Exploring the Power Demand and Efficiency Performance Limits of Heat Pumps with Thermal Storage

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ABSTRACT

Heat pumps can be combined with thermal storage to enable the heat pump to operate at the time of day desired by the operator. Moving the heat pump operation to a different time of day can reduce the power draw during the grid peak time and can affect the efficiency by resulting in heat pump operation at different ambient temperatures. This work explores the performance limits of HP-TES systems. Fundamental limits are explored (assuming Carnot heat pump operation), and realistic limits are explored (using realistic vapor compression cycle performance). The performance is evaluated with respect to efficiency and power demand during peak grid times. This manuscript investigates the potential for both energy and demand reduction offered by heat pumps (HPs) integrated with thermal energy storage (TES) systems, employing both analytical and numerical modeling techniques for HPs. Simulation analysis explores the conceivable temperature configurations in HP-TES systems, including the application temperature, TES temperature, and ambient temperature. The findings suggest that maximum energy savings are predominantly achieved when the temperature of the TES closely aligns with that of the application. Conversely, a substantial temperature differential between the TES and the application yields the greatest reduction in peak demand. Furthermore, the potential for energy conservation increases with the increase in the amplitude of ambient temperature fluctuations.

1. INTRODUCTION

This paper seeks to leverage an idealized and sometimes symbolic analysis that can lead engineers and other practitioners to develop faster and more insightful intuitions about thermal energy storage. 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. The aggressive carbon reduction goals set by the United States are increasing the need for thermal energy storage (TES) technologies. 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. Besides, the retirement of coal-fired power plants throughout the United States could present new opportunities for TES.

Adding TES to building HVAC systems usually involves integrating the heat pump system with a TES component to shift most of the electricity used for space cooling and heating from peak to off-peak periods. Taking space cooling as an example, TES systems produce ice chiller water or phase change material (PCM) during off-peak periods and then discharge the cooling capacity during peak periods. Commonly used TES material include paraffin wax, ice, and salt hydrates. 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 (De Gracia and Cabeza (2015)). 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 (Sharma et al. (2009)). An alternative solution to address the load shifting on the power grid is to add actively integrated PCM with building equipment (Skach et al. (2017)). However, most of the previous TES integration approaches were developed for new buildings (Jacobson et al. (2018)), or require significant modifications on the existing envelope.

Figure 1 compares the energy conversion flow configurations for building space conditioning. It shows the transition from the conventional heat pump to TES integrated heat pump. The middle section shows a prospective system employing electrical energy storage (EES), wherein electricity from the grid is buffered by the electric battery. The bottom section shows an alternative future configuration where thermal energy storage (TES) is utilized; in this setup, the grid supplies power to the heat pump, and the thermal energy is buffered by the TES before being delivered to the building. It explores the potential for TES to perform similar functions as electrical battery storage in heat pump application scenario.

