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Optimal Operating Temperatures for a Variable-Temperature Thermal Energy Storage System

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ABSTRACT

Thermal energy storage (TES) systems are used with heating, ventilation, and air conditioning (HVAC) systems in buildings to reduce the electricity cost for HVAC where time-of-use rates are in place. Latent heat storage, primarily using ice as a phase-change material (PCM), is the most commonly-used form of TES in buildings due to its high energy density. However, latent heat storage is fixed-temperature; the storage system must be charged and discharged at the phase-change temperature (PCT) of the PCM. A variable-temperature TES system would have the advantage of allowing the system to be charged and discharged at the operating temperatures that would minimize the required power input. Furthermore, if the temperature could be varied sufficiently, the same PCM could be used for both heat storage and cold storage (which is not possible for fixed-temperature systems). High energy-density variable-temperature storage could potentially be achieved using thermochemical energy storage. In addition, finding ways to tune the PCT of a PCM has been an active area of research in recent years. In this paper, we examine how to obtain the most cost savings from a variable-temperature TES system by optimizing the PCT of the PCM in both heating and cooling modes. A model of a building HVAC system is developed, which includes a heat pump, secondary loop, auxiliary electric heating, and a variable-temperature TES tank. An algorithm determines the operating temperatures of this system in terms of the PCT of the PCM. An optimization algorithm is used to determine the values of the PCT that will minimize operating costs. It is shown that varying the PCT during operation results in cost savings for both cooling and heating modes, and that the majority of these cost savings can be obtained by using only two different values of the PCT each day.

1. INTRODUCTION

Thermal energy storage (TES) is used with heating, ventilation, and air conditioning (HVAC) systems in buildings in order to reduce operating costs when time-of-use (TOU) electricity rates are in place (Tam et al., 2019), reduce the required size of other components in the HVAC system (Rawlings, 1985), and store excess power produced by on-site solar power (Lee et al., 2015). The form of TES used most commonly in practice in buildings is ice storage, where is ice is frozen and melted to store and release cooling loads (Potter et al., 1995). Ice storage is used only for cold storage since energy must be stored and released at the melt temperature of ice, which is lower than room temperature. If a single TES system could be used for both heat and cold storage, it could achieve higher cost savings, particularly in residential buildings, where TOU rates have become more common in recent years (Tam et al., 2019) and there can be significant cooling and heating loads throughout the year. Sensible heat storage in water, also used in buildings, can be used for both heat storage and cold storage but has a much lower energy density (Hasnain, 1998; Lee et al., 2015). Combined heat and cold storage using a single, high-density TES system requires that the system be able to operate at a variable storage temperature so that it can operate above room temperature for heat storage and below room temperature for cold storage. This could potentially be done using thermochemical energy storage (Krane et al., 2022). In addition, recent research (Lau et al., 2021) examined the feasibility of altering the phase-change temperature (PCT) of a phase-change material (PCM), which could allow for using latent heat storage for both cooling and heating.

In addition to being used for both heat and cold storage, a variable-temperature TES system could also achieve higher cost savings by dynamic tuning of the storage temperature. This could be done by modifying the storage temperature

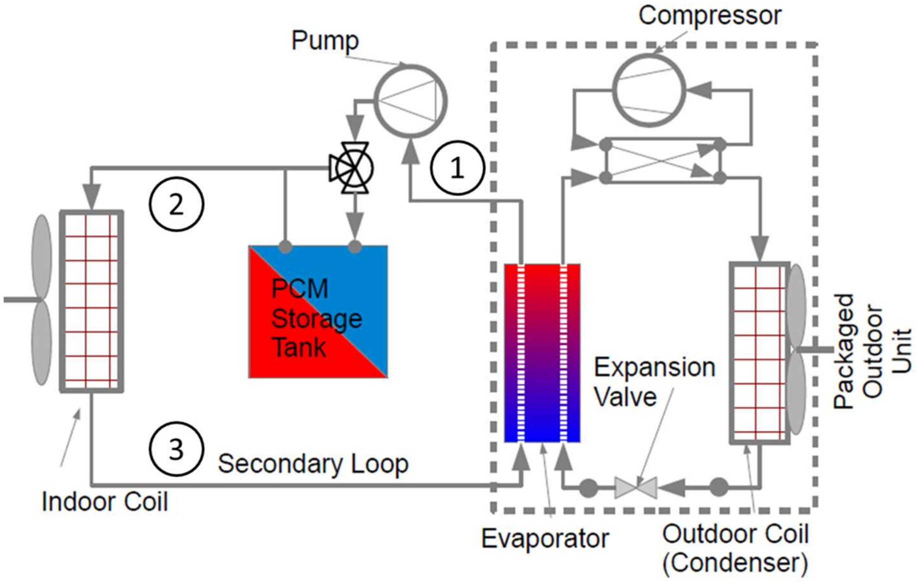

Figure 1. Schematic of an HVAC system with variable-temperature PCM storage.

during operation to set it to whatever value will result in the lowest operating costs for the HVAC system. Since variable-temperature storage has only recently begun to be studied (Krane et al., 2022), there has not been any previous study of how to set the storage temperature so as to obtain the most cost savings from dynamic tuning. Therefore, in this paper we will use a model of a building HVAC system using a variable-temperature storage system (here modeled as a PCM storage tank with a variable PCT) to examine how to obtain cost savings from dynamic tuning of the PCT. This model will be used for a week in the summer and a week in the winter to see what the maximum potential savings are in each case and to what extent these savings can be achieved by using two PCT values each day, depending on whether the system is being charged or discharged.

