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Carbon Mitigation Potential of Heat Pump Integrated with Thermal Storage for Grid-Interactive Residential Buildings

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Abstract

Residential buildings' heating and cooling loads are associated with significant carbon emissions and peak electricity demand. Phase change material (PCM) based thermal energy storage (TES) can be used for space heating and cooling by embedding into the heat pump equipment. Past work on TES integrated with heat pumps (HP) has demonstrated significant load shifting and economic benefits. However, the potential for TES to reduce carbon emissions has not been widely explored. This study evaluates carbon mitigation potential of an ice-based TES coupled to HP (HP-TES) based on a simple rule-based control strategy accounting for electric grid emissions data. A vapor compression HP model using Engineering Equation Solver (EES). The modeled HP-TES system for single-family residential building demonstrates decreased carbon emissions with reduced peak utility cost.

Keywords: Thermal Energy Storage; Marginal Grid Emissions; Carbon Mitigation; Heat pump; Space cooling; Residential Buildings;

1. Introduction

Heating, cooling, and ventilation loads in residential buildings account for about 10% of energy consumption and CO_2 emissions worldwide and comprises 50% of the building electricity consumption [1]–[3]. More than 74% of electric use in United States is attributed to buildings where heat pumps (HP) exacerbate the demand issues, as, during the summer peak times, 50% of the electric load comes from residential buildings, which is largely HVAC (Heating, Ventilation, and Air Conditioning) load [4]. The potential of onsite thermal energy storage (TES) has mostly been underestimated even though its significance for decarbonization and demand reduction has been established by researchers [2].

TES systems locally decouple heating or cooling demand from its production. The thermal storage properties can be leveraged from phase change materials (PCM) to not only design a demand response strategy for peak load shifting, but also for decarbonization. PCM which can be incorporated as passive or active storage, have a capability to store the off-peak energy that can be released during on-peak time.

Studies can be found in literature that investigate the demand response potential of TES. Peak thermal loads have been shifted to off peak time using utility pricing and demand-based controls [2], [5]–[7]. However, only a handful of research works reported in literature have investigated TES for carbon emissions reduction accounting for HP loads. The table below summarizes the literature investigating TES potential for demand management and carbon mitigation. Noticeably, gas consumption for furnace as a base case is compared against electric HP in most papers.

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Table 1: Load shifting, and carbon mitigation reported in literature using PCM-TES

Author	Location	System Description	Demand Impact	Carbon Mitigation
[8]	Turkey, Spain	PCM in buildings using passive TES and Active Aquifer TES	Loads reduced by 7% for cooling and 10% for heating	~26%* CO_2 emission reduction
[9]	Ithaca, NY	Borehole TES coupled to heat pump	Not reported	64% CO_2 emission reduction
[10]	Spain	Passive PCM in buildings	HVAC loads reduced by 20%	5.5% CO_2 emission reduction
[11]	Italy	TES with Photo Voltaic system and heat pump	41% energy cost reduced by peak load shifting	50% CO_2 emission reduction
[12]	Iran	Bio PCM integrated in wall and construction material of building	4% annual cooling and heating load reduction	2-5% CO_2 emission reduction
[13]	Saudi Arabia	3 different PCMs (18, 23, 25°C) in building envelope	Not reported	6.8-56.9% CO_2 emission reduction
[14]	UK	PCM in floor, coupled to air source HP	50% annual load reduction	36% CO_2 emission reduction
[15]	Saudi Arabia	PCMs (18, 21, 24, 25, 28°C) in wall, coupled to HVAC	Not reported	9.4-61% CO_2 emission reduction
[16]	Mexico	PCM (25°C) in building envelope	11-58% annual load reduction	~25%* CO_2 emission reduction
[17]	Turkey	PCM in wall, configuration and temperature optimized	17.2% annual energy savings	18.4% CO_2 emission reduction

*Calculated from the data given in the paper

As shown in Table 1, the papers reported in literature are either passive or hybrid TES systems. Most researchers either employed passive cooling or heating by using PCM in building envelope or in case of active system, integrated TES with an additional energy production sources like PV systems. There is a large disparity in savings reported. Majority of the works evaluate the electric heat pump CO_2 emission reduction in comparison to gas furnaces as a reference, which yields more than 40% reduction [9], [11], [14]. Other studies compared PCMs with various insulations and passive configurations [13], [16]. In optimization studies, different PCMs and their melting points have been investigated to optimize the savings [15], [17].