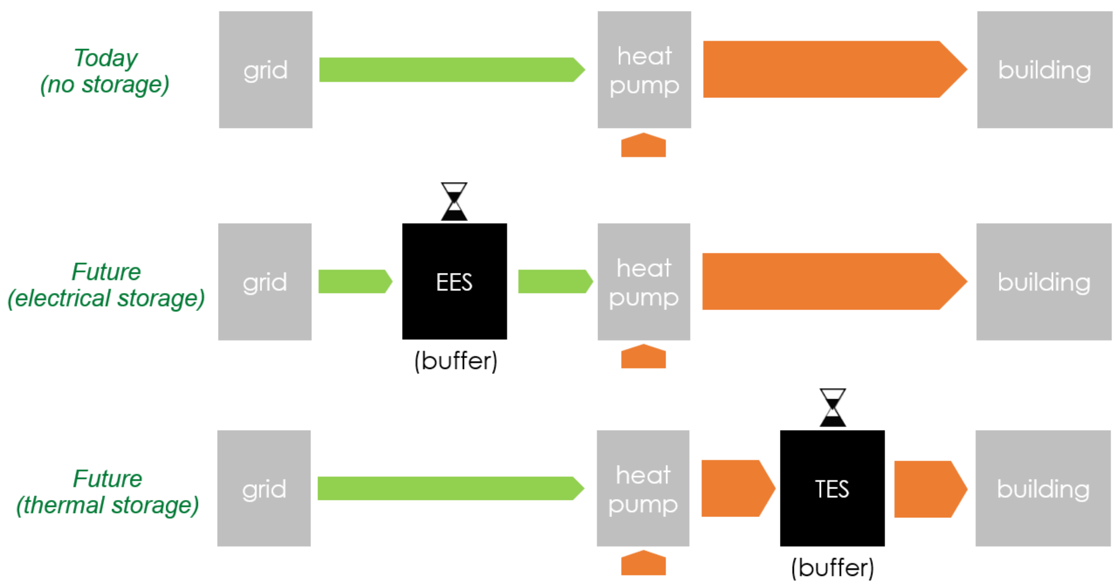

Figure 1: A high level view of how thermal storage can serve as an alternative to electrical energy storage for building space heating.

2. TES TEMPERATURE RANGES

If the heat load is given, and we assume that the heat pump capacity is large enough to meet the load, then the energy consumed within block of time (for example, an hour) will be proportional to the inverse of the COP. In this context, this allows us to indicate the effect of a Carnot heat pump on peak demand (assuming we are measuring peak demand as the energy consumed over a finite time interval, where that interval is significantly larger than the typical on/off cycling time of the equipment). As a summary, in the analytical evaluation of TES integrated with Heat Pumps, the following assumptions are made:

1. Equivalence of thermal loads during normal operation and TES discharging, $Q_{application,normal} = Q_{application,TES\_discharging}$, facilitates a comparative analysis between the conventional and TES-integrated systems.

2. Invariant thermal conductance of the TES during both charging and discharging phases ensures consistent thermal transfer rates, $Q_{C,TES} = Q_{H,TES} = Q_{TES}$.
3. Adequate TES capacity to fulfill all thermal loads during peak demand periods, thereby eliminating the need for conventional HP operation at these times.
4. The finite storage capacity of the TES implies that its heat accumulation or depletion is governed by the conservation of energy across the heat pump system, necessitating energy corrections for efficiency and storage capacity interdependence.
5. The TES undergoes complete recharging in off-peak periods, avoiding any partial charge scenarios and ensuring the system returns to full capacity following depletion.
6. The TES maintains isothermal conditions throughout its operation, with energy transactions occurring exclusively as per operational directives, precluding any unsolicited energy losses or gains.

Equipped with these assumptions, we can proceed to evaluate the impact on peak demand of ideal Carnot heat pumps. First, let's assume a fixed temperature of TES (such as a PCM) is to be used. This assumption will be relaxed later but is an important category to consider. This allows the construction of **Figure 2**, with four relevant temperature ranges, some of which overlap.

In **Figure 2**, in the range marked H_D, the TES is hotter than the heating distribution fluid, making it hot enough for direct heating using the existing distribution system. The rank marked H_I indicates the TES is warmer than the ambient on a typical cold day, making it useful as a heat source on cold winter days. C_I indicates the TES is cooler than the ambient on a typical hot day, making it useful as a heat sink on hot summer days. C_D means the TES is colder than the distribution cooling fluid, making it usable to directly condition the space in the existing distribution system without any boost from a heat pump.

