Analysis of Residential Time-of-Use Utility Rate Structures and Economic Implications for Thermal Energy Storage

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ABSTRACT

Thermal energy storage (TES) is an increasingly popular tool to level out the daily electrical demand and add stability to the electrical grid as more intermittent renewable energy sources are installed. TES systems can locally decouple high thermal loads from the operation of a heat pump or reduce the electrical energy demand of the heat pump by providing a more favorable temperature gradient. In addition, many policy makers and utility providers have introduced time-of-use (TOU) rate schedules for residential customers to better reflect the price of electricity generation and demand for specific times. TOU rate schedules price grid-provided electricity differently throughout the day depending on the region's climate, time of year, and electrical production portfolio. Large differences between on-peak and off-peak electrical prices may create an economic advantage for a residential customer to install a TES system. In this work, the economic and energy savings are calculated for a modeled 223 square foot residential building with water/ice-based TES using a TOU rate structure. The weather data is from Fresno County, CA, ASHRAE climate zone 3B, and a representative residential TOU utility rate structure from a utility provider in California was used. The simulation was carried out for cooling only during a week of extreme hot summer daytime temperature and the results showed that total energy consumption could be reduced by 14.5% with an 87.5% reduction in on-peak energy usage when the TES is installed. The cost of operating this system for space cooling was reduced by nearly 20% using the sample utility rate plan.

1. INTRODUCTION

As of 2018, buildings in the United States accounted for about 40% of the total U.S. energy consumption and 75% of the total electricity consumption (U.S. Department of Energy, 2011; US EIA, 2020). The major electric load comes from the residential buildings comprising 80% of the total electricity use, and 78% of the peak period use during 2-8 PM local time. Peak periods, generally, have the largest energy demand on the grid. Heating, ventilation, and air conditioning (HVAC) loads comprise 50% of building electricity consumption (Goetzler *et al.*, 2019). HVAC systems and the need for space cooling may exacerbate electrical demand issues during summer peak times, since as much as

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50% of the grid electricity demand comes from homes mostly used for air conditioning (Cui *et al.*, 2017). Residential buildings can play a major role in reducing peak hour energy demand while maintaining the occupants' comfort by introduce energy storage mechanisms to shift load from on-peak to off-peak hours (Arteconi *et al.*, 2019; Junker *et al.*, 2018).

Time-of-use (TOU), real-time-pricing (RTP), and other time-based utility rate structures are becoming more available to residential customers. TOU structures price electricity differently at specific hours during the day depending on the climate, time of year, the utility provider energy generation portfolio, and historical or predicted demand. On-peak hours are those where the electrical price is highest per unit energy for all electricity used from the grid in that time span. In summer months of warm climates, on-peak hours may be mid- to late-afternoon. In winter months of colder climates, on-peak hours may be early- to mid-morning. TOU rates vary wildly across the US. TOU rates are predetermined and static during the contract period. The TOU analyzed here is an energy rate prized per kWh of energy used. Some TOU rates are demand based priced per average kW over short intervals. RTP rates reflect the instantaneous cost of bulk wholesale of electricity. Typically, prices are not disclosed to the customer more than a few days' notice but can be as short at three hours' notice the day prior. RTP rates are rare for residential customers due to this uncertainty. However, RTP rates generally do follow an hourly and monthly trend that may give the customer an economic advantage with proper controls and forecasting.

Researchers have investigated the impact of time-based utility pricing on residential electricity use with different load and energy demand control strategies. Findings suggest that electrical utility costs and peak hour energy demands associated with air conditioning can be reduced depending on utility rate structure, weather, building occupancy, and building thermal capacitance (Newsham *et al.*, 2010).

Yoon *et al.*, (2016) demonstrated that depending on the size of house and utility price, up to 24.7% of HVAC loads can be reduced during peak times via demand response control and can provide up to 10.8% cost savings while maintaining occupant thermal comfort. Schibuola *et al.*, (2015) simulated heat pump control based on RTP, with up to 30% of electricity consumption cost savings. Gottwalt *et al.*, (2011) simulated the cumulative load profiles using TOU tariffs with smart appliances and concluded that the TOU tariffs could create new grid-level demand peaks which may not benefit the users economically, however, this practice may still benefit the utility providers by shifting more energy load to off-peak hours and effectively smoothing the demand curve.