Figure 1 below shows the reduced carbon emissions in literature for different regions. Passive TES have varying benefits but for all regions, heat pump coupled systems consistently report more than 35% reduction.

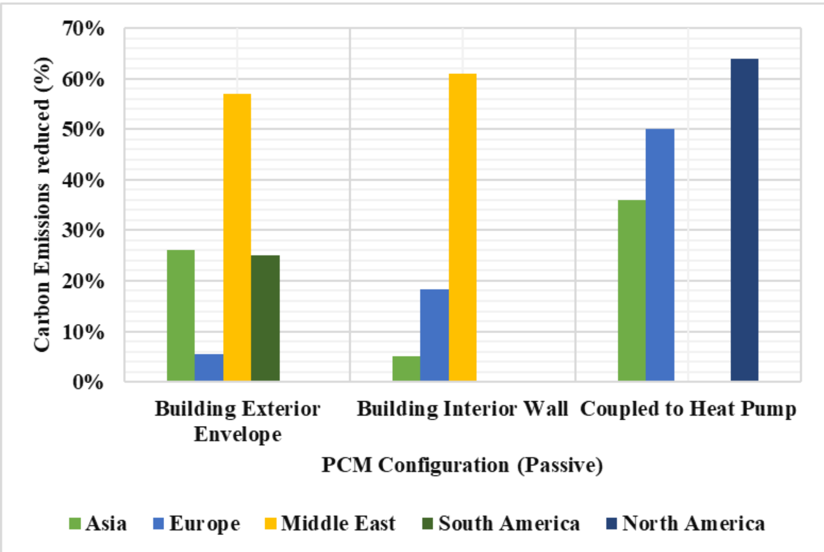

Figure 1: One representative reference reporting emission reduction by using PCM in various locations and configurations

The focus of this paper is to evaluate the carbon mitigation potential of TES assisted heat pumps against the normal heat pump operation, to compare the emissions with and without TES using a rule-based control strategy. Heat pump integrated TES has especially garnered attention for its demand response potential, flexible configurations, and less space requirements. Active HP-TES systems were reviewed to establish that peak loads and cost associated with HVAC loads can be successfully reduced [18]. Many researchers have used demand response control strategies to shift the peak load, but very few papers have investigated the decarbonization potential of TES. Peak load was shifted using various controls and configurations for residential HP-TES, and corresponding emissions were reported [19]. The emissions have been calculated by deriving relations to the energy consumption and power usage. Abu Hamdeh *et al.* (2022) multiplied the power usage by the amount of greenhouse gases emission per kWh [13]. Arce *et al.* (2011) used European Commission emission factors, load reduction and energy savings to calculate the carbon emissions reduced [10]. Cabeza *et al.* (2015) defined CO_2 factor as a corelation between CO_2 emissions (g) and energy consumption (kWh). The CO_2 footprint (g/kWh) is 0.08 times energy consumption [8]. No studies were found that utilize emissions data into the control strategy of HP-TES systems.

Table 2: Table showing gap in literature and scope of this work

Reference	Active HP-TES mediated by heat pump	Carbon Emission controls for HP-TES	CO_2 emissions reported	Electric heat pump baseline vs PCM	Utility based controls for peak load shifting
[8]	×	×	■	×	×
[9]	×	×	■	×	■
[10]	×	×	■	×	×
[11]	×	×	■	×	■
[19]	×	×	■	×	■
[12]	×	×	■	■	×
[13]	×	×	■	■	×
[14]	×	×	■	×	■
[3]	■	×	×	■	■
This work	■	■	■	■	■

The electricity sector has seen a shift from traditional centralized system to a smart grid device. This phenomenon has been ushered in by the increased integration of renewable energies. The rapid proliferation of the 'Internet of Things' (IoT) [20], allow major loads, such as HP, to be controlled with the goal of reducing peak power consumption on the electrical grid. In a smart grid, HP can be considered part of the demand side that can be actively managed to stabilize voltage fluctuations caused by high demand or high penetration of renewable energy [21]. With smart control of HP-TES, the system can switch between charging and discharging mode depending on the outdoor temperature, electricity price, desired indoor temperature, renewable energy generation, and COP of HP [20]. It is important to describe how to incorporate a grid's GHG (greenhouse gases) condition into a site-specific MPC. The grid system-wide emission rate in a specific grid region depends on the total power production rate from grid power generators, and other factors that affect system operating conditions, such as weather. The marginal operating emissions rate (MOER) is the partial derivative of the systemwide emission rate with respect to the total production rate [22]. It means the change of the emission rate in the grid region with respect to the last megawatt produced by dispatchable generators having the unit of metric Ton CO_2-equivalent per MWh [mTonCO_2/MWh]. Intuitively, this indicates how much carbon emission rate increases/decreases in a grid region when one consumes one megawatt more/less. Therefore, MOER allows for associating the power usage at a specific site with the carbon emission rate in the grid region by simply multiplying the on-site power consumption with the MOER signal. In this paper, we used the MOER signal, based on a proprietary model [22], but adapted for real-time use [23].