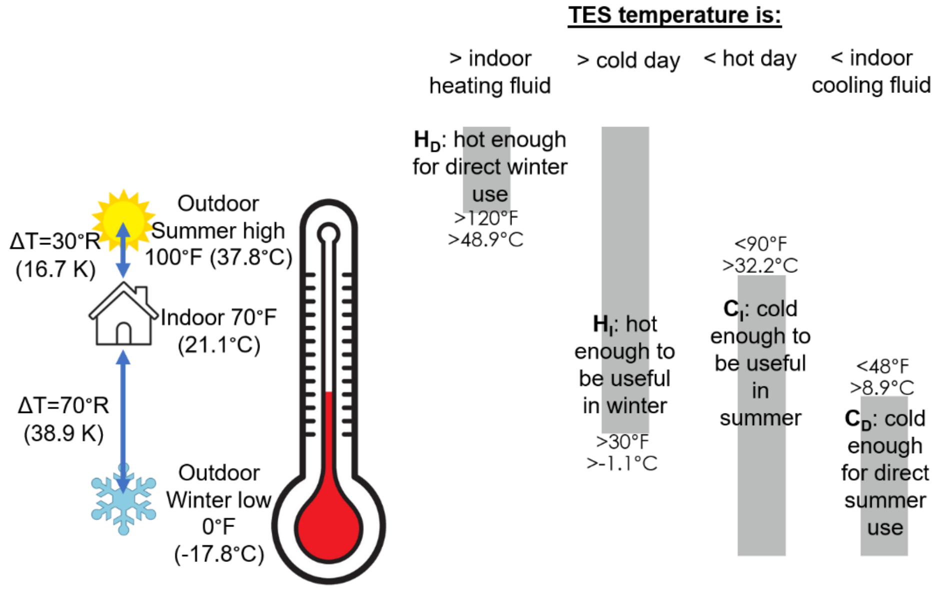

Figure 2: Four relevant ranges that indicate the usefulness of a thermal storage medium to space conditioning, illustrated with some temperatures typical in the US. H_D, H_I, C_I, and C_D are defined in the text.

By inspection of Figure 2, we can observe that some ranges overlap, and some do not. This is illustrated more clearly in **Figure 3**. On the left are the same temperatures as in **Figure 2**, typical for an air ducted heating and cooling system, while the right shows how the ranges overlap with different temperatures for the method of distributing heat to and from the building. The right figure uses distribution temperatures typical of distribution systems with very low approach temperature due to very high surface area, such as underfloor heating and chilled beam ceilings. The middle two bars are dependent on climate and are kept constant in this figure. Comparing the left and right, using lower-approach temperature cooling distribution expands the range of TES than can be used both directly and indirectly in cooling (H_IC_D), and also makes possible a new region (H_DC_I) that did not exist on the left. An appropriate version of the figure can readily be generated for each set of climate, application, and distribution temperatures.