Thermal energy storage (TES) is a popular energy storage solution to alleviate peak energy demand and may provide economic advantages to its users. TES can be realized by incorporating phase change materials (PCMs) into heat exchangers either coupled to the existing HVAC system or interfacing directly with the space to be conditioned, thus creating a high-performance demand response energy storage system (Dong *et al.*, 2019). TES systems allow conventional air conditioning machinery to operate during off-peak hours, but leverage the isothermal storage properties of PCM to provide cooling during on-peak hours (Dincer *et al.*, 1997). PCMs may be incorporated as passive or active TES. Passive systems have no coupling to HVAC systems and do not respond to control schemes, but still may reduce building energy consumption (Akeiber et al., 2016; Arivazhagan et al., 2020; De Gracia et al., 2015; Soares et al., 2013; Sonnick et al., 2020).

Active TES systems, the focus of this paper, couple the TES to the HVAC system to respond to pricing and thermal signals. Active systems offer a high level of control of the TES and can improve energy storage efficiency (Ali et al., 2015; Sarbu et al., 2018) evaluated residential HVAC loads' demand response potential, suggesting that value can be added by using even a small TES system. Table 1 summarizes studies on the energy and cost savings with PCM-based TES active storage.

The literature in Table 1 confirm that the cooling energy demand can be significantly shifted to off-peak times by using PCM-based active TES system integrated with building equipment such as HVAC (Dong et al., 2019; Waqas et al., 2018). In addition, some studies have concluded that using PCM-based active TES to offset the peak load is more financially viable in the regions having higher electricity prices for on-peak hours and where the cooling systems dominate the demand (Liu et al., 2012; Waqas et al., 2018).

Table 1. PCM-based active TES for load shifting

Author	Location	System Configuration	Energy savings	Cost savings
Bruno *et al.*, 2014	Adelaide, Australia	PCM storage with chiller	13% energy savings	Not reported
Sehar *et al.*, 2012	Various USA locations	Ice storage coupled with chiller	Peak time savings	35% annual cost savings
Mosaffa *et al.*, 2016	Tehran, Iran	PCM slabs coupled with vapor type compressor	7-9% energy savings	Not reported
Jaber *et al.*, 2012	Amman, Jordan	PCM coupled with indirect evaporative cooling system	80% less cooling load	7-8-year payback
Zhu *et al.*, 2011	Beijing, and Hong Kong	PCM layers in air conditioning system	20% peak load reduction	11% cost reduced
Real *et al.*, 2014	Madrid, Spain	PCM storage tanks with HVAC	18.97% energy saved	Not reported
Chaiyat, 2015	Chiang Mai, Thailand	PCM integrated in conventional HVAC system	Load decreased by 3.09 kWh/d	9.1% cost saved, 4.15 yr payback
Pop *et al.*, 2018	Variable (12 global climates)	PCM integrated in fresh air-cooling system	7-41% energy saved	Not reported
Hirmiz *et al.*, 2019	UK	Heat pump integrated PCM	Load shift of 6 hr., COP increased	Not reported
Dong *et al.*, 2019	Knoxville, TN, USA	PCM integrated with electrical Heat Pump	13% less power consumed	Electricity cost saved 19%

The literature survey shows that previous work on demand side management to off-set peak load using time-based utility pricing is mostly based on a demand response control without a TES. Some studies investigate an active PCM storage with heat pump, HVAC, or air conditioning system but most of them have focused on energy savings by shifting the load from high demand periods to low demand periods without considering the time-based utility pricing and a direct use of conventional VCS to accomplish heat transfer with TES.

In this work, a southern California residential building's summertime cooling load during a week of extreme high temperatures is comparatively modeled with and without active TES. The TES is directly coupled to a vapor compression system and serves as the VCS condensing unit during peak hours rather than the ambient air. The PCM embedded in the TES for this analysis is ice/water with a phase change temperature of 0°C, and only interacts with VCS, not directly with the building. A residential TOU utility rate from a utility provider in California, corresponding to the climate zone 3B, is used to assess the potential economic savings for the customer. The VCS was modeled using Engineering Equation Solver (EES). Section 2 explains the methodology for this work including control mechanisms. Section 3 describes the component model. Results are presented and discussed in Section 4.

