase change material (PCM) during off-peak periods and then discharge the cooling capacity during peak periods. Commonly used PCMs include paraffin wax, ice, and salt hydrates. Other examples of PCM use in building space-cooling applications include integrating paraffin wax into building walls, which can provide passive cooling by solidifying overnight and then slowly absorbing heat throughout the day [1].

With the development of TES technology, stakeholders are developing new and expanded market opportunities. Combining TES with energy-efficient appliances and demand control can increase end-users' energy savings and participation in demand response programs without reducing comfort. States have developed and promoted various behind-the-meter incentive programs for end-users. The benefits of incentive programs related to TES include:

- **Capitalizing on time-of-use (TOU) rates.** With TOU rates, residential building customers can save money if they reduce electricity use during system peak periods. TES can help customers schedule and shift the use of electricity to low-cost periods.

- **Reduce demand charges.** TES can help customers reduce their peak demand, thereby avoiding large demand charges, which can help commercial and industrial buildings reduce energy costs.

This report analyzes the cost value of deploying TES in buildings. It enumerates the financial benefits of the TOU rate, advanced demand reduction (DR) programs, and deferred peak power plant costs, thereby helping policy makers design new incentive programs that do not undervalue the potential of TES.

4.1.2 METHODS

4.1.2.1 SCOPE OF THIS REPORT

The entire cost targets to achieve commercially viable TES in building application are shown in Figure 1.

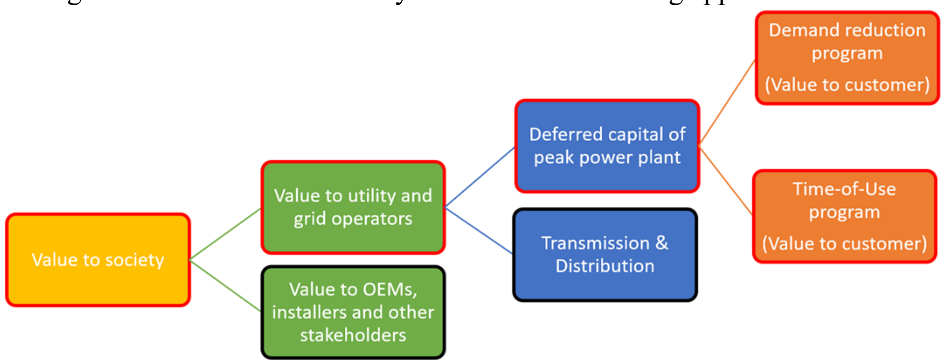

Figure 1. Selected value creation path for cost target calculations

The value of TES to the entire society consists of value to the utility, OEMs, facility installers, and other stakeholders. This report focuses on the value to the utility with emphasis on the deferred capital of peak power plant. The value to the transmission and distribution is not included in this report. The value from the deferred capital of peak power plant is manifested to the customer in the form of demand reduction program and Time-of-Use utility rate program.

In this report, we make an initial estimate of the value of TES by assuming the deferred capital cost of power plant is the full value to reduce peak demand. Therefore, the cost targets within the scope of this report are highlighted in red rectangular outline as shown in Figure 1. Two methods are used to calculate the benefits from deferred capital cost of peak power plant. The first method calculates the aggregated benefits from demand reduction program and the Time-of-Use program. The second method calculates the installed system value directly by sourcing the capital cost of power plants from different technologies. The results from both methods are presented in this report.

4.1.2.2 SIMULATION OF PCM-INTEGRATED HVAC SYSTEM

This study used EnergyPlus to perform whole-building simulations for two typical residential buildings in Indianapolis and Atlanta and assess energy consumption and utility cost of the HVAC systems with PCM energy storage. The PCM drives a chilled water coil and meets the cooling load during peak hours.

For this EnergyPlus simulation, the current EnergyPlus air-source integrated heat pump (IHP) was modified to simulate a multifunctional unit. The IHP object was expanded to include a variable-speed air-source chiller, which charges a PCM storage tank defined in the IHP. Figure 2 shows the TES-integrated HVAC system configuration. It integrates a direct expansion (DX) cooling coil with a supplemental chilled water coil, a PCM storage tank, and an air-source chiller to charge the PCM tank. Since using one compressor to meet both space conditioning and PCM charging would be a multi-functional heat pump to accommodate the mode management logic. EnergyPlus did not have this module and control logic. On the other hand, EnergyPlus is able to simulate two back-to-back systems as shown as in Figure 2. That is why this hardware system was simulated to represent the cost saving under TOU schemes.

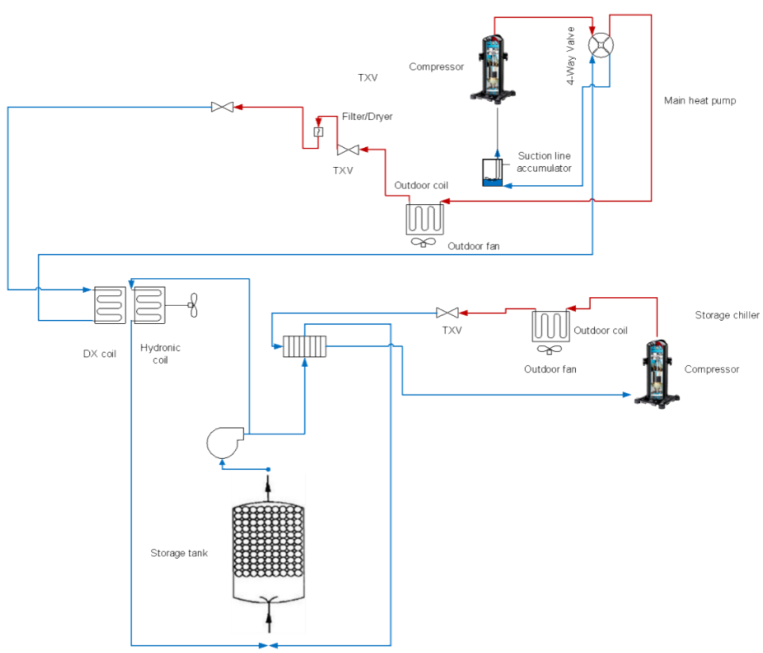

Figure 2. System configuration of a variable-speed DX cooling coil integrated with a PCM energy storage, water cooling coil, and air-source chiller.