2. MODEL

The system architecture modeled here can be seen in Figure 1. A vapor-compression heat pump is used to meet both heating and cooling loads of the house. These loads are met using a secondary loop that also exchanges heat with a PCM storage tank. This PCM in the tank is assumed to have a variable PCT and thus can be used for both heat storage and cold storage.

A diagram of the model used to analyze this system can be seen in Figure 2. An EnergyPlus model of a residential building developed by DOE and PNNL (Department of Energy & Pacific Northwest National Laboratory, 2021) is used to determine the cooling or heating loads and non-HVAC electricity consumption in the building at each point in time based on Typical Meteorological Year 3 weather data (National Renewable Energy Laboratory, n.d.-a). Load-shifting control logic is used to determine the heat pump loads for charging and discharging the storage system each day, and then to determine the load for each individual time step. The load-shifting control logic used here in cooling mode is described by Tam et al. (2019) and the logic for heating mode is described by Krane et al. (2022). Different control logic is used for heating and cooling because initial tests showed that this reduced operating costs.

Setting the heat pump loads according to the load-shifting control logic for each 15-minute time step is part of a larger solution of the state of the system that performs an energy balance for each component in the secondary loops, updates the state of the storage tank based on the heat transfer there, and determines the heat pump performance as a function of water glycol mass flow rate and inlet temperature and ambient temperature. The heat pump model uses correlations that were determined based on the results of a model of a heat pump with a scroll compressor for a range of operating conditions. Performance data for a real compressor was used in this model to solve for each set of operating conditions (Emerson, 2019). The secondary loop model is described in more detail in Section 2.1, and the storage tank model in Section 2.2. The system model is run inside of an optimization function, discussed in Section 2.3, that determines what values of the PCT result in the lowest operating costs.

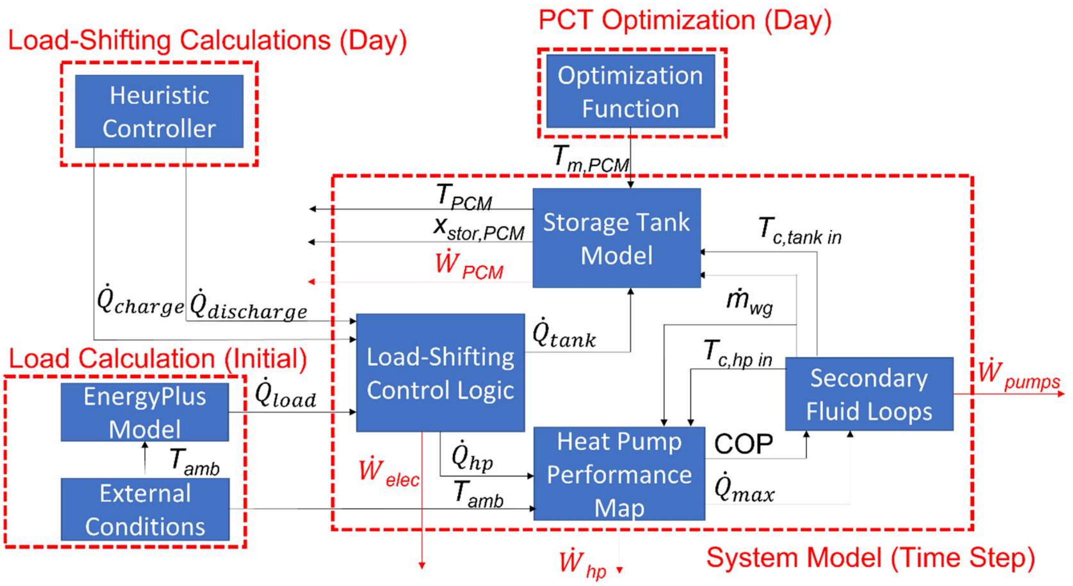

Figure 2. Diagram of the model used for the variable-temp storage system. At each time step, the model takes inputs from the load calculations performed before any other calculations in the model, as well as the load-shifting calculations and optimization of the storage tank operating temperature performed each day. Then, at each time step, the model determines the appropriate heat pump loads, calculates the heat pump work using the secondary loop model and heat pump performance map, and updates the state of the storage tank.