2. METHODOLOGY

The complete modeled system is modular with several models converging including a simplified building, an R410A vapor compression system (VCS), TES with embedded PCM and heat exchanger, thermostatic controls, and a TES control strategy. The thermostat monitors the building indoor temperature and dispatches a call for cooling to the VCS system. The TES control strategy determines if the cooling is provided from the TES or by traditional VCS operation coupled to the ambient based on the time of day and utility electrical rate. The TES control strategy uses this same data to recharge the TES system using the same VCS, coupling the TES to the ambient when appropriate. The PCM used in this study is water/ice. The ambient weather data and TOU utility rate structure are from the same geographic region, ASHRAE climate zone 3B. The system is simulated for one week with a time step of one minute.

2.1 System Overview

A basic vapor compression system (VCS) is coupled to the water/ice-embedded TES. The TES heat exchanger is assumed to have infinite heat transfer coefficient and is at 0°C at all times. The PCM heat exchanger can serve as either evaporator or condenser in the VCS, depending on the mode of operation.

Figure 1a shows the baseline system whereby the building is cooled with VCS acting as a conventional air conditioning system. The building air is cooled by the VCS evaporator and heat expelled into the ambient at the condenser. The VCS moves heat from the building to the ambient across a positive temperature gradient. The increasing width of arrows represent added heat.

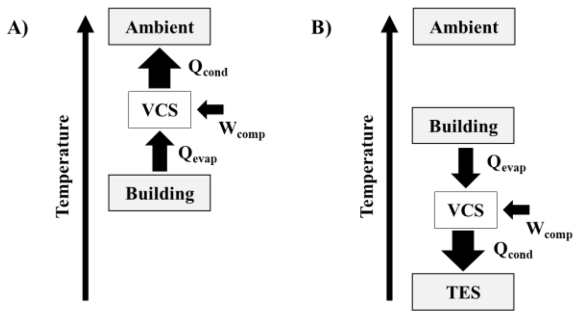


Figure 1: Comparison of temperature gradients for a) normal VCS operation and b) TES-assisted cooling

The building cooling performance can be improved with PCM-embedded TES, using negative temperature lift to introduce a more favorable gradient for which the VCS to operate, as illustrated in the Figure 1b. In this mode, the VCS condenser is coupled to the colder temperature of the PCM, 0°C in this system. Thus, the VCS has a negative temperature gradient to move the building thermal load. This allows the VCS to operate at a much higher performance as compared to the baseline.

2.2 System Operating Modes and Controls

There are four operating modes (0,1,2,3, respectively) of the system as shown in Figure 2.

- In standby mode (0), the VCS is off the building responds to ambient thermal loads and solar heat gains.
- In the normal operating mode (1), the building is cooled by conventional VCS refrigeration with no TES involvement. The condenser heat, $Q_{cond,}$ is the heat being dumped to the ambient and the evaporator heat, $Q_{evap,}$ is the heat removed from the building and directed to the heat pump.
- In charging mode (2), the PCM HX operates as the evaporator and the latent heat of freezing is removed from the PCM. The VCS condenser heat is rejected to the ambient.
- In discharging mode (3), the PCM HX is the condenser and the heat, Q_{cond}, is absorbed by the PCM through the latent heat of melting. In this mode, the COP is higher than in normal operation.

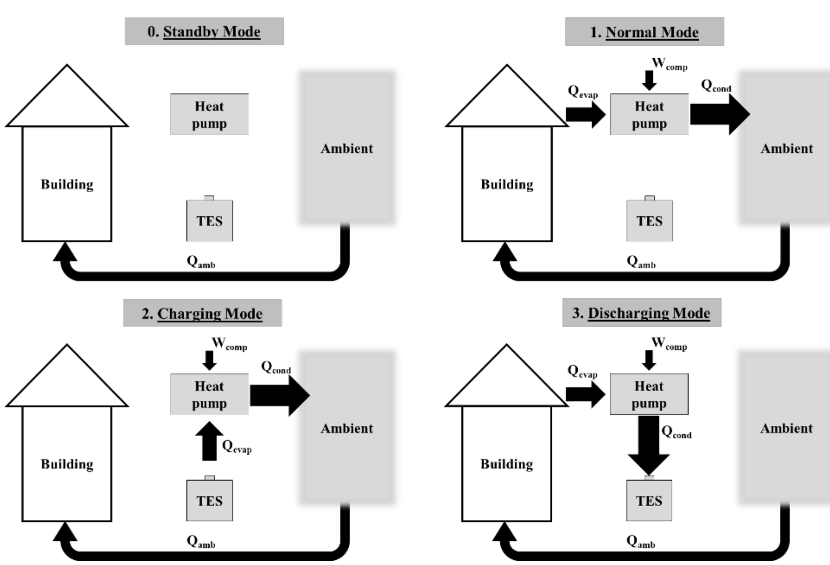


Figure 2. Energy flows in the four operating modes for summer (cooling only)