In our previous work, we used time-based pricing to determine the economic value of residential TES system [6]. The PCM was incorporated into the conventional HVAC and time-of-use (TOU) utility rate schedule was analysed to evaluate the demand impact and energy savings. The objective of this present work is to evaluate the simple control strategy to reduce grid emissions while shifting the peak load, accounting for both grid and utility data. Marginal grid emissions data is used to determine if the emissions are relatively higher than the average of the previous day. The controls are then applied for the heat pump and TES operation, and emissions are reported.

A simple building thermal energy model and HP model is evaluated with an active configuration implying direct use of TES for the building cooling during the discharge. The TES is based on water/ice PCM with 0°C storage temperature. TES is not directly conditioning the building but interacts with HP to mediate the heat transfer. The potential reduction in grid emissions is assessed using marginal grid emissions data and peak load is shifted using residential TOU utility tariff. Both correspond to the ASHRAE climate zone 3B, in California. For modelling, Engineering Equation Solver (EES) and Microsoft Excel are used. System overview and decision controls are explained in the Methodology (Section 2).

2. Methodology

The model comprises of various components connected to the building and HP using R410-a refrigerant. A TES heat exchanger with embedded PCM is integrated into HP to modify the vapor compression system and is transferring energy to and from the ambient. Thermostat controls monitor the building indoor temperature. The ambient weather data, TOU utility data, and marginal grid emissions data obtained for the same climate location, ASHRAE climate zone 3B. Marginal grid emissions data and electric utility schedule controls the heat pump to cool the building, and charge and discharge the ice-based TES. The analysis is performed for cooling only during the hottest week of June. The building energy consumption, HP work, and emissions are calculated in Microsoft Excel according to the rule-based control strategy in the minutely time steps.

2.1. System Overview and Configuration

The conventional vapor compression cycle of HP is modified by coupling TES to the system. TES is integrated with HP via active configuration and assists the HP cooling. TES does not cool the building directly, but heat transfer occurs through HP, as shown in Figure 2. PCM-TES can function either as a condenser or an evaporator, dependent upon the mode of operation. It is assumed that TES has an infinite coefficient of heat transfer and is always at constant temperature of 0℃.

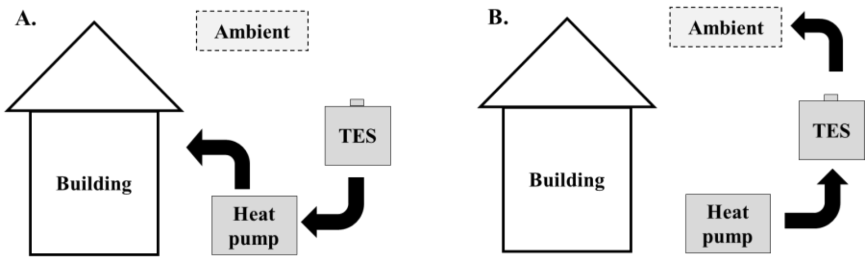

Figure 2: HP-TES configuration in cooling mode (A. TES Discharging B. TES Charging)

HP has four modes of operation. HP is turned off in the standby mode and only thermal energy from outdoors is being transferred to the building. HP is turned on to cool the building through refrigeration cycle in normal mode, and no TES is involved. During charging mode, TES stores the energy from HP as Q_{PCM} to be used at later time. During discharging mode, TES releases the already stored energy into the building via HP. This mode has increased COP than the normal mode due to favourable temperature gradient. TES, which is at a colder temperature, is coupled to HP condenser and creates a negative temperature lift to move the condenser heat from building to TES.