4.1.2.3 Building models and utility schedule

To create the building annual energy simulations, a single-family home was chosen from the EnergyPlus library of template buildings. These two houses have 2,500 ft^2 and a slab foundation. It was built according to the International Energy Conservation Code (IECC) 2006 energy code, and the model is specific to individual climate zones. Two homes based on the EnergyPlus template were simulated. One is located in Atlanta (representing a typical southern US climate), and the other is located in Indianapolis (representing a typical northern US climate). The cooling set point used in the model was 23.3°C (73.9°F) throughout the year. A comparison was conducted between the TES-integrated HVAC system and a baseline air-source heat pump system without TES.

To assess the utility saving effect of TES, the utility rate schedule was implemented as shown in Figure 3. Since real-time pricing information is not available in Atlanta at the time of this research, we used TOU rates from Chicago to conduct the case study. Figure 3 depicts hourly electricity prices (cents/kWh) in summer. This is the typical pricing pattern in the cooling season based on average pricing data provided by the ComEd Company, the sole electric provider in Chicago and much of Northern Illinois, for January 2016 through December 2019. This grid signal is implemented using the 'Schedule:Compact' feature in EnergyPlus.

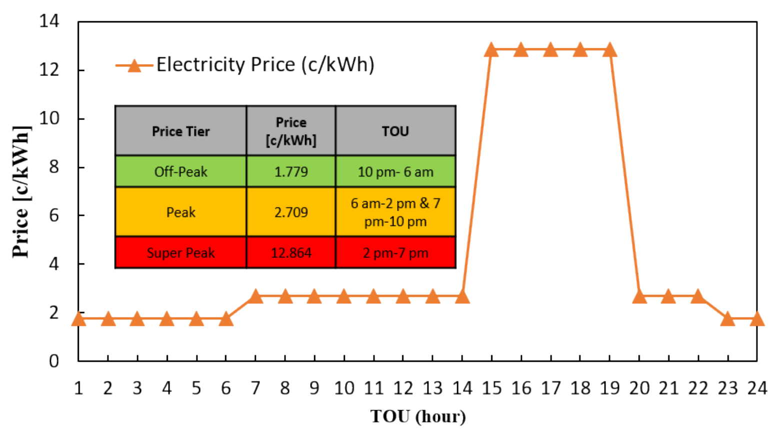

Figure 3. TOU utility rate schedule implemented in the EnergyPlus building simulation.

When the hourly electricity price was above $0.10/kWh, which covers the period from 12 p.m. to 6 p.m. (peak hours) in summer, the TES regulating strategy was to discharge the PCM tank. During peak hours, the compressor was turned off, whereas the fan was still running the airflow rate corresponding to the high (nominal) compressor speed. The PCM storage tank drove the chilled water coil to provide supplemental cooling. The water coil supply air temperature was controlled at 13.0°C. This operation strategy is typically referred to as *load shedding* in demand charge management strategies.

The chiller was auto-sized with the DX cooling coil to maintain a constant ratio between the rated capacities. For charging of the TES system, when the solid PCM fraction was below 90%, the chiller began charging until the solid PCM fraction reached above 99%. The chiller was only allowed to run when the electricity price was below $0.10/kWh (i.e., during off-peak hours). This control strategy can be further optimized by including additional parameters such as ambient temperature. To simplify the analysis, the PCM storage tank was assumed to have an exit temperature of 4.5°C to the chiller during charging and 10.0°C to the water coil during discharging. The PCM had an onset phase change temperature of 5°C and termination temperature of 6°C. The UA, i.e., heat transfer coefficient multiplied with heat transfer area, were auto-sized to satisfy the temperature settings.

Table 1 shows cooling energy simulation results when coupled with PCM storage in Atlanta. During the peak hours, the PCM TES drove the water coil to meet the zone load. The total cooling energy delivered, and the total electricity consumption contains, the energy from both the DX cooling coil and air-source chiller during off-peak hours. Although the energy consumptions with PCM storage for this specific system architecture are higher than the baseline, the total utility costs are lower because the charging operations used low-cost electricity in off-peak hours.

Table 1. Cooling seasonal energy simulations in Atlanta, coupled with PCM energy storage.

	Total cooling delivery (kWh)	Annual unmet comfort hours (hr)	Total electricity consumption (kWh)	Total seasonal coefficient of performance (W/W)	Cost ($)	Peak DR (kW)
Baseline	11,069.8	0	2,423.0	4.57	251.1	0
PCM storage	10,806.7	0	2,523.6	4.28	175.0	2.44

Table 2 presents cooling energy simulation results when coupled with PCM storage in Indianapolis. It indicates similar utility cost saving as the case in Atlanta.

Table 2. Cooling seasonal energy simulations in Indianapolis, coupled with PCM energy storage.

	Total cooling delivery (kWh)	Annual unmet comfort hours (hr)	Total electricity consumption (kWh)	Total seasonal coefficient of performance (W/W)	Cost ($)	Peak DR (kW)
Baseline	8,351.6	0	1,797.6	4.66	191.7	0
PCM storage	8,374.9	0	1,921.9	4.37	137.1	2.09

4.1.2.4 THE VALUE OF REDUCED PEAK DEMAND

The goal of this study is to streamline the cost targets to achieve commercially viable thermal storage in buildings. TES systems, unlike adding electricity generation capacity or building new power plants, are traditionally owned, operated, and maintained by the end-user, but different business models could be evaluated where the utility shares some of these costs. End-users and utilities should be encouraged to install TES systems because their overall benefits compare favorably to those from adding generation capacity or implementing demand response programs. The cost savings from reducing peak demand in the following three aspects are addressed in the next subsections:

1. Cost savings from existing TOU rates offered by utility companies to residential customers.

2. Financial value from existing DR incentives offered by utility companies to commercial customers.

3. Cost value from directly from the capital deferment for new peaking generation.

4.1.2.5 Cost savings from existing TOU utility rate

Utility companies use several different pricing schemes for demand response. Among all the schemes shown in Figure 4 (adapted from [2]), TOU pricing is the most common scheme for utility companies. Therefore, this report used TOU utility rate as a representative to demonstrate cost savings.