The operating mode of VCS-TES system is selected by the controls decision tree shown in Figure 3. The selection depends on the on-peak/off-peak time, the need to cool the building, and PCM state of charge (SOC). When the thermostat calls for cooling during off-peak times, the VCS will enter normal mode operation. Normal mode is conventional HVAC operation. Charging mode restores the energy stored in the TES by refreezing any melted PCM and is only activated during off-peak times when the thermostat is not calling for building cooling to take advantage of the lower electrical cost and, incidentally, usually lower ambient temperatures. Charging mode can be interrupted by the thermostat if the building requires cooling and the system will enter normal mode, maintaining building indoor comfort. During on-peak time, when the thermostat calls for cooling, discharging mode will activate which cools the building with the TES. During discharging, the PCM in the TES is being melted and the latent heat associated with melting maintains a constant cold TES temperature. The TES can only operate when there exists some frozen PCM inside. Once all the PCM is melted, the TES can no longer absorb isothermal heat and the normal mode must be used to cool the building. All other times the VCS is in standby mode.

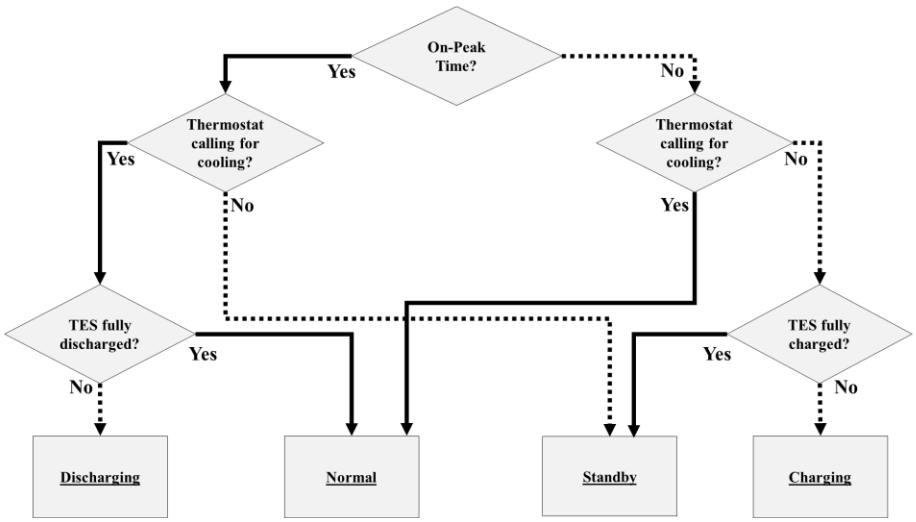


Figure 3. Controls decision tree

The overall flow of information in the model is depicted in Figure 4. The decision tree works as the main control to coordinate all these components. The feedback arrows represent the updated (i+1) values being fed back to the main models.