2.1 Secondary Loops Model

The water glycol in the secondary loop changes temperature at three locations (where it exchanges heat with the heat pump, the storage tank, and the house). To determine the state of the system at each point in time, an energy balance is calculated for each component, as follows:

$$\dot{Q}_{hp} = \dot{m}_{wg} c_{wg} (T_1 - T_3) \tag{1}$$

$$\dot{Q}_{tank} = \dot{m}_{wg} c_{wg} (T_2 - T_1) \tag{2}$$

$$\dot{Q}_{house} = \dot{m}_{wg} c_{wg} (T_3 - T_2) = \begin{cases} -\dot{Q}_{load,house}, & cooling \\ -\left(\dot{Q}_{load,house} - \dot{Q}_{elec}\right), & heating. \end{cases} \tag{3}$$

The heat pump load at each time step, $\dot{Q}_{hp}$, is determined by the load-shifting control logic. This gives us 5 equations and 7 unknows (3 temperatures, 3 heat transfer rates, and the mass flow rate). Therefore, it is necessary to set the value of two temperatures in order to have a closed set of equations. The inlet temperatures for the storage tank and heat pump (T_1 and T_3) are used for this. The tank inlet temperature T_1 needs to be defined in terms of T_{PCM} so that the storage tank is able to deliver the appropriate load. The heat pump inlet temperature T_3 is defined since it determines the performance of the heat pump, so the system should try to operate at the temperature that will optimize this performance. Heuristic values for these variables are determined, and an algorithm updates these values as needed to ensure the system is operating in a physically consistent manner.

Heat pump and electric work are calculated using the equations:

$$\dot{W}_{hp} = \frac{|\dot{Q}_{hp}|}{COP}. \tag{4}$$

$$\dot{W}_{elec} = \dot{Q}_{elec}. \tag{5}$$

Pump work, for moving the water glycol in the secondary loop, was found to be negligible and so is not included here. Using these work terms, and the assumed loads for non-HVAC work in the building (calculated using the EnergyPlus model), the operating cost at each time step is determined using:

$$C_{tot} = C_{hour} \left(\left(\dot{W}_{hp} + \dot{W}_{elec} + \dot{W}_{non-HVAC} \right) \Delta t \right). \tag{6}$$

2.2 Storage Tank Model

The TES system used for variable-temperature storage is modelled as a PCM with a variable PCT. An energy balance on the storage tank gives us the equation:

$$\dot{Q}_{tank} = \dot{Q}_{lat} + \dot{Q}_{sens}. \tag{7}$$

In this equation, the storage tank is assumed to be fully insulated so that the only heat transfer in or out of the tank is the heat transfer to and from the circulating water glycol ($\dot{Q}_{tank}$). This heat transfer is equal to the sum of the latent heating ($\dot{Q}_{lat}$) and sensible heating ($\dot{Q}_{sens}$) in the storage tank. Sensible heating is included in this model because the storage tank does not stay at a fixed temperature, as an ice storage system does, due to the changes in the PCT. When the PCT changes, sensible heating or cooling is required to change the temperature of the PCM to match the new PCM. Therefore, sensible heating only occurs at times when the temperature of the storage tank (T_{PCM}) is different from the melt temperature of the PCM ($T_{m,PCM}$) since the system will not continue charging or discharging if the PCM is fully melted or fully frozen. If the sensible heating or cooling load is delivered by the heat transfer from the water glycol ($\dot{Q}_{tank} = \dot{Q}_{sens}$), then the updated temperature is calculated from the sensible heating rate:

$$T_{PCM,new} = T_{PCM,old} - \frac{\dot{Q}_{sens}\Delta t}{m_{PCM}c_{PCM}}. \tag{8}$$

If the heat transfer to the tank is greater than the sensible heating load required to change the PCM temperature to the new PCT value, or if the sensible heating required has the opposite sign as the load being delivered to the tank, then the sensible heating rate and storage tank temperature at a given time step is calculated using the equations:

$$\dot{Q}_{sens} = \frac{m_{PCM}c_{PCM}(T_{PCM} - T_{m,PCM})}{\Delta t}, \text{ and} \tag{9}$$

$$T_{PCM,new} = T_{m,PCM} \tag{10}$$

At every time step, the state of charge (x) is updated based on the latent heating rate:

$$x_{new} = x_{old} + \frac{\dot{Q}_{lat}\Delta t}{m_{PCM}L_{PCM}}. \tag{11}$$

The state of charge is constrained so that the system will not charge the storage tank past $x = 0.9$ and so that sensible heating or cooling will not increase it past $x = 1$. Similarly, the state of charge will never go below $x = 0$, and the load-shifting control logic calculates the discharge loads so that it normally will not go below $x = 0.1$.