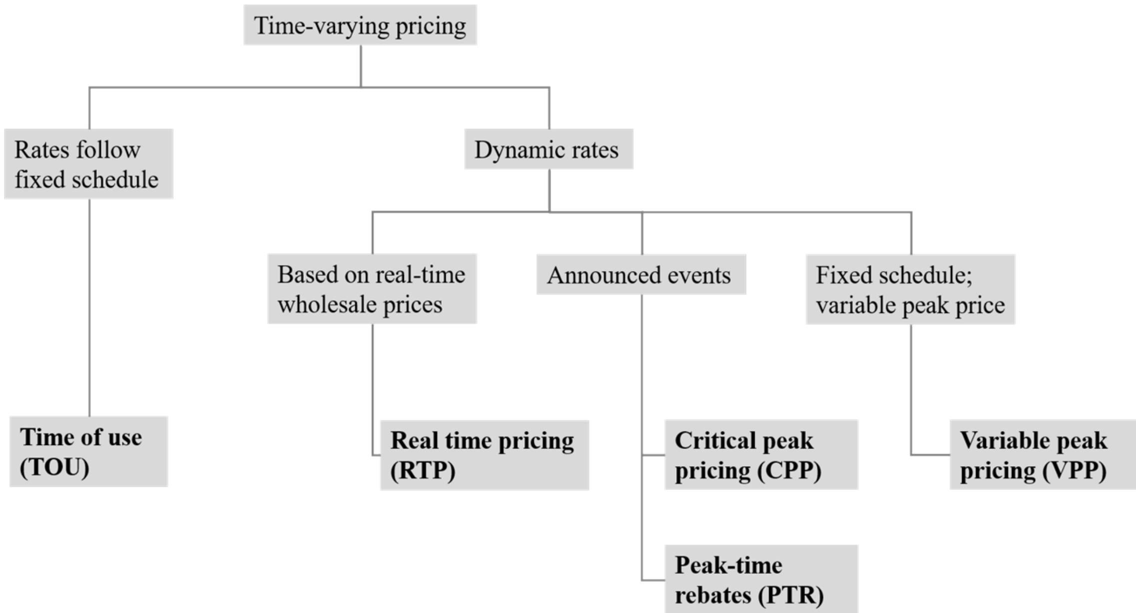

Figure 4. Common utility pricing schemes adapted from [2].

In the United States, residential customers in some states pay a flat rate for electricity, whereas in other states, customers are charged using real-time pricing. TOU utility rates are common for commercial and industrial customers [2], and TOU programs are the most common approach to incentivize demand response. Table 3 lists the cost savings to end-users from TOU pricing in Atlanta and Indianapolis from the EnergyPlus building simulation described above. The annual utility savings are $76.10 for the building in Atlanta and $54.60 for the building in Indianapolis. The TOU cost savings per unit DR are $41.10/kW for Atlanta and $35.20/kW for Indianapolis.

Table 3. Cost savings to end-users from TOU utility savings in simulated residential building in Atlanta and Indianapolis.

	Maximum electrical power of DR (kW)	Minimum electrical power of DR (kW)	Average electrical power of DR (kW)	Utility savings ($)	Utility savings/average DR ($/kW)
Atlanta	2.44	1.25	1.85	76.10	41.10
Indianapolis	2.09	1.00	1.55	54.60	35.20

4.1.2.6 Value from existing DR incentive programs

In addition to TOU programs, utility companies can provide financial incentives to consumers in return for the consumers' ability to control their equipment during peak demand periods. This consumer-based control enables the utility company to reduce the load for that period and avoid using peaking capacity. Additionally, utility companies can alert consumers to opportunities to receive financial compensation for voluntarily reducing their load during peak demand periods. Examples of this type of program include emergency demand response programs, capacity biding programs, and ancillary service programs.

However, the cost savings from existing Demand Response incentive programs are subject to regulations of the electrical grid administrator. These regulations are set by three primary entities: The Federal Energy Regulatory Commission, independent system operators, and public utility commissions. Each of these entities oversees a different area of control. The Federal Energy Regulatory Commission monitors energy transfer across state lines, independent system operators monitor transmission and generation in the area in which they operate, and public utility commissions regulate the activities of utilities within their respective states, including capacity acquisition, which can apply to the integration of TES [3].

This survey of Demand Response incentive programs focuses on three regions: California, Texas, and New England. Taking California as an example, Southern California Edison (SCE) offers a one-time incentive of $300/kW when joining the company's qualifying DR program. The benefit of joining the SCE DR incentive program ranges from $50/kW to $240/kW depending on the combinations of enrolled DR programs, which include automated critical peak pricing, real-time pricing, capacity bidding, and demand response auction. After considering various combinations of Demand Response programs, the average cost savings from participating in the SCE Demand Response program is estimated to be $400/kW. Table 4 shows the estimated cost savings from existing Demand Response incentive programs in California, Texas, and New England.

Table 4. Cost savings from existing DR incentive programs of California, Texas, and New England regions.

Utility	Cost savings ($/kW)	Reference
California (SCE)	400	[4]
Texas (Austin Energy)	350	[5]
New England (Eversource)	250	[6], [7]

4.1.2.7 Cost savings from capital deferment for new peaking generation

In 2015, coal-fired power plants accounted for more than 80% of the nearly 18 GW of retired capacity. The US Energy Information Administration projects that approximately 90 GW of coal-fired capacity and 62 GW of older natural gas and oil capacity could retire by 2040 as a result of the Clean Power Plan unveiled by the Obama administration [8]. The US Environmental Protection Agency and US Energy Information Administration have both projected that renewables and newer natural gas plants will overtake most of the generation share currently held by coal, whereas the generation share held by nuclear power will remain relatively constant.