2.1.1. Cooling Mode

Operating modes for cooling and respective energy flows are shown in Figure 3. Ambient is at a higher temperature than the building. During cooling normal operation, the condenser heat, Q_{cond}, is discarded to the ambient while the heat of the evaporator, Q_{evap}, is removed from the building and directed to the heat pump.

TES behaves as condenser or evaporator depending on the mode of operation. Evaporator is assumed to be the TES during charging. So, the TES is being cooled directly. The heat, Q_{evap}, is removed from the TES though latent heat of freezing. TES solidifies as the heat stored from the TES is discarded to the ambient via heat pump. In the discharging mode, the TES is defined as the condenser and the evaporator was tied to the building. The Q_{cond} is now being stored to the TES instead of ambient and the PCM within the TES is being liquified.

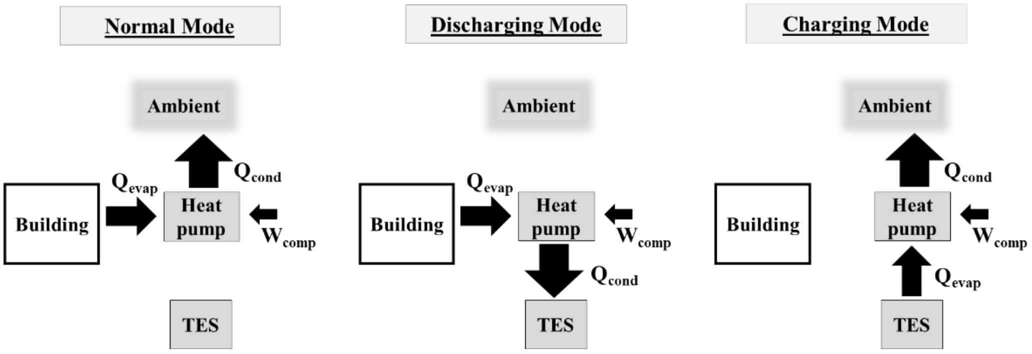

Figure 3: Operating modes in cooling

2.2. System Controls

The operating mode of HP-TES is determined by the thermostat decision whether the building needs to be cooled or not, utility off-peak and on-peak time, state of charge of PCM (SOC), and grid emissions. The control strategy of HP-TES model is regulated based on four decision variables: 'Thermostat call', 'Utility Peak', 'Emissions Peak' and 'State of Charge'.

The thermostat model (section 3.5) regulates the indoor temperature and determines if cooling is needed at a given time to call for cooling. A cooling temperature setpoint is fixed at 21°C, and the need is determined when the indoor temperature is higher than the cooling setpoint. The utility model, explained in section 3.1, determines the utility peak time. The emissions are obtained from the grid emissions model in section 3.6, while the TES model (section 3.5) determines the PCM state of charge.