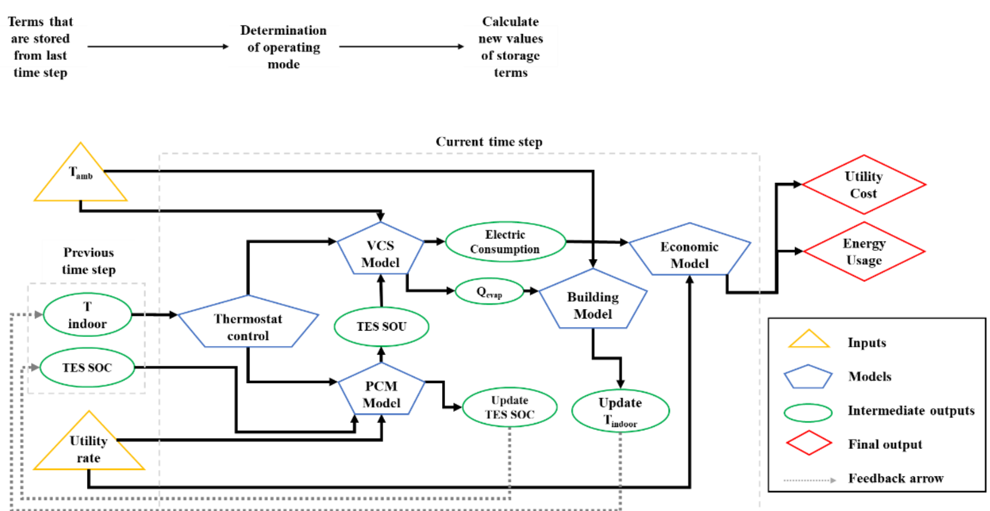


Figure 4. Total system information flow and relation between sub-models

3. COMPONENT MODELS

3.1 Weather Data

The system's performance is evaluated for a hot week in a dry climate of southern California, ASHRAE climate zone 3B, June 24-30, 1994. TMY 3 weather data for Fresno County, CA was used. The location correlates to the utility pricing. The dry bulb temperature is shown in Figure 5 with the indoor comfort temperature range shown for reference.

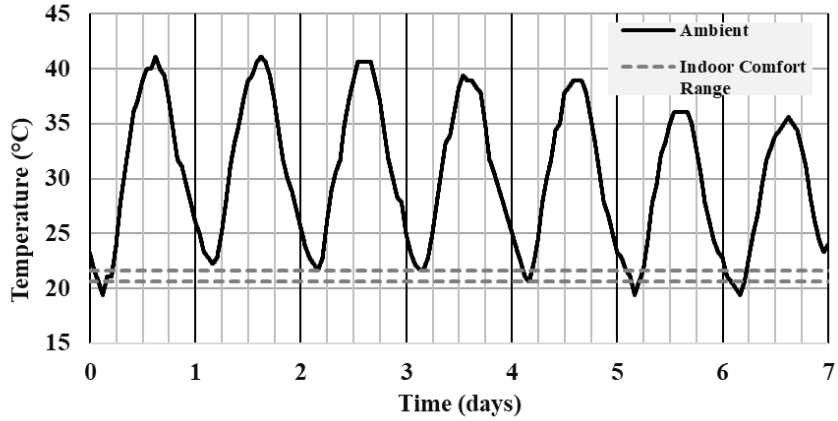


Figure 5. Ambient dry bulb temperature for the simulated week

3.2 Building Model

A simplified building model is used to simulate the thermal response of the building. The simplified model calculates the indoor temperature depending on the ambient heat load, VCS heat load, and the building thermal capacitance. The ambient heat load is modeled by using an assumed building balance point temperature of 18°C with the heat exchange from the ambient proportional to the difference between the outdoor ambient temperature and the point balance temperature, as shown in Equation (1). The effective heat transfer coefficient, *U*, was estimated to be 0.21 kW-K^{-1}.

$$Q_{amb} = U * (T_{amb} - T_{bal}) \tag{1}$$

The indoor temperature is determined based on the heat balance according to Equation (2) where Q_{VCS} is the cooling load provided from the VCS in either normal or discharging modes dependent on the controls in Figure 4. The time step, dt, in this simulation is one minute. An overall effective building thermal capacitance, C, of 16459 J/K was chosen to represent a typical single-family house with 223 m^2 (2400 ft^2) area (Dong *et al.*, 2019).