Application of TES can enable deferring investments in new peak electricity generation since power supply and demand variations can be buffered via storage, which enables a plant's generation capacity to be more closely matched to the average daily power demand as opposed to the peak demand spikes that are present without TES. In this manner, TES can complement existing power plants to meet energy system needs and save the capital costs of building new power plants. Table 5 lists the net annualized life cycle cost of power generation for different types of new power plants over a 30-year lifecycle. These values are obtained from NREL's 2021 Electricity Annual Technology Database, using same assumptions as for the levelized cost of electricity (LCOE) [9]. New power plants using nuclear and biopower have the highest capital cost. Power generation using photovoltaics with electricity storage is based on the rated power and 25% capacity factor is assumed.

Table 5. Estimated cost of new peak power plants using different technologies.

Power plant type	Annualized cost ($/kW)
Photovoltaics (with 8-hour electricity storage)	908
Concentrated solar power	411
Natural gas	454
Nuclear	648

Biopower	650

4.1.3 RESULTS AND CONCLUSIONS

The market for energy storage poses many challenges, and the monetization of services provided to the electrical grid by TES can improve its market potential. The economic value from implementation of TOU utility rates, participation in DR incentive programs were aggregated (or "stacked") to see the range of benefits from using TES in buildings. Figure 5 shows the installed system incremental value to building owners and to the utilities from TES implementation in buildings. The colored region in Figure 5 spans the expected range of demand reduction from a TES system per typical single family residential building. The range of 1 to 2.4 kW shown here was obtained from the whole-building simulation described in Section 2.1. It will vary by building size, TES system type and size, and climate, but the range of 1 to 2.4 is expected to be roughly representative of US single family residential buildings. The red area indicates the savings from implementing the TOU utility rate alone, which gives utility savings between $35 and $100.The green area indicates the aggregated value from implementing the TOU utility rate and DR incentive programs. Depending on the different incentive programs in different regions, the combined cost savings range from $288 to $1,069. The maximum savings are observed under California's DR incentive program. The installed system value from deferred capital cost of peak power plant is calculated in Figure 6.

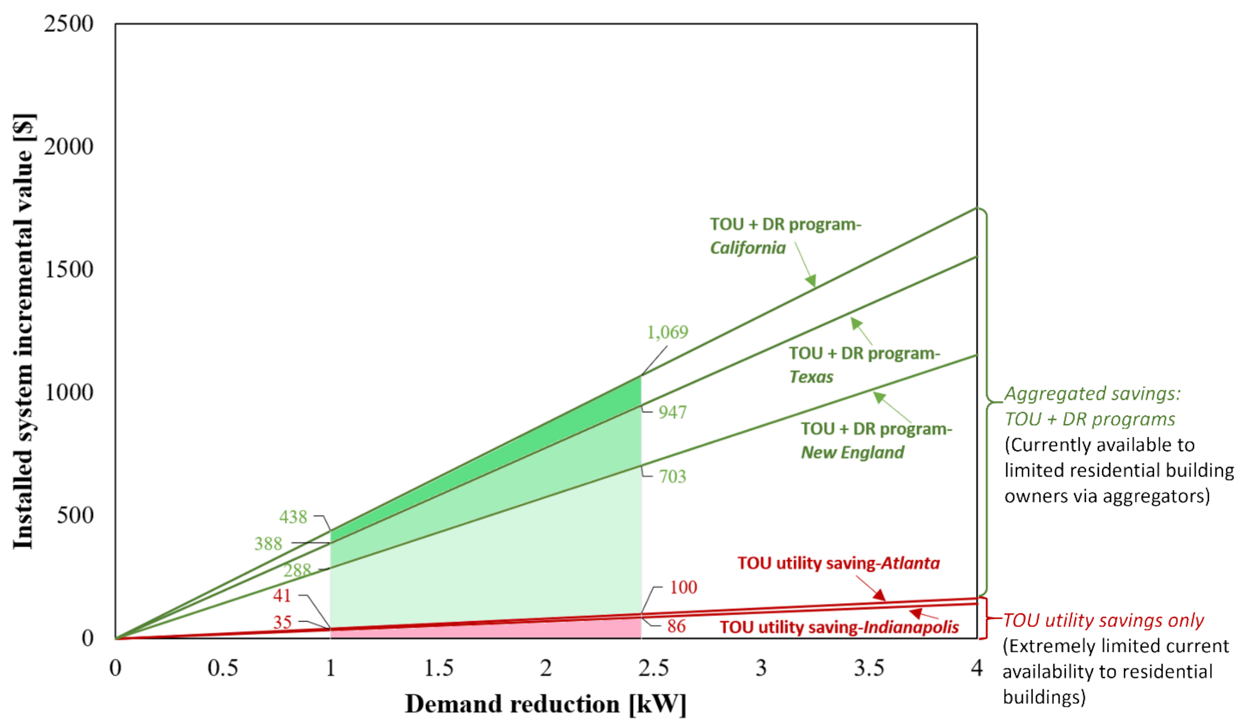

Figure 5. Installed residential system incremental value from TOU and DR programs for TES application in buildings.