2.3 Optimization Problem

The model described in Sections 2.1 and 2.2 is used to determine the electricity consumption and resulting operating costs for a variable-temperature TES system given input values for the PCT of the storage material at each time step. To determine the potential cost savings from variable-temperature TES, an optimization problem is solved to determine which values for the PCT result in the lowest operating costs for the building. This optimization problem is solved for each day in the simulation, with each day starting at the end condition from the case which achieved optimal results the previous day. The optimization problem being solved has the form

$$\begin{gathered} \min costfnc\left(T_{m,PCM}(t), T_{\infty}(t), \dot{Q}_{load,hou}\quad(t)\right) \\ s.t\ T_{m,PCM,min} < T_{m,PCM} < T_{m,PCM,max}. \end{gathered} \tag{12}$$

In this equation, the minimum and maximum PCT values, $T_{m,PCM,min}$ and $T_{m,PCM,max}$, are [-10°C, 10°C] for cooling and [30°C, 50°C] for heating. The cost function is calculated using:

$$costfnc\left(T_{m,PCM}(t), T_{\infty}(t), \dot{Q}_{load,house}(t)\right) = \sum_{day} C_{tot} + C_{pen,rem\ charge}. \tag{13}$$

The cost penalty $C_{pen,rem\ charge}$, which is included in the cost function for optimization but not in the actual operating cost calculations, is intended to represent the approximate cost of charging the system from its state at the end of the day if the system is not fully charged at that time:

$$C_{pen,rem\ charge} = C_{off-peak}\frac{(0.9 - x)E_{stor,PCM}}{CO\ _{est}}. \tag{14}$$

This penalty is used because the optimization period (a calendar day) does not align with one cycle of charging and discharging the storage system (which would start either at the beginning or the end of the on-peak period). Therefore, without this cost penalty, there is the possibility of the solver finding a solution that minimizes cost for the day by doing less charging after the on-peak period, thereby reducing costs for the day but increasing overall costs. This can be avoided by adding the cost penalty shown here, as well as by using a week instead of a day for the optimization time horizon. The first option generally results in lower computation time without a loss of performance, but the second can lead to improved results if there is a loss of charge due to the change in the PCT at the beginning of the day that is not made up due to high loads in the morning. This loss is not captured by the cost penalty because the system is fully charged at the end of the day.

Table 1. Residential TOU rate structure for Elizabeth City, NC

Season	On-Peak Hours	On-Peak Rate	Off-Peak Rate
Winter	6-10 AM, Mon-Fri	27.6 ¢/kWh	5.52 ¢/kWh
Summer	2-7 PM, Mon-Fri	27.6 ¢/kWh	5.52 ¢/kWh

3. RESULTS

To examine the potential cost savings from dynamic tuning of the PCT, we compare three different cases for a week in the summer (June 1-7) and a week in the winter (January 1-7) in Elizabeth City, NC. The first case uses a constant PCT for the whole week (10°C for cooling mode and 30°C for heating mode) to determine the operating costs without dynamic tuning as a benchmark. The other two cases solve the optimization function for dynamic tuning, one for the case where the PCT changes every hour and one for the case where different PCT values are used for different operating modes (charging and discharging) each day. In the second case, the PCT changes from the discharge to the charge value at the end of the on-peak period, and from the charge to the discharge value either when the tank is fully charged or at the start of a calendar day (whichever comes last). For the case where charge and discharge temperatures are used in the winter week, an optimization period of a week is used instead of a day because here loss of charge due to a change in the PCT at the beginning of the day that is not made up due to high morning loads is a significant issue. For all other cases, where this is not a concern, a day is used as the optimization period to reduce computation time.

Costs are calculated using TOU rates for this location from the NREL Utility Rate Database (National Renewable Energy Laboratory, n.d.-b); a description of this rate structure can be seen in Table 1. All the results shown are for a system with a 2-ton (7.03 kW) heat pump (sized to meet the peak cooling load at the building for a full year) with a 50-gallon (0.189 m^3) PCM storage tank.

3.1 Optimization Results Comparison

Weekly operating costs for the system for the summer and winter weeks can be seen in Figure 3. Looking at the results for the summer week, we can see that some cost savings can be obtained through dynamic tuning of the PCT. However, these cost savings are very small, with less than $0.15/week in savings compared to the case with a constant PCT. Changing PCT values twice a day for charge and discharge gives essentially the same results (within $0.01).

In heating mode, the cost savings from dynamic tuning of the PCT are significantly higher than they are for cooling mode, at around $0.65/week instead of $0.15/week. Also, unlike cooling mode, changing the PCT every hour does

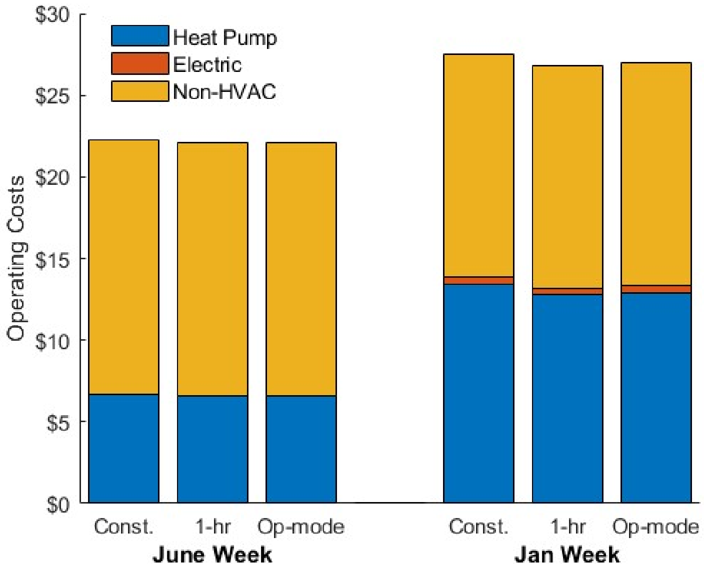

Figure 3. Comparison of operating costs for a summer week and a winter week between the case with a constant PCT (Const.), the case where the PCT changes each hour (1-hr), and the case where different values are used for charging and discharging modes (Op-mode).