$$T_{indoor,i+1} = \frac{-(Q_{VCS} - Q_{amb}) * dt}{C} + T_{indoor,i} \tag{2}$$

3.3 Building Thermostat Model

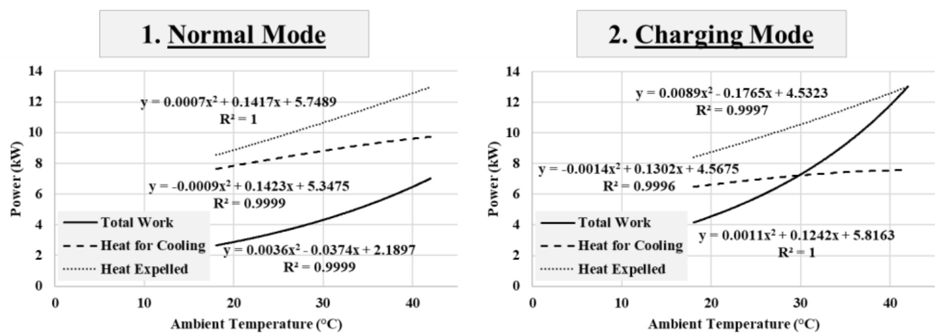
The thermostat control has a constant setpoint of 21.1°C (70°F) and a deadband of ±0.5°C (±1.8°F). When the building temperature rises above the setpoint temperature plus the deadband, the VCS will be activated to cool the building in either normal or discharging mode dependent on the decision tree of Figure 3. The building will cool until the temperature falls below the setpoint temperature minus the deadband where the VCS will be shut off for direct building cooling.

3.4 VCS Model

An R410 VCS was modeled in Engineering Equation Solver. The discharging, charging, and normal modes were modeled independently, and lookup tables developed. For all modes the compressor has the same constant volumetric flow rate, 2.5e-6 m^3. In the normal and discharging modes, the VCS interfaces with the building with an evaporator at a near constant 15°C temperature. In the normal mode the condenser is coupled to the ambient, thus the ambient temperature, as shown in Figure 5, was used as an input. In discharging mode, the condenser is coupled to the TES, kept at a constant 0°C. Fans with a power draw of 0.585 kW are present only in the building air handling unit and the outdoor condensing unit and are activated when the operating mode dictates. The TES does not have a fan.

While in charging mode, the VCS evaporator interfaces with the TES and the condenser to the ambient. Thus, the TES heat exchanger must be able to be switched from a condensing mode to evaporating mode. For a real system of this type, controllable valves, check valves, switches, and other special components may be necessary for the TES system to make this switch. The simplicity of this model assumes these challenges can be met.

The work and heat for all modes was calculated and called upon by the building and thermostat models as determined by the decision tree of Figure 3 and the information flow of Figure 4. The values of work and heat are shown in Figure 6 plotted against the ambient temperature where applicable. The discharging mode has no external temperature dependence and thus its operating parameters are constant.



3. Discharging Mode

Total Work	**0.7485 kW**
Heat for Cooling	**5.181 kW**
Heat Expelled	**5.285 kW**

Figure 6. VCS operating power for normal, charging, and discharging modes

3.5 TES Model

The VCS is coupled to the TES system; the TES does not interact with the building directly and is insulated from ambient exposure. The PCM embedded in the TES is water/ice with a melting temperature of 0°C, in an assumed 80-gallon tank, which provides nearly 27.8 kWh of cooling capacity. The necessary heat exchanger in the TES is assumed to have near infinite heat transfer rate such that the temperature within the TES is constant at 0°C. The state of charge (SOC) is the percentage of maximum energy stored within the TES. When the TES is operated in the discharging or charging modes, the energy contained and SOC are reduced or increased, respectively, by the amount of heat determined by the VCS model.

This model only charges the TES between the hours of 1am and 7am. Different time controls or schedules may be utilized in real systems to avoid off-peak power demand spikes as predicted by Gottwalt *et al.*, (2011) or to take advantage of abundant energy on the grid from daytime solar or heavy wind periods, depending on the energy portfolio of the utility provider or any off-grid energy sources a customer may have.

3.6 Utility Rate Analysis

The TOU utility tariff used in this analysis is Pacific Gas and Electric (PG&E) Electric Schedule E-TOU-B (Pacific Gas and Electric, 2020). This is a legacy tariff as of May 1, 2020, no longer accepting new customers, but the pricing structure is representative of the difference between on-peak and off-peak prices for current tariffs in the region (California Public Utilities Commission, 2019). The tariff is priced as follows: from June 1 to Sep 30, peak hours are 4pm to 9pm, Monday through Friday with a rate of $0.39689/kWh; all other hours, including all weekend hours, are off peak rates of $0.29383/kWh. Winter rates (Oct 1 – May 31) differ.

4. RESULTS AND DISCUSSIONS

For the simulated 7-day period, the electric consumption of the HVAC system and the total utility cost are compared for systems with and without water/ice-based TES. Figure 7 shows the total electric consumption as well as the on-peak hour consumption. Note that only the first five days (weekdays) have on-peak pricing; weekends are considered off-peak. The baseline system without TES used 353.2 kWh total with 98.1 kWh used during on-peak hours: weekdays, 4pm – 9pm. With the TES system, the total electrical usage was reduced 14.5% to 302.1 kWh including an 87.5% reduction of on-peak usage to 12.3 kWh.