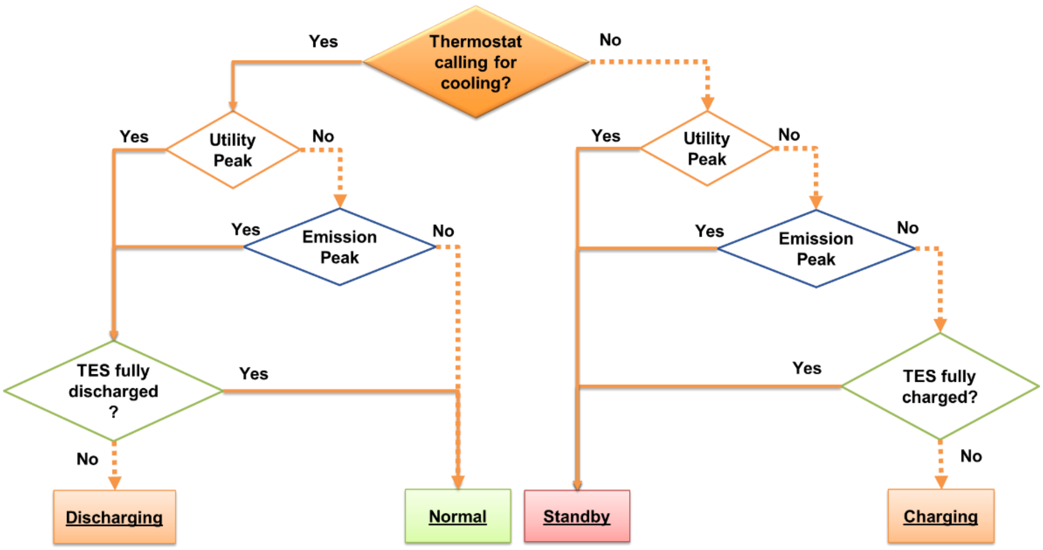

Figure 4: Controls decision tree used in this work

The operating modes are shown in the decision tree diagram (Figure 4). Assuming the initial PCM SOC as 50%, if the thermostat is calling for cooling during the utility peak time defined by TOU tariff, PCM discharging mode will turn on. But during utility off peak, the emissions peak will determine if the discharging mode should be on. Charging mode is only activated during off-peak times to take advantage of the lower electrical cost and emissions, while thermostat is not calling for cooling, and PCM is not already charged. If during utility off-peak time, thermostat is calling for cooling, the HP goes into normal operation depending on emissions peak. Emissions peak is determined by average of grid emissions in the past 24 hours, if emissions are greater than the average of last 24 hours at a given point, it's emissions peak. In previous work [6], emissions were not included, and controls were based only on utility data.

2.3. Information Flow

The overall system flow is depicted in Figure 5, which depends on the component models to analyze the weather, utility and emissions data. All the components are mainly coordinated by the decision tree as a main control to maximize the system efficiency. Some values are updated to use as intermediate inputs in the model, represented by feedback arrows. The building model, HP model, and TES model are used from the previous work [6].

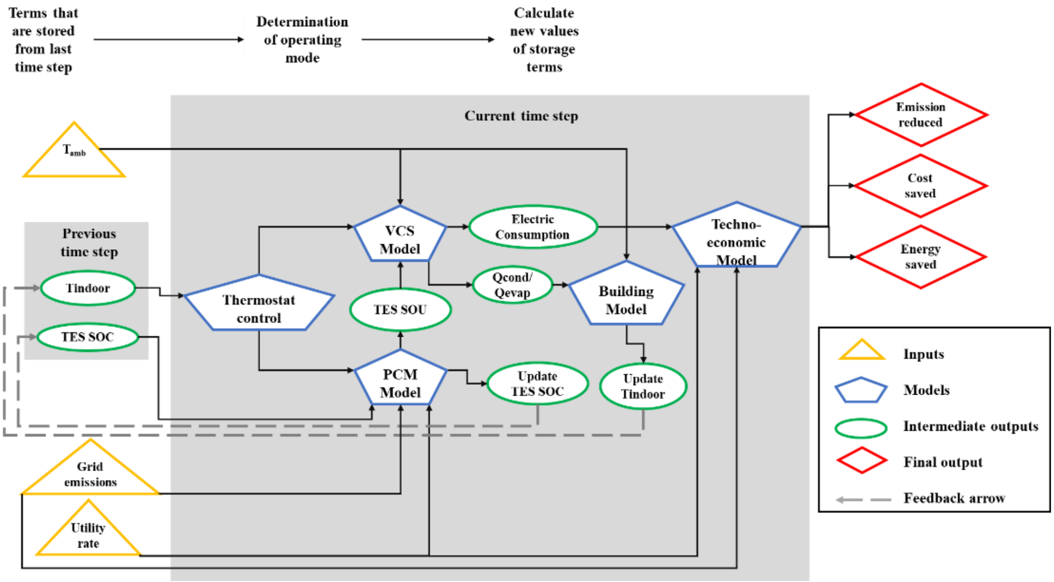

Figure 5: Information Flow Diagram

3. Component Models

3.1. Weather and Utility Data

The TMY 3 weather data used is of Fresno, CA which corresponds to ASHRAE climate zone 3B. The location correlates to marginal grid emissions and utility tariff. The Time of Use (TOU) utility data is a fixed utility rate schedule from Pacific Gas and Electric (PG&E) Electric Schedule E-TOU-B. The analysis for cooling is performed considering both peak and off-peak hours for a hot week of June 24-30, 1994. The peak hours vary by season. For cooling season defined from June till September, on-peak hours are observed from 4pm to 9pm on weekdays, and the utility rate is $0. 39689/kWh. At other times, including the weekends, the off-peak rate is $0. 29383/kWh. The difference between on-peak and off-peak utility rate is $0.103/kWh.

Figure 6 shows ambient temperature versus utility rate for cooling season. The cost for cooling increases when the demand increases as a function of outdoor dry bulb temperature. The design objective is to take advantage of the low rates and assist heat pump operation using TES when the cost is high during peak hours.

