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A proposed methodology to reduce heat pump size with integrated thermal energy storage

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Abstract

Thermal energy storage (TES) offers a unique storage solution wherein heat is stored for later use to thermally condition an application. Heat pumps (HPs) move heat from relatively cold to a relatively hot with an input of work. Integrating TES into a HP system adds a third temperature body, and the HP can be selectively coupled to operate between any two bodies: a constant temperature application, a temporally fluctuating ambient temperature, or a constant temperature TES. Since the HP-TES system enables operation under different conditions depending on the pair of temperature bodies, changes in efficiency and capacity can be expected. Thus, TES can shift HP operation to more favorable conditions to deliver heat to the application. Consequently, TES increases the apparent capacity of the HP which might enable a nominally smaller HP to be used effectively for an application. This paper outlines a method by which TES can reduce the size of a HP without sacrificing heat delivered to the application. The method is demonstrated for a building cooling application which realized a reduction in nominal HP size from 3 tons to 2.4 tons.

Keywords: thermal energy storage; heat pump;

1. Introduction

Thermal energy storage (TES) is posed to be a critical technology for the Energy Transition. TES can benefit many everyday applications and services, but its relevance and performance is dependent on the temperature at which energy is stored. Analogous to electrical energy storage (EES) which might be characterized by its voltage, TES is characterized by its storage temperature. However, unlike EES which can have its voltage transformed to higher or lower values, TES can only transfer heat down a temperature gradient from relatively hot to relatively cold. However, by integrating TES into a heat pump (HP) system, heat may be upgraded to move up a thermal gradient with an input of work. This opens the possibilities for TES to be deployed for a wide variety of applications without needing quite specific storage temperatures (*e.g.*, a cooling application can effectively utilize a TES storage temperature higher than the application temperature). The TES analyzed in this report is assumed isothermal, but real systems might have small TES temperature changes or internal temperature gradients during use.

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Fig. 1 shows the possible HP-mediated modes that the HP-TES system can take for thermally conditioning an application. A conventional HP might operate only between the application and the ambient, providing heating to the application when the ambient temperature is low and cooling when the ambient temperature