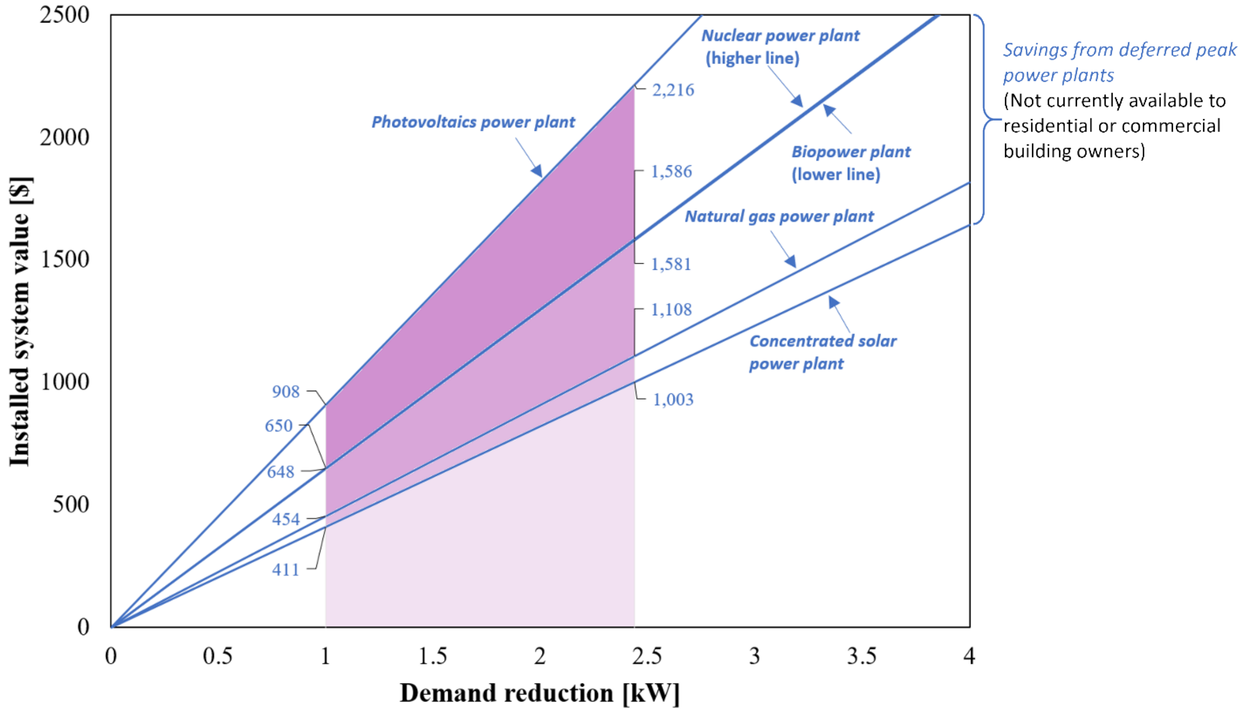

Figure 6. Installed system value from peak power plants for TES application in buildings.

The purple area represents savings from the deferred capital cost of peak power plants from different technologies. As compared to Figure 5, the aggregated value from implementing the TOU utility rate and DR incentive programs is already included in the deferred capital cost of peak power plants, therefore, the cost benefits shown in Figure 6 is larger than those in Figure 5. Depending on different types of power plants, the cost savings range from $411 to $2,216. If TES is used as an alternative for a photovoltaics based peak power plants, the maximum cost savings are $2,216. For the most common peak power plant (i.e., a natural gas power plant), the maximum cost savings are $1,108.

Figure 5 and Figure 6 summarizes the results of this study by displaying the benefits of deploying TES in buildings. Figure 5 aggregates the financial benefits of the TOU rate, advanced DR programs, and Figure 6 shows the benefits from deferred peaking power plant costs. This information helps policy makers design new incentive programs that do not undervalue the potential of TES. Existing incentives offered to residential customers are inadequate to stimulate a market for thermal energy storage. TES technology will be ready for widespread commercialization once a business model is created to link building owners and utilities to the full value of the technology.

4.2 SIMULATION OF A PCM INTEGRATED HEAT PUMP USING TIME-OF-USE UTILITY STRUCTURE BASED CONTROL STRATEGY FOR DEMAND RESPONSE

4.2.1 OBJECTIVE

As described in section 4.1.1, taking advantage of the thermal energy storage ability, a number of feasible PCM application schemes have been proposed to reduce the energy consumption of buildings ([10]). Most schemes are designed to utilize the thermal storage ability in a passive way by exploiting the diurnal ambient temperature swings. For instance, in building space-cooling applications, paraffin wax is integrated into building walls and provide passive cooling by solidifying overnight and then slowly absorbing heat throughout the day ([11]). An alternative solution to address the load shifting on the power grid is to add actively integrated PCM with building equipment ([12]). However, most of the previous PCM integration approaches were developed for new buildings ([13]), or require significant modifications on the existing envelope.

The 2nd part of this project evaluated a novel PCM integrated heat pump (PCM-HP) system via simulation to reduce the residential HVAC electrical demand using a Time-of-Use based control strategy to help building end-users shift the use of electricity to low-cost period. The proposal PCM-HP system for heating and cooling can enable year-round demand flexibility for the power grid.

4.2.2 METHODOLOGY

4.2.2.1 Discretized PCM Heat Exchanger (PCM-HX) Model

A one-dimensional PCM tank model, which discretizes the PCM tank and refrigerant tube into small control volumes was developed as shown in Figure 7. Each control volume can have different PCM temperatures, properties and heat transfer coefficients as model inputs. The PCM tank is charged by a wrapped tank condenser and discharged by an internal refrigerant coil. The model accounts for the PCM heat conduction between adjacent nodes. The PCM mixing and natural convection between adjacent control volume are neglected for simplicity.

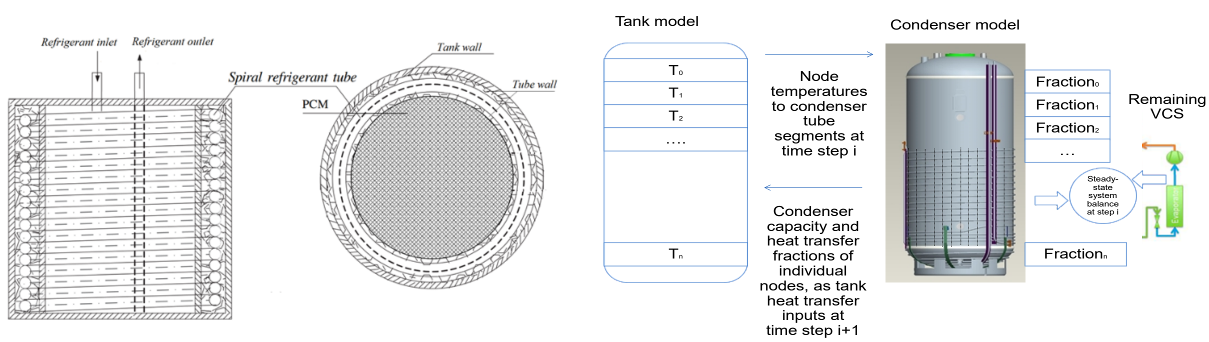

Figure 7: One-dimensional wrapped tank PCM-HX model.