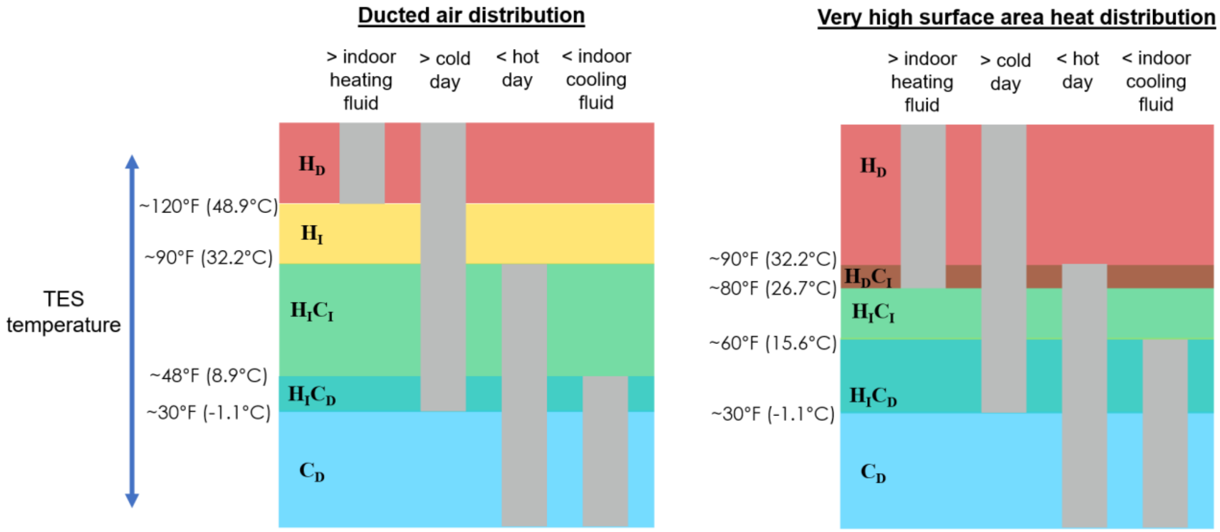

Figure 3: Illustration of how the four ranges of TES usefulness overlap to give rise to numerous usefulness regimes.

Two possibilities were drawn in **Figure 3**. By exploring the possibilities for these four temperature ranges, there are 7 possible outcomes: H_D, H_I, H_DC_I, H_IC_I, H_IC_D, C_I, and C_D. These 7 are provided with their relevant operating modes in **Table 1**. Depending on the case, there are between 4 and 7 operating modes available. Some cells are marked "maybe," because in the case where the TES has a temperature extreme enough to allow direct distribution to the load, the option also exists to use a heat pump-mediated approach instead (this may be desired if, for example, a designed wants to use an existing refrigerant-based distribution system without introducing an additional hydronic one for direct TES usage).

Table 1. System operating modes for each of the 7 possible TES temperature categories

		TES temperature category						
Operating mode	**Heat flow**	**H_D**	**H_I**	**H_DC_I**	**H_IC_I**	**H_IC_D**	**C_I**	**C_D**
Normal heating	Amb→bldg	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Discharging: direct heating	TES→bldg	Yes	No	Yes	No	No	No	No
Discharging: HP-mediated heating	TES→bldg	Maybe	Yes	Maybe	Yes	Yes	No	No
Charging: heating	Amb→TES	Yes	Yes	Yes	Yes	Yes	No	No
Normal cooling	Bldg→Amb	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Discharging: direct cooling	Bldg→TES	No	No	No	No	Yes	No	Yes
Discharging: HP-mediated cooling	Bldg→TES	No	No	Yes	Yes	Maybe	Yes	Maybe
Charging: cooling	TES→Amb	No	No	Yes	Yes	Yes	Yes	Yes
Sum: # of operating modes		4-5	4	6-7	6	6-7	4	4-5

Figure 4 shows the 6 possible operating modes for a TES system for building space conditioning. In this figure, the thermal reservoir of the ambient air is shown as an oval, and the heat sinks/sources of the building and TES are shown as rectangles. Arrows indicate heat flow. Charging is always the mode that replenishes the TES for further use, and discharging is the mode that utilizes the TES for building conditioning, avoiding the need to have heat transfer with the ambient. This means that charging in heating season adds heat to the TES, and charging in cooling season removes heat from the TES.

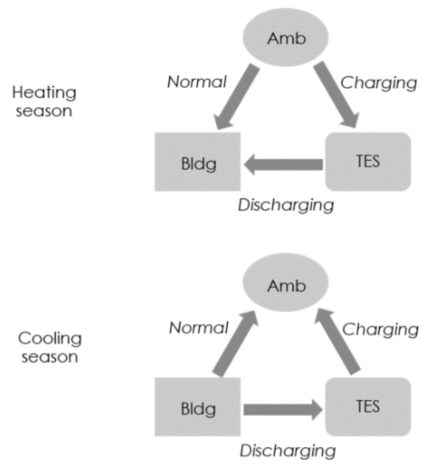

Figure 4: Six operating modes of a TES system.

Next, combining **Figure 3 and 4**, a selection of the various temperature categories is shown in **Figure 5**. Here, a circle is shown where a heat pump is required to move heat to a sink that is warmer than a source. Starting on the left, H_IC_I uses a TES temperature that allows a fully heat pump-mediated approach, where all 6 modes of operation require the heat pump. This is useful both winter and summer but has the least potential for demand reduction because the compressor must run in every mode, even in discharge mode during grid peak times. H_D uses a TES temperature too hot for any cooling use, and offers the best winter demand reduction, but is not useful in summer. H_C provides the best summer demand reduction but is not useful in winter.