provide some savings compared to using just two different PCTs for charge and discharge. The savings for using two PCTs are around $0.55/week.

To see how the system achieves cost savings for summer, detailed hourly results are shown in Section 3.2 for the case with two PCT values associated with charging and discharging. For winter, hourly results are included for both optimization approaches in Section 3.3 (since here the 1-hour PCT variation did outperform the 2-PCT approach).

3.2 Summer Week Results

To see how using different charge and discharge PCT values results in cost savings in cooling mode, key system parameters are shown in Figure 4 for the period of June 1-4. A 4-day period is used instead of the full week so that the results can be seen more clearly. The heat pump loads shown in Figure 4a differ from the house loads when the system is charging or discharging. Because of the load-shifting control logic used, the system charges quickly at a high, but non-constant, load (because it charges at the capacity of the chiller, which changes with ambient temperature) while it discharges at a constant heat pump load. However, we can also see two sudden spikes where the heat pump load exceeds the house load at $t = 24$ hours and $t = 72$ hours. As seen in Figure 4c, the PCT decreases at these times, since the control logic switches to the discharge value for a day at the beginning of the day if the system is finished charging. The state of charge decreases at these times as the PCM melts until its temperature reaches the PCT. The spikes in the heat pump load are the system charging to make up for this lost charge.

The PCT is always 10°C when charging but is lowered for two of the three discharge periods. This indicates that the optimal way to change the PCT between operation modes is to charge the system at the highest PCT but sometimes lower the PCT when discharging the system. The maximum PCT is used in charging mode because here flow leaves the heat pump and enters the storage tank at a lower temperature than the PCT in order to charge the tank. For charging

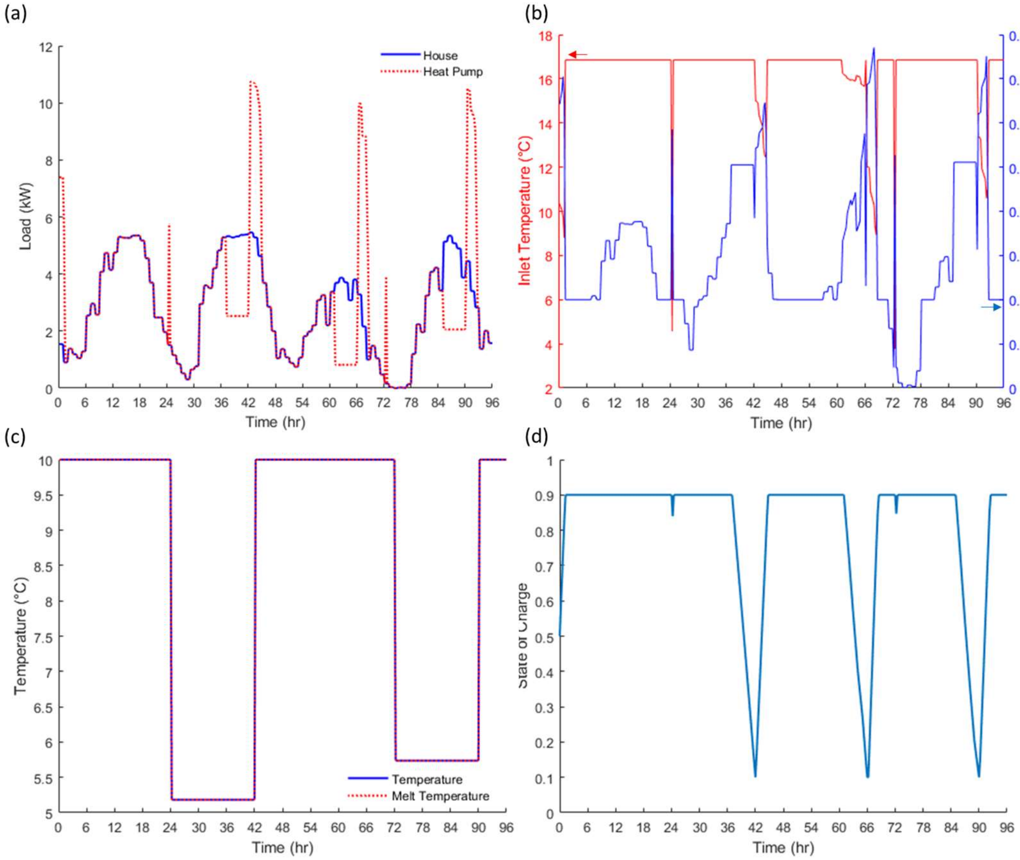

Figure 4. (a) House and heat pump loads, (b) water glycol mass flow rate and heat pump inlet temperature, (c) PCT and operating temperature and (d) state of charge of the storage tank for June 1-4 for the case where different PCT values are used for charging and discharging the system.

mode, this constraint is usually more restrictive than the maximum outlet temperature from the house, so the heat pump inlet temperature is less than this maximum temperature, as seen in Figure 4b. Therefore, increasing the PCT increases the heat pump inlet temperature, thereby increasing its COP.