The properties of the graphene enhanced PCM used in this study is listed in Table 6 .

Table 6: Properties of PCM Material ([14]).

Properties	Unit	Value
Melting temperature	°C	37

Latent heat	kJ/kg	210
Thermal conductivity	W/m*K	0.15 (liquid), 0.25 (solid)
Density	kg/m^3	840 (liquid), 920 (solid)
Specific heat	kJ/kg*K	2.63 (liquid), 2.21 (solid)

Figure 8 shows the PCM heat transfer coefficient at the outer surface of the tube is a function of PCM melt fraction.

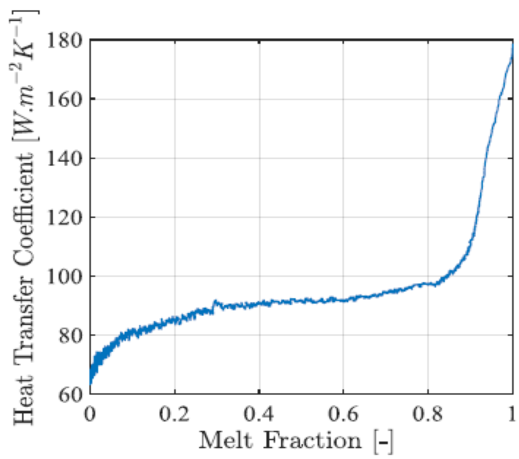

Figure 8: PCM side heat transfer coefficient versus PCM melt fraction ([14]).

To demonstrate the simulation capability of the PCM heat exchanger model, Figure 9(a) shows the heat pump charging process. Different node represents different control volumes. The charging heat is not uniform among different control volumes at the starting phase (as shown by the scattering points), but the heat is balanced out via heat conduction through the charging process. Figure 9(b) shows that heat pump COP decreases with the increase of the PCM temperature during PCM melting process.

(a) (b)

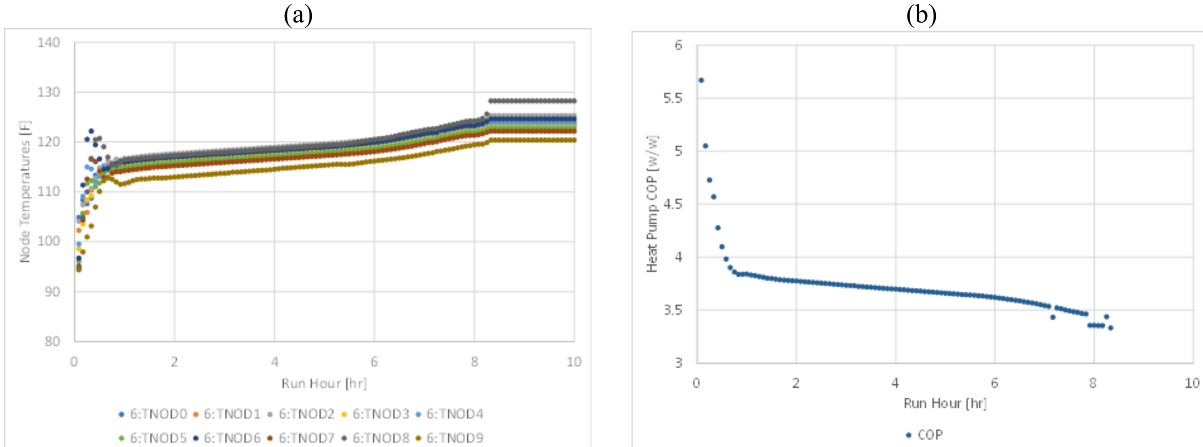

Figure 9: (a) Transients of PCM tank charging process; (b) Transients of PCM integrated heat pump COP during charging process.

The PCM integrated heat pump is to be operated under continuous switching between charge and discharge modes. Figure 10 shows the temperatures of PCM control volumes during continuous charge and discharge operations.

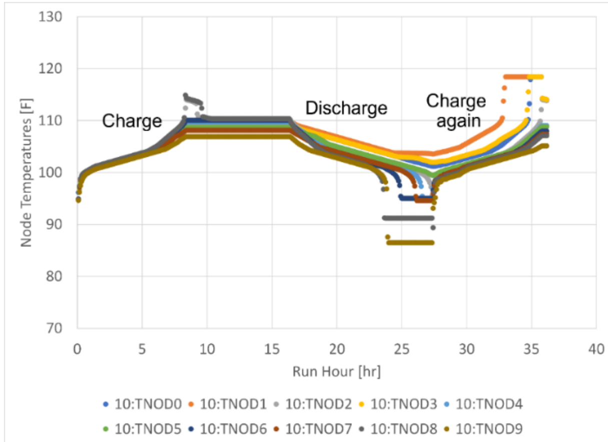

Figure 10: PCM node temperatures during continuous charge and discharge operations.

4.2.2.2 System Simulation

The PCM heat exchanger component model described in previous section was added to the component library of the DOE/ORNL Heat Pump Design Model ([15]). HPDM allows user to integrate this PCM heat exchanger model with other component models to assemble a PCM integrated heat pump system. Figure 11 shows the system configuration of PCM integrated heat pump simulated in this study. For instance, when the system is operated in heating charge mode, the heat in sub-cooler is used to melt PCM. When the system is operated in heating discharge mode, it elevates stored heat for space heat at low ambient temperatures and bypass the outdoor coil.