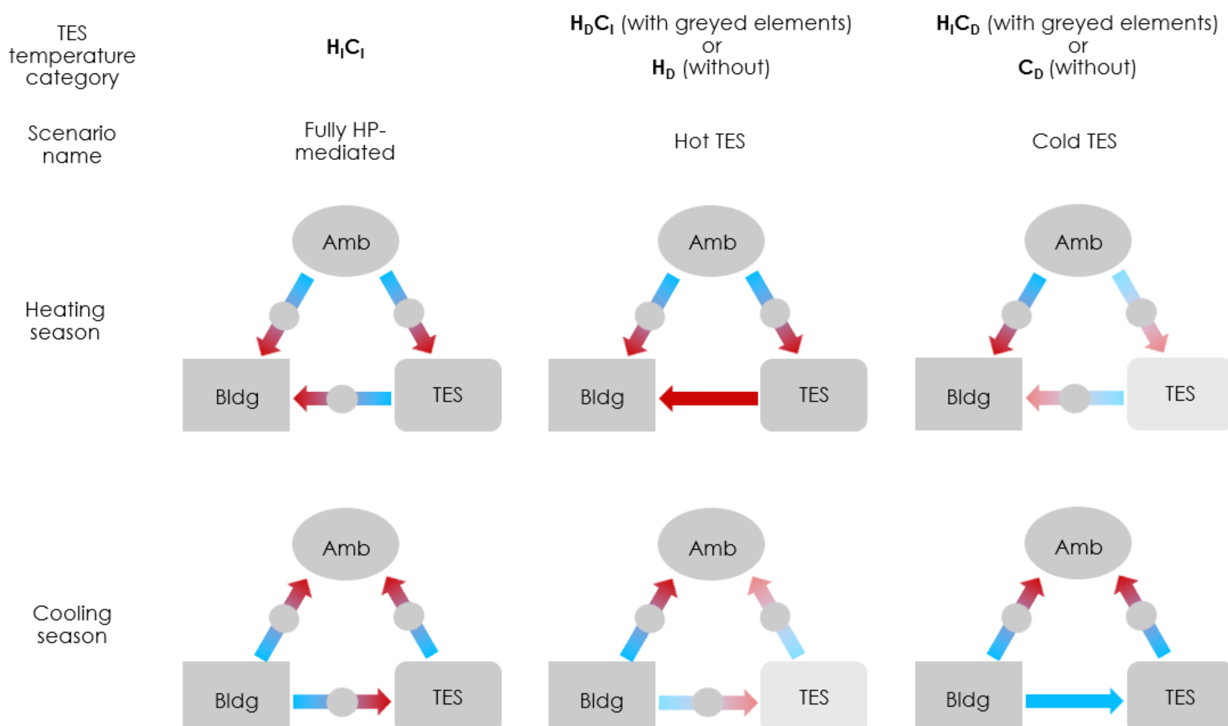

Figure 5: Five of the seven possibilities from Table 1: H_IC_I, H_DC_I, H_D, H_IC_D, and C_D.

The seven possibilities shown in **Table 1** assumed a fixed TES temperature. Relaxing this assumption by allowing multiple TES temperatures opens additional possibilities, such as the H_DC_D case shown in **Figure 6**. This H_DC_D is only possible by using two TES temperatures, one in the summer and one in the winter. Multiple TES temperature are possible by using multiple PCMs, using a tunable PCM, or using a sensible storage medium that stores heat at different temperatures depending on the time of year. It would offer the best demand reductions in both seasons.