It can also be seen in Figure 4b that the heat pump inlet temperature when the system is discharging is usually constant, since this temperature is not constrained by storage tank outlet temperature because the constraint on house outlet temperature is more restrictive. This is because the flow leaves the storage tank at a temperature above the PCT, so flow enters the house at a higher temperature than it does in cooling mode. This means that in discharge mode, it is possible to reduce the PCT without reducing the heat pump inlet temperature. Thus, lowering the PCT will improve performance if it leads to a more optimal mass flow rate. Because of this, the PCT is lowered on the 2nd and 4th days, in order to increase the change in water glycol temperature when delivering the cooling load and thus reduce the mass flow rate. As can be seen in Figure 4b, the mass flow rate is a constant value close to 0.25 kg/s during both of these periods, which is around the optimal value for the heat pump model used in this case when operating in cooling mode. However, on the 3rd day the heat pump and house loads are lower, so the mass flow rate is already lower than the optimal value for most of the period. Therefore, the PCT is not lowered on this day, since it would lead to a lower COP.

3.3 Winter Week Results

Results for the case where charge and discharge temperatures are used during a winter week are shown in Figure 5. There are several important differences between these results and those for the summer week. One difference, which can be seen in Figure 5a, is that the system now charges at a flat heat pump load due to the different load-shifting control logic used. This causes the storage tank to become charged later in the off-peak period, as seen in Figure 5d.

Looking at the PCT values used, it is important to remember that in heating mode, a lower inlet temperature to the heat pump is desirable for a higher COP, which is why the case with a constant PCT uses the minimum PCT value allowed (30°C) instead of the maximum as in cooling mode. Given this, it is significant that a high PCT is used for charging the system on the first day. This is done to take advantage of the increase in state of charge when the PCT is lowered at the end of the charge period, which raises the state of charge to x=1 and thus means the system ends the first on-peak period at a higher state of charge. This is an artifact of the model starting with the temperature of the storage tank being its initial PCT and could not be used to obtain cost savings in a real system. However, only around $0.05 of the cost savings come from this, so it is not the main reason why cost savings from dynamic tuning are higher in heating mode. Note that when x=1, the storage tank temperature does not equal the PCT, since all of the PCM is frozen, there is no latent heating term and thus no sensible heating when there is no heat transfer to or from the tank.

Except for this case, the PCT values selected are all within 5°C of the value used in the constant-PCT case. However, there are differences in the values selected for both charging and discharging that can be seen in Figure 5c. In charging mode, higher PCT values are used even though these lead to less optimal inlet temperatures (as can be seen by looking at days 3 and 4 in Figure 5b). There are two reasons for this. The first is that in heating mode, mass flow rate has a stronger effect on heat pump performance relative to inlet temperature. This means that cost savings can be obtained by increasing the PCT to move the mass flow rate closer to its optimal value (which in this case is lower, usually in the range of 0.0.8-0.12 kg/s depending on inlet and ambient temperatures) even if this means operating at a higher inlet temperature. Secondly, on day 4, the heating loads at the end of the day (and also those at the beginning of day 5) are very high, so a higher PCT is used since it would be hard to make up for a loss of charge when switching to a higher PCT for discharge mode the next day. To avoid this, a higher PCT is used for charging so it does not have to be increased when switching to the best discharge value the next day.

In discharge mode, the main difference when compared to cooling mode is that it is more common for the storage tank to be the primary constraint, and thus for a higher inlet temperature than the minimum to be used. This means that the system cannot necessarily operate at the optimal mass flow rate when discharging, so instead it operates at a PCT that results in a near-optimal inlet temperature as well as a lower mass flow rate than would be the case for a PCT of 30°C.

As mentioned in Section 3.3, here (unlike in cooling mode) higher cost savings are obtained by using a 1-hour time step than by using two PCTs a day for charge and discharge. To see why this is the case, the results for the 1-hour optimization case in heating mode are shown in Figure 6.