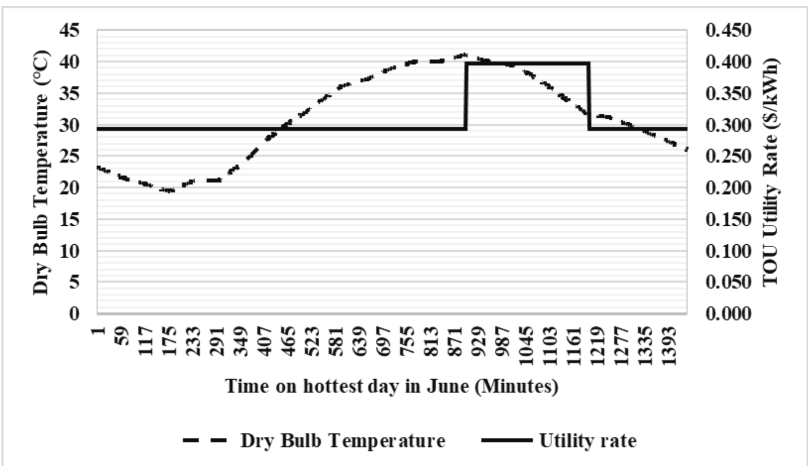

Figure 6: Ambient Temperature and Utility data for cooling day

3.2. Building Model

Building's thermal response is simulated by a simple building model that calculates indoor temperature. The model takes into account the heat pump load, building's thermal capacitance, and ambient load. A balance point temperature of 18°C is assumed to model the ambient load, as shown in Equation 2. An overall heat transfer coefficient of 0.25 kW/K is estimated based on cooling design day.

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

Indoor temperature is determined by the energy balance where Q_{VCS} is the cooling or heating load output from the heat pump model in either normal or discharging modes, in one minute time step. A single-family house with 223 m^2 (2400 ft^2) area was selected and the building capacitance was estimated to be 16459 J/K [6]. It was chosen to result in a reasonable rate of change of building.

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

3.3. Thermostat Model

The thermostat model tracks the indoor temperature and calculates the variable 'thermostat call'. It uses a constant setpoint temperature to turn on cooling mode. Due to thermal loading from the ambient temperature, when the building indoor temperature exceeds the setpoint cooling temperature of 21°C (with a dead band of +/- 0.5°C), the thermostat calls for cooling. Depending on other conditions (time of day, emissions, and outdoor temperature), the HP will enter into either discharging mode where TES will be used, or normal mode where HP cools the building without TES.

3.4. Heat Pump Model

A heat pump model was simulated in EES and the operating modes with TES were modelled separately. The vapor compression model calculates the COP for cooling from the evaporator output and electric consumption by compressor [6]. The compressor has a constant volumetric flow rate of $2.5e^{-6}$ m^3. Equation 4 defines the cooling COP.

$$COP_c = \frac{Q_{evap}}{W_{comp}} \quad (3)$$

The outputs of heat pump model, Q_{evap} from the evaporator and Q_{cond} from the condenser are called into Excel, where they are coupled to the PCM-TES or ambient depending on the operating mode. The condenser is tied to the ambient in normal mode, thus the dry bulb temperature was used as an input. The condenser is paired to the TES in the discharging mode. Where TES is kept at a constant 0°C. The discharging mode does not depend on ambient temperature and thus its operating parameters are constant. Because the temperature gradient is more favourable, total work during discharging is 0.748 kW, much lower than the normal mode which varies between 2.65 and 7 kW depending on the ambient temperature.

The condenser is coupled to the ambient in charging mode, and now the evaporator interacts with the TES. The decision tree (Figure 4) and thermostat model was used to control the HP and PCM state of use.

3.5. TES Model

The HP vapor compression system is coupled to PCM via heat exchanger in such a way that TES does not interact directly with the building and is not affected by the ambient temperature. An ice/water based PCM with phase change temperature of 0°C is embedded in the TES. TES heat exchanger is assumed to have an indefinite heat transfer rate at a constant temperature maintained at 0°C. TES is modelled as an 80-gallon tank, which can provide up to 27.8 kWh of cooling capacity. The operating modes are controlled by the PCM state of charge which is a function of peak time, and indoor temperature.