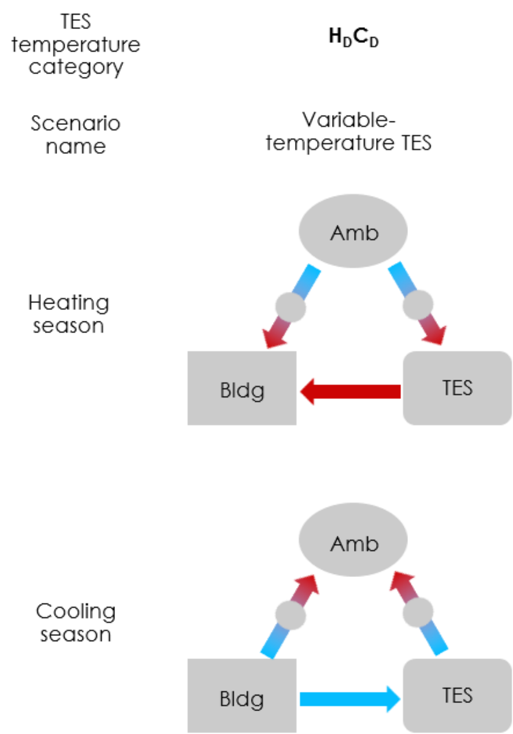

Figure 6: Additional case made possible by different TES temperature in each season.

This yields the 8 possibilities summarized in **Table 2**.

Table 2. Summary of 8 possible TES temperature categories

		In heating mode, TES is		
		H_0: not useful	H_I: useful indirectly (HP-mediated)	H_D: useful for direct heating, or HP-mediated
In cooling mode, TES is	C_0: not useful		$\mathbf{H_I}$	$\mathbf{H_D}$
	C_I: useful indirectly (HP-mediated)	$\mathbf{C_I}$	$\mathbf{H_IC_I}$	$\mathbf{H_DC_I}$
	C_D: useful for direct cooling, or HP-mediated	$\mathbf{C_D}$	$\mathbf{H_IC_D}$	$\mathbf{H_DC_D}$

3. PERFORMANCE ANALYSIS

Not all the scenarios have been evaluated by experiment, nor have they all been evaluated by simulation. In this work, the H_IC_I scenario was selected for further study. This scenario was selected because it has the lowest potential for demand reduction, so we can assume that it represents a “floor” on demand reduction performance and is particularly instructive to evaluate.

The Carnot-based analytical evaluations of TES-integrated HP aim to calculate:

(1) the percentage of total energy savings during on-peak periods compared to traditional systems as quantified in Equation 1;

(2) the percentage of on-peak demand reduction offered by TES-HP compared to conventional heat pump, as defined in Equation 2.

$$\% \, Energy \, Savings = 100 \times \frac{W_{conv,on\text{-}peak} - W_{TES,roundtrip}}{W_{conv,on\text{-}peak}} = 100 \times \left(1 - \frac{COP_{conv,on\text{-}peak}}{COP_{TES,roundtrip}}\right) \quad (1)$$

$$\% \, Demand \, Reduction = 100 \times \frac{W_{conv,on\text{-}peak} - W_{TES,on\text{-}peak}}{W_{conv,on\text{-}peak}} = 100 \times \left(1 - \frac{COP_{conv,on\text{-}peak}}{COP_{TES,on\text{-}peak}}\right) \quad (2)$$

Figure 7 illustrates the potential for energy savings and on-peak demand reduction in H_1C_1 case from Carnot analytical analysis: commercial refrigeration with an application temperature of 3°C and domestic hot water at 60°C. A maximum ambient temperature differential ($\Delta T_{ambient}$) of 20°C is assumed as a realistic limit for these scenarios. The results indicate that optimal energy efficiency and demand reduction occur when the Thermal Energy Storage (TES) temperature is equal to the application temperature, and that energy savings are amplified with larger $\Delta T_{ambient}$ values.