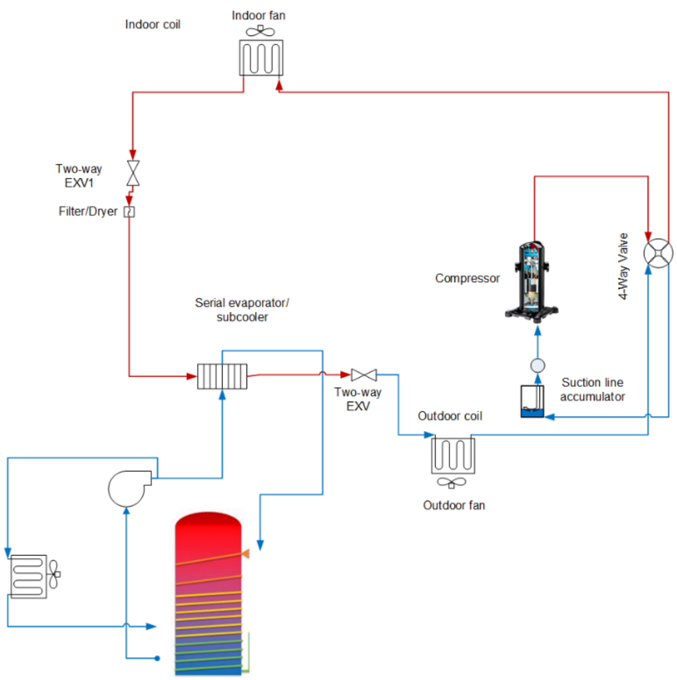

Figure 11: System configuration of PCM integrated heat pump.

In addition to the PCM-HP, a 4.5-ton single-stage heat pump was simulated as the baseline for comparison. The baseline direction expansion system has rated EER of 13.0, and HSPF of 9.0 per AHRI 210/240 test standard ([16]), and was calibrated using the manufacturers product specification. For the

PCM integrated heat pump, four modes, i.e., cooling charge, cooling discharge, heating charge, heating discharge, were modelled. Since the response of PCM tank are much slower than the heat pump, the PCM integrated heat pump simulation can be treated as quasi-steady-state or steady-state simulation. This is a widely accepted assumption, for example, the heat pump water heater model in EnergyPlus is a quasi-steady-state model ([17]). To size the PCM tank, The coldest day in December 2019 and the the hottest day in August 2019 in Chicago are used to calculate the required PCM capacity to maintain 4-hour 50% peak load reduction. The resulting capacity of PCM tank is 14.78 kWh.

(a) (b)

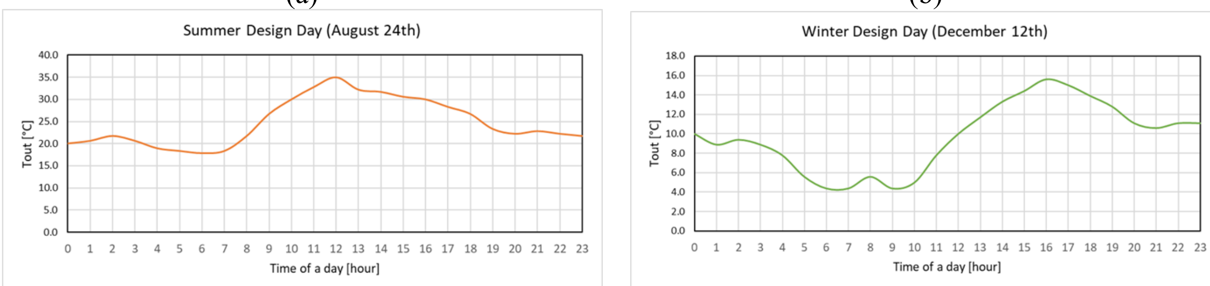

Figure 12: Sizing PCM tank capacity using (a) summer design day; (b) winter design day.

To schedule the mode switching of PCM-HP, the system is operated under discharge mode during utility peak hours until the PCM tank is exhausted. Once the stored energy in PCM tank is exhausted, the system switches to charge mode, meanwhile, offer space cooling in summer or space heating in winter.

4.2.3 CASE STUDY

To obtain the building load, EnergyPlus was used to simulate a 2,500 ft^2 single-family home which was selected from the EnergyPlus library of template buildings. The case study adopted weather data in Chicago and a sample utility TOU structure in ComEd utiltiy company to demonstrate the efficacy of the PCM integrated heat pump system. It was assumed that for both baseline direction expansion system and the PCM integrated system, the indoor heat exchanger capacity always satisfies the building load. For summer application, the indoor set point was specified as 80 °F. Figure 13 shows the electricity consumption for cooling mode application during August 17th to August 20th, 2019. The red shaded area represents the grid peak. The PCM integrated heat pump shows significnat demand reduction during grid peak under discharge mode. During off-peak hours, PCM-HP consumes more power than the baseline system when it is operated under charge mode.

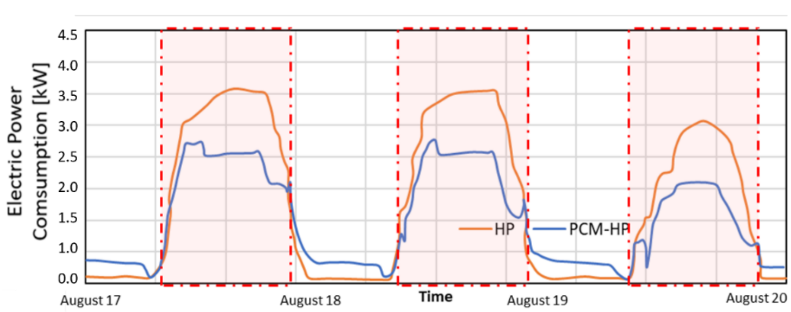

Figure 13: Power consumption of PCM-HP vs DX-baseline, August 17-20th, 2019, Chicago (summer application).