The fraction of maximum energy that can be stored by TES is defined as state of charge of PCM (PCM SOC). The PCM SOC is increased during charging to store the energy and reduced during discharging mode when it is consumed. For charging mode, the state of use of PCM (SOU) is -1, for discharging it is +1, and PCM SOU is 0 when it is not being used.

3.6. Grid Emissions Model

Marginal grid emissions schedule is obtained for Fresno, CA from a data driven tool that uses an empirical model. The tool generates emissions schedule based on continuous emissions and electricity generation data from major fossil fuel plants in the U.S. Figure 7 shows the hourly emissions data for the year of 2022 obtained on November 15. The data from January until November 15 is real time, and rest is projected based on historical data. Controls are designed based on average of the last 24 hours and variable called 'Emission Peak' is defined. If at any given point, the emissions exceed the average of last 24 hours, it will be considered emission peak. Discharging mode will be turned on if cooling is needed at that time. This strategy avoids using HP during both utility and emission peak times, to assess the maximum grid emission savings.

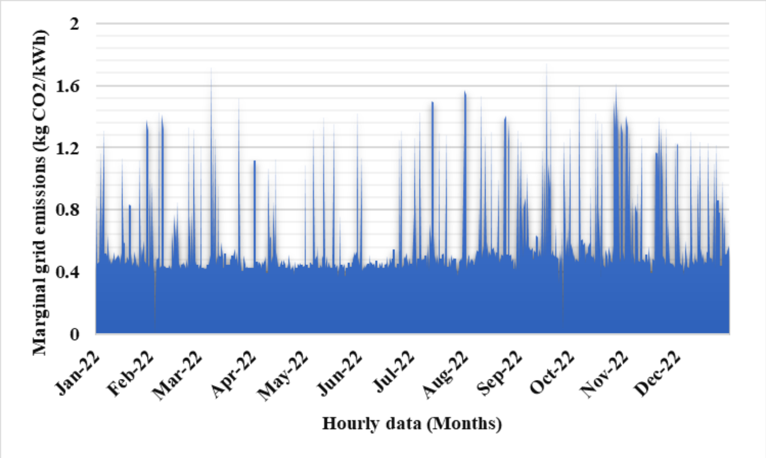

Figure 7: Fresno annual grid emissions during 2022

4. Results and Discussions

The analysis is performed for one week of cooling season to report utility cost, electric consumption, and carbon emission reduction. The indoor temperature was maintained at 20°C for cooling. For the simulated 7-day period, the grid emissions corresponding to the HP electric consumption are compared for the cases with and without PCM TES. The baseline system is defined as the case without TES.

4.1. Carbon Emissions

Figure 8 shows the grid emissions for both baseline and TES systems. The no-TES baseline case resulted in 181.78 kg of CO_2 over the simulated week, while using the TES system, emissions were 160.1 kgCO_2, reducing 11.92% grid emissions for the simulated week. These savings were achieved by using TES to discharge during emission peak and utility peak.

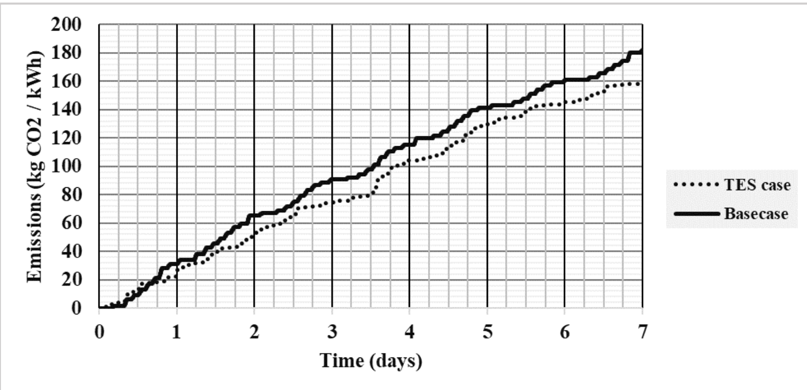

Figure 8: Emissions reduced using TES

4.2. Electric Consumption

Figure 9 shows the HVAC electric consumption and the peak electric consumption for both baseline and TES systems. TOU tariff for Fresno, CA is used for this study and the on-peak pricing applies from Monday through Friday only, excluding weekends. For the baseline system, where no TES was used, total electric consumption was 353.2 kWh, and on-peak consumption was 98.1 kWh. For the system with TES, the total electric consumption was reduced by 10.19% to 317.2 kWh. TES on-peak usage was 48.8 kWh, which means 50.2% of peak load was shifted. In our previous study [6], 87% of peak load was shifted to off-peak hours using TES under TOU tariff. The present study also implements grid emissions-based controls and TES is more frequently used in discharging mode than in previous study.