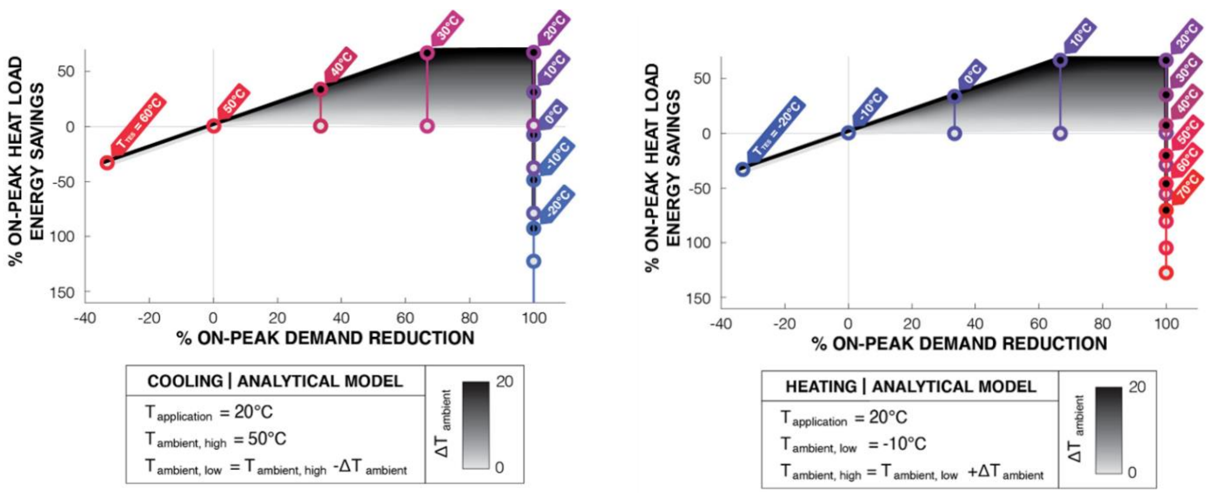

Figure 7. Analytical HP-TES performance results for H_1C_1

Using the same methodology described in Hirschey et al. (2023), the energy savings and demand reduction were computed for the H_IC_I case, and the results are shown in **Figure 8 and 9**. These figures depict a more realistic results by modeling a 5-ton heat pump system using DOE/ORNL Heat Pump Design Model developed by Shen (2019). A more detailed explanation of this component-based vapor compression system simulation tool can be found in Hirschey et al (2023). The results use realistic heat pump performance, with idealized PCM performance: zero glide, and zero subcooling or superheat.

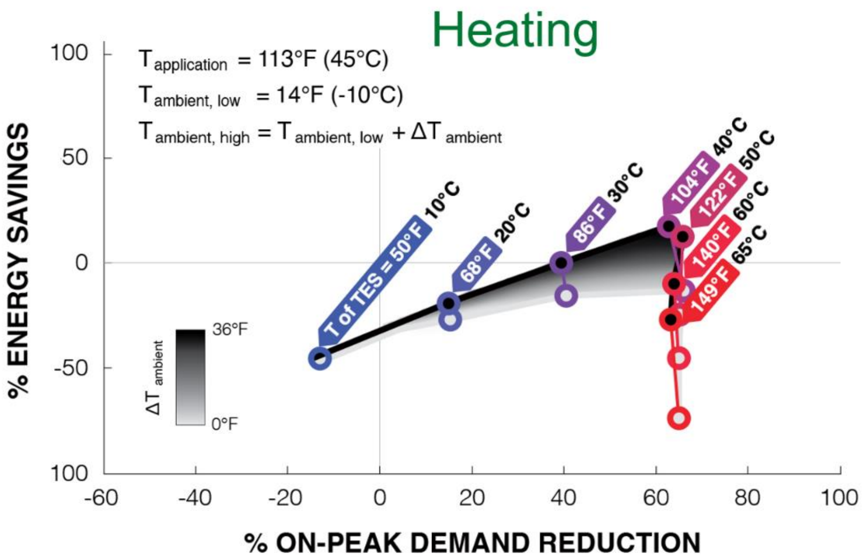

Figure 8: Heating mode (winter) energy savings and demand reduction possible for the fully heat pump-mediated H_IC_I scenario, computed for realistic vapor compression performance and ideal PCM.