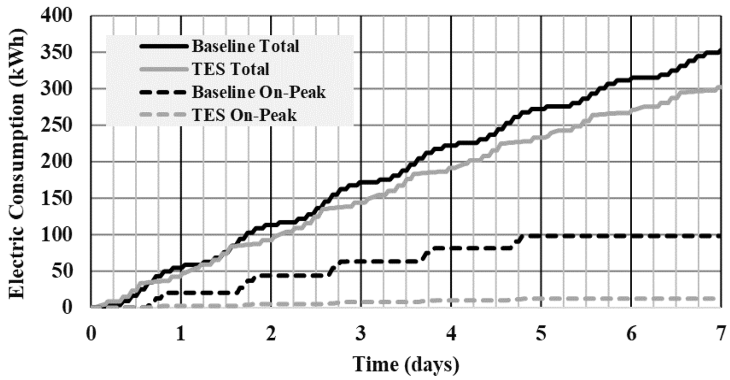


Figure7: Electric Consumption comparison with and without TES

The utility cost to cool the building is shown in Figure 8. The baseline model without the TES resulted in $112.52 but use of the TES system cost nearly 20% less at $90.04 for this simulated week. It should be noted that California has some of the highest utility costs in the US and this week simulated has particularly hot temperatures. These results should neither be extrapolated to yearly savings nor may be representative of other climates or regions. However, this does show that during extreme heat events, TES will be a crucial energy saving mechanism, reduce on-peak energy demand, and may be economically beneficial for the customer.

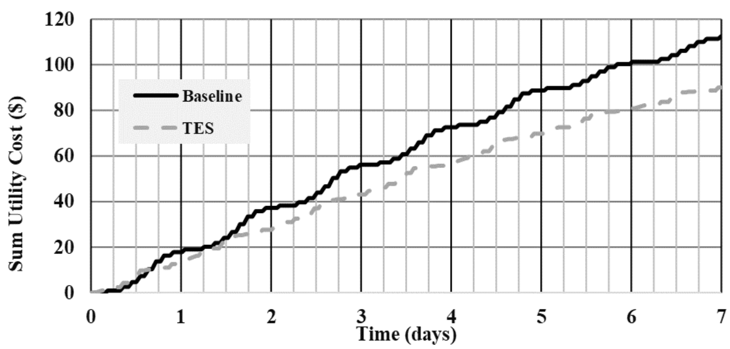


Figure 8: Total electrical utility cost with and without TES

5. CONCLUSIONS

A residential building was modeled with PCM-based TES and the economic and energy savings were estimated under a TOU rate structure with a rate difference of 0.103$/kWh between on-peak and off-peak. The TMY3 weather data was used for ASHRAE climate zone 3B. The analysis showed that the total energy used to cool the space was reduced from 353.2 kWh without TES to 302.1 kWh with TES, a 14.5% reduction. The on-peak energy usage was reduced by 87.5%, from 98.1 kWh without TES to 12.3 kWh with TES. In addition, the cost to the customer was reduced by nearly 20%, from $112.52 without TES to $90.04 with TES.

Since only 7 days were simulated, the results should not be extrapolated for annual savings, but highlights the potential for reducing peak energy demand during weather extremes. This work also suggests that the demand side management systems, including TES, with on time-based electricity prices may create an economic advantage for residential customers to shift peak energy loads without compromising comfort. TES are a valuable tool to level out electrical grid demand and add stability to the grid.

NOMENCLATURE

PCM	Phase Change Material	
TES	Thermal Energy Storage	
EPRI	Electric Power Research Institute	
EES	Engineering Equation Solver	
TOU	Time of Use	
AC	Air Conditioning	
AHU	Air Handling Unit	
VCS	Vapor Compression System	
COP	Coefficient of Performance	
SOC	State of Charge	
SOU	State of Use	
t	Time	
T	Temperature	(°C)
Q	Energy	(kW)
W	Electric Consumption	(kWh)
C	Building Thermal Capacitance	($J\text{-}°C^{-1}$)

Subscript/Superscripts

cond	Condenser
evap	Evaporator
comp	Compressor

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