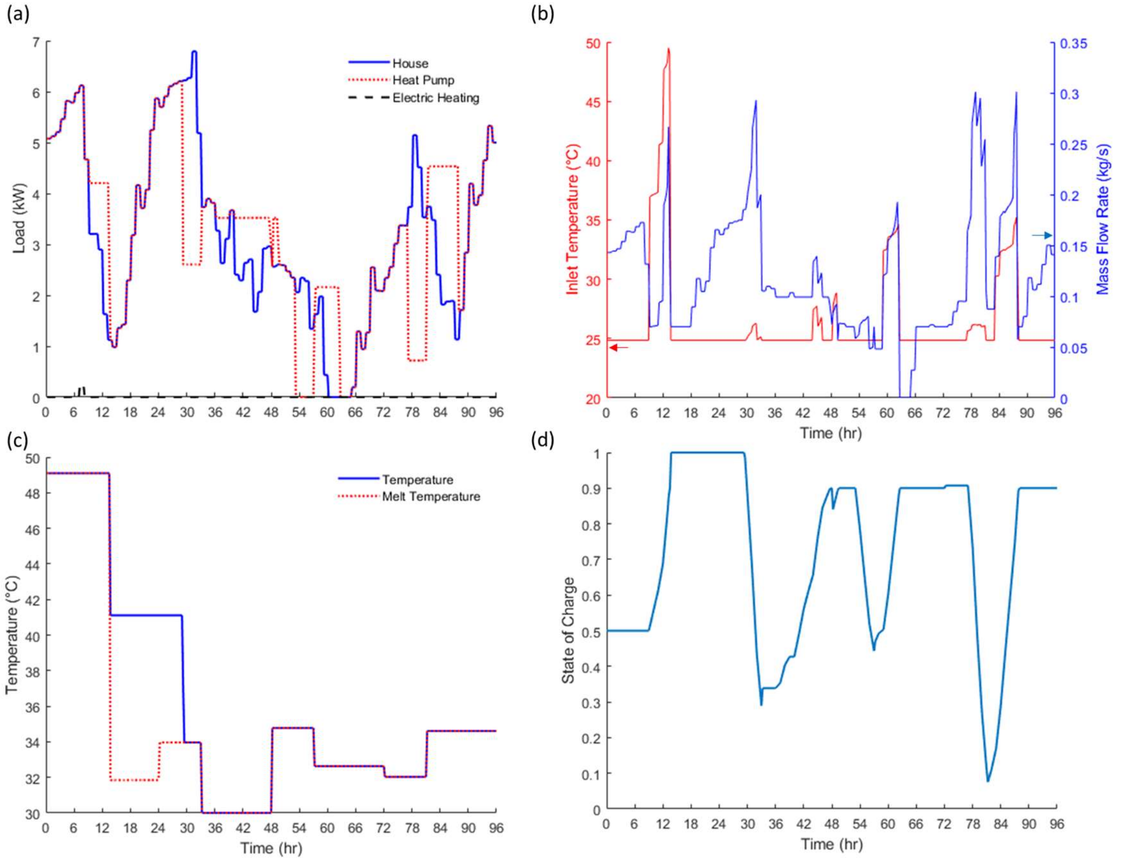

Figure 5. (a) House and heat pump loads, (b) water glycol mass flow rate and heat pump inlet temperature, (c) PCT and operating temperature and (d) state of charge of the storage tank for January 1-4 for the case where different PCT values are used for charging and discharging the system.

The most obvious difference between this case and the case with charge and discharge temperatures is that the PCT changes rapidly throughout the entire time, with the exception of morning on the 3rd day. The fluctuations during the on-peak period on the 2nd day (seen between *t* = 30 hours and *t*= 36 hours in Figure 6a) allow the system to operate at a lower inlet temperature (except one brief point where it is significantly higher) while remaining near the optimal mass flow rate, as seen in Figure 6b. Similarly, the fluctuations in the PCT when charging on the 4th day (seen between *t* = 78 hours and *t*= 84 hours in Figure 6c) allow for the system to charge alternatively at a high and a low (near-optimal) mass flow rate, as seen in Figure 6b, rather than consistently charging at a high mass flow rate, as in Figure 5b.

Overall, these results show that there is significantly more potential for cost savings from frequent changes to the PCT in heating mode than there are in cooling mode. This is the case largely because of the lower optimal mass flow rate and different load-shifting control logic used here, which make it less consistent whether the house or storage tank temperature is the more significant constraint, and thus make it more likely that the optimal operating conditions at each point in time during a charge or discharge period will be different. This in turn creates a greater incentive for more frequent changes to the PCT, in order for the system to operate closer to optimal conditions at all times during the on-peak or off-peak period. This allows for higher cost savings than are seen in cooling mode, but requires more complicated control logic to determine what PCT values will result in the highest savings.