For winter application, the indoor set point was specified as 70 °F. Figure 14 shows the electric power consumption of PCM integrated heat pump and the baseline direct expansion heat pump for heating application from December 5th to 9th, 2019. Similar to the cooling application, the PCM-HP consumes less power than baseline system during peak hours and the PCM-HP has more electric consumption during the off-peak hours when it is operated in charge mode.

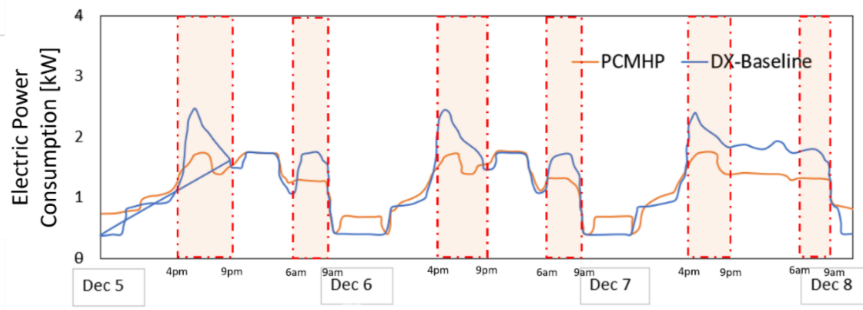

Figure 14: Power consumption of PCM-HP vs DX-baseline, December 5-8th, 2019, in Chicago (winter application).

Table 7 shows the overall utility cost using PCM-HP and the baseline system in August 2019 and December 2019. The utility saving is 24.6% for cooling application and 25.8% for heating application.

Table 7: Monthly utility cost in Chicago using PCM-HP and baseline in August and December 2019.

	Operation Mode	
	August 2019, Cooling Mode	December 2019, Heating Mode
Baseline DX system	\$ 110.98	\$ 194.21
PCM-HP	\$ 83.6 (24.6%↓)	\$ 144.94 (25.8%↓)

As a summary, the potential for using phase change material (PCM) as a thermal storage medium to enable grid-responsive control of heat pump (HP) system was evaluated. The objective of this research is to design a novel and practical PCM integration with existing heat pump system. High-fidelity models for building, heat pump and PCM heat exchangers were developed. A Time-of-Use utility structure-based control strategy was implemented to regulate the PCM tank charge and discharge mode switching. Compared with a conventional electric heat pump, the PCM integrated heat pump shows superior performance on load shifting and utility cost reduction. It demonstrates 24.6% utility saving in a summer month and 25.8% utility saving in a winter month.

5. COMMUNICATIONS, COMMERCIALIZATION POSSIBILITIES, AND FUTURE COLLABORATION

The following conference paper was published and presented, which summarizes the main findings of this work:

Li, Z., Catano, J., Gluesenkamp, K., Shen, B., Laclair, T., Comparin, R., Welch, D., 2022. Simulation of a PCM Integrated Heat Pump Using Time-of-Use Utility Structure based Control Strategy for Demand Response. 19th International Refrigeration and Air Conditioning Conference Purdue. Paper # 2508.

Regarding commercialization opportunities, the focus of the work was to quantify the benefits available from thermal energy storage integrated with heat pumps. It was found that the benefits can be greater than the costs; however, the benefits do not currently accrue to the same stakeholders that would bear the cost. Thus, policy and market mechanisms need to be aligned to enable the value to be captured. Specifically, currently the benefits of thermal storage accrue primarily to utilities and transmission and distribution operators, whereas the costs of thermal storage are primarily borne by building owners.

This report leaves the identification of market and policy approaches for future work. Nevertheless, a brief comment is warranted here: an example of a way to bring the benefits and costs in alignment would be utility tariffs that accurately reflect the cost of peak operation to each building owner. Of course, many approaches are possible, and each approach has challenges. The partners in this project anticipate future collaboration for joint development to identify components and systems that can enable cost-effective thermal storage systems for buildings.

6. CONCLUSIONS

The full value of TES to the entire society consists of value to the utility, OEMs, facility installers, and other stakeholders. This report focuses on the value to the utility with emphasis on the deferred capital of peak power plant. The value from the deferred capital of peak power plant is manifested to the customer in the form of demand reduction program and Time-of-Use utility rate program. An initial proxy of the value of TES is made by assuming the deferred capital cost of power plant is the full value to reduce peak demand. Three levels of financial value of TES systems were assessed. Two are currently available to some residential customers: (1) the benefit from TOU pricing alone and (2) the benefit from TOU pricing in combination with DR incentive programs. The third level was computed as the full cost of deferred capital cost of peaking power plants. This represents the potential value that could be gained by the utilities or conceivably be offered to consumers.

This report suggests that the traditional value analysis that focuses on ROI for the building owner significantly undervalues TES technology making economic viability difficult. A more comprehensive value analysis that includes peak demand management and deferred capital for peaking power plants shows that TES should be economically viable for the utility and requires large market penetration and aggregation to fully realize the benefits. Therefore, to facilitate commercialization, new business models are needed that include the broader range of stakeholders and distributes the value of TES proportionally.

In addition, this report evaluated the benefits of a novel phase change material (PCM) integrated heat pump configuration via simulation. A one-dimensional PCM heat exchanger model which discretizes the PCM tank and refrigerant tubes into small control volumes is developed. Each control volume can have different PCM temperatures, PCM properties, and heat transfer coefficients. The PCM tank is charged by a wrapped tank condenser and discharged by an internal refrigerant coil. The PCM heat exchanger model is integrated into DOE/ORNL Heat Pump Design Model for heat pump system simulation.

To demonstrate the performance of the PCM integrated heat pump, a case study in Chicago was performed. A Time-of-Use utility structure-based control strategy is implemented to schedule the PCM tank charging and discharging mode switching. Compared with a conventional electric heat pump, the PCM integrated heat pump shows superior performance on load shifting and utility cost reduction. As a result, the proposed system demonstrates 24.6% utility saving for cooling application and 25.8% utility saving for heating application.

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