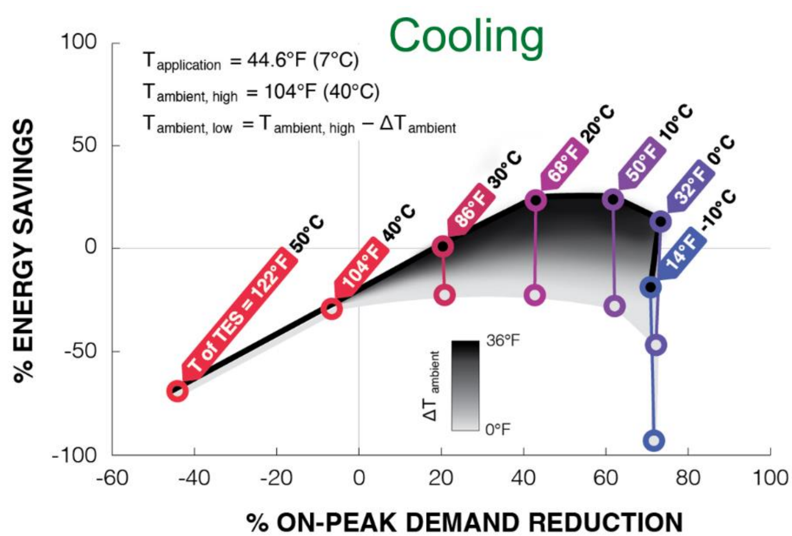

Figure 9: Cooling mode (summer) energy savings and demand reduction possible for the fully heat pump-mediated H_IC_I scenario, computed for realistic vapor compression performance and ideal PCM.

The following observations can be made by inspection of **Figures 8 and 9**:

- Demand reduction of about 65% in heating mode and 75% in cooling mode are possible with a fully heat pump-mediated approach
- A larger diurnal temperature swing ($\Delta T_{ambient}$) makes possible larger energy savings, but does not affect demand reduction.
- The optimal TES temperature range for heating is approximately 40–50°C (104–122°F). For TES temperature hotter than this, demand reduction is constant, but round-trip energy consumption increases.
- The optimal TES temperature range for cooling is approximately 0–20°C (32–68°F). For TES temperature colder than this, demand reduction is constant, but round-trip energy consumption increases.
- When selecting a phase change temperature for these space conditioning application temperatures, there is a tradeoff between cooling season performance and heating season performance. For example, choosing

25°C (77°F) results in about 1/3 reduction in demand in heating and cooling modes, while typically increasing energy consumption.

- Using different TES temperatures for each season would maximize the performance in each season.

Only the fully heat pump-mediated $H_I C_I$ case was evaluated in detail in this work. Efficiency and demand reduction potential will be improved by exploring other cases as well, in future work.

6. CONCLUSIONS

This study evaluates the energy saving and peak demand reduction potential in TES integrated heat pump systems across a range of application temperatures. Using Carnot-based analysis and assigning peak periods to correspond with ambient temperature extremes, the benefits of TES-HPs is compared against conventional HP without TES. It was found that energy savings are maximized when TES and application temperature difference is minimized, a principle applicable to both heating and cooling functions, with increased savings as ambient temperature rises. However, peak demand reduction is maximized when temperature of TES and application is optimal, because it facilitates direct heat transfer and reducing HP workload during peak times. A physics-based detailed vapor compression modeling shows that TES and application temperatures yield both energy conservation and demand reduction. 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. Integrating TES with heat pump (HP) enables electrification of space cooling and heating devices without overtaxing the grid.

NOMENCLATURE

COP	coefficient of performance
EES	electrical energy storage
HP	heat pump
HPDM	DOE/ORNL Heat Pump Design Model
PCM	phase change materials
TES	thermal energy storage

Subscript

conv	conventional heat pump (without TES)
c	cooling operation
h	heating operation
I	indirect (heat pump-mediated)
D	direct

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