4. CONCLUSIONS

In this paper, we have examined the possibility of achieving cost savings from dynamic tuning of the operating temperature of a TES system. Such a system could be developed using either through thermochemical energy storage or through finding ways to alter the PCT of a latent heat storage system. A simple model of a hypothetical variable-temperature TES system, considered here as a PCM with a variable PCT, integrated with a building HVAC system was developed and an optimization function used to find what operating temperatures resulted in the lowest operating

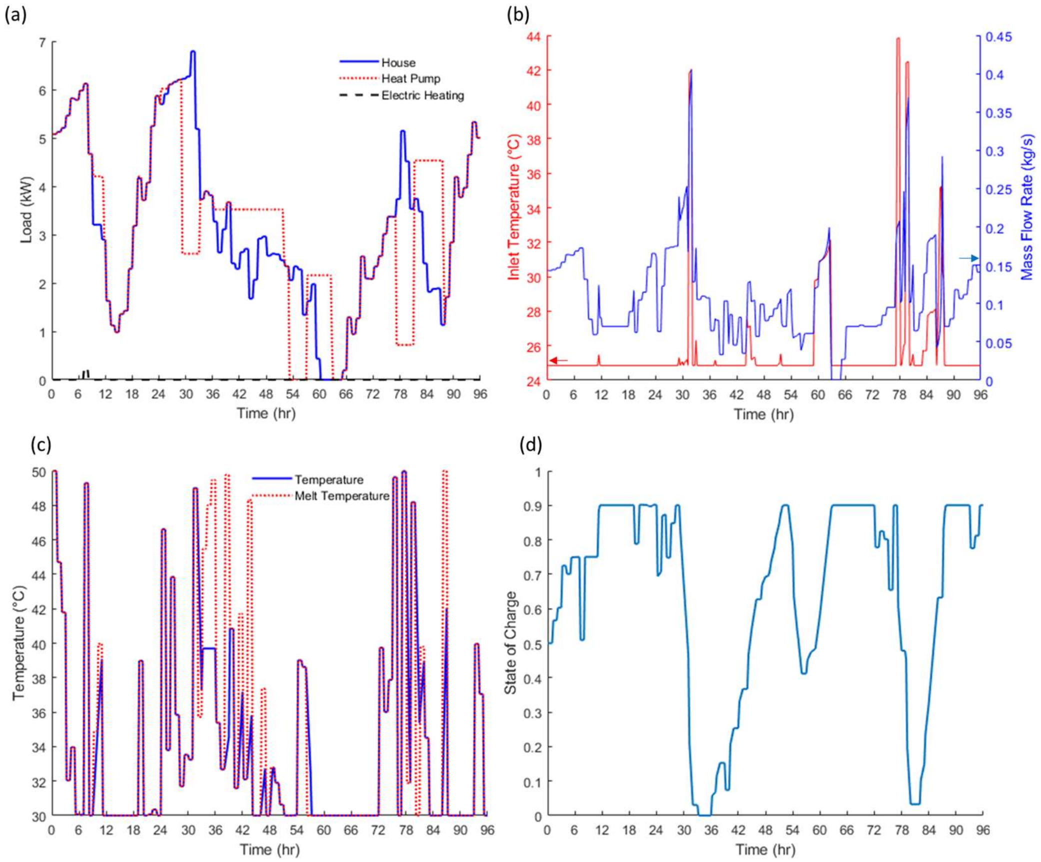

Figure 6. (a) House and heat pump loads, (b) water glycol mass flow rate and heat pump inlet temperature, (c) PCT and operating temperature and (d) state of charge of the storage tank for January 1-4 for the case where the PCT can change every hour.

costs. Dynamic tuning is shown to result in cost savings, particularly in heating mode. The highest cost savings in cooling mode, and the majority of the maximum potential cost savings in heating mode, can be obtained by using two PCT values a day, one for charging and one for discharging. In cooling mode, this is done by using the maximum PCT when charging to optimize the inlet temperature and using whatever PCT value optimizes the mass flow rate in discharging. However, the optimal operating temperatures are more complicated to determine in heating mode because here it is less consistent whether inlet temperature is constrained by the storage tank or the house in charging and discharging modes. This means that the values chosen when using different temperatures for charging and discharging are less consistent, and that higher cost savings can be achieved by more frequent changes to the PCT. Even in heating mode, the highest cost savings achieved from dynamic tuning are less than 6% of the operating costs of the HVAC system, and thus too low to justify the development of a variable-temperature TES system on their own. Further study is needed to see how much larger these savings would be for locations with higher heating and cooling loads or with utility rates that are higher or that more strongly incentivize energy storage, as well as examining if the cost savings could be improved by modifying the sizing of the storage tank or the operating temperatures of the system.

NOMENCLATURE

C	cost	(US$)
c	specific heat	(J/kg K)
COP	coefficient of performance	(-)
costfnc	cost function	(US$)
E_{stor}	energy storage capacity	(J)
L	latent heat	(J/kg)
m	mass	(kg)
$\dot{m}$	mass flow rate	(kg/s)
$\dot{Q}$	heat transfer rate	(W)

T	temperature	(K)
$\dot{W}$	power	(W)
x	state of charge	(-)
Δt	time step	(s)

Subscript

day	day
elec	electric heating
est	estimated
house	house
hp	heat pump
lat	latent heating
load	load
m	melt
new	new
non-HVAC	non-HVAC electricity usage
off-peak	off-peak
old	old
on-peak	on-peak
PCM	phase change material
pen	penalty
rem charge	remaining charge
sens	sensible heating
tank	tank
tot	total
wg	water glycol
∞	ambient

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