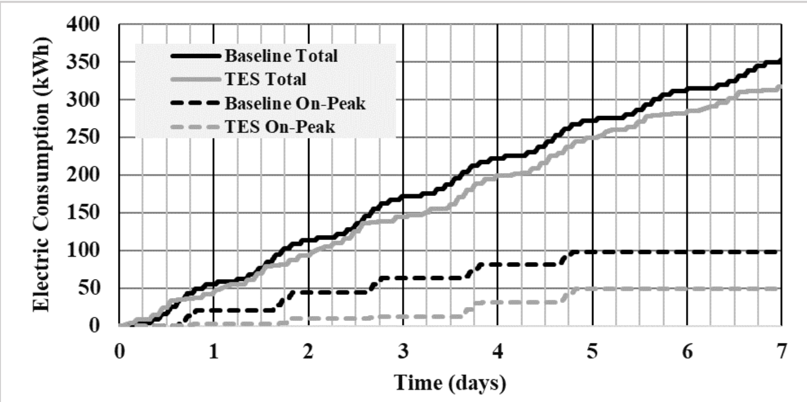

Figure 9: Electric Consumption with and without TES

4.3. Operating Cost

The utility cost to cool the building is shown in Figure 10. Compared to baseline, 12.68% of system operating cost was saved using TES. The baseline system without TES accumulated $112.52 for cooling during the simulated week, while TES accounted for $98.25. In the previous study [6], 20% utility cost was saved using TES. The cost for the present system has increased when additional emission-based controls were introduced. In the control strategy, the emissions peak has precedent over the utility peak. Therefore, cost savings are not as significant as was seen in the previous study when only cost peak was considered.

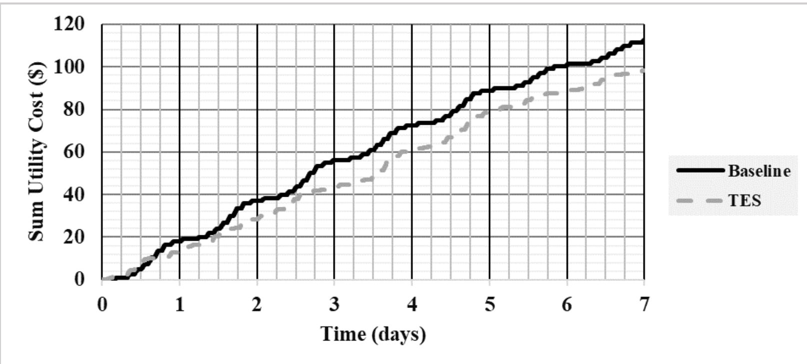

Figure 10: Utility Cost reduced using TES

5. Conclusion

The objective of this work is to assess the carbon emissions reduction potential of HP-TES using a rule-based strategy accounting for marginal grid emissions data and time-of-use utility tariff. An HP-TES configuration was evaluated with an ice/water based PCM coupled to the HP. A vapor compression model was developed using EES, and Excel was used to compute results for the integrated HP-TES system. The analysis was performed for one week of cooling season. The utility cost for cooling was reduced by 12.68% using TES while also maintaining occupant comfort. The total electric consumption was also reduced by 10.19% and 50.2% of peak electric load was shifted to off-peak time. 11.92% of grid emissions were reduced by using TES during emissions and utility peak times defined in the control strategy. The study concluded that while this configuration can still create some economic advantage with a simple control strategy, controls should be further optimized to reduce peak energy consumption.   The analysis was performed for 7 days only, and the results should not be extrapolated for annual savings. This work highlights the potential for reducing grid emissions using a rule-based strategy.

Nomenclature

PCM	Phase Change Material	
TES	Thermal Energy Storage	
EES	Engineering Equation Solver	
HP-TES	Heat Pump integrated Thermal Energy Storage	
MGE	Marginal Grid Emissions	
TOU	Time of Use	
VCS	Vapor Compression System	
SOC	State of Charge	
COP	Coefficient of Performance	
Q	Energy	(kW)
W	Electric Consumption	(kWh)
C	Building Thermal Capacitance	(J-°C^{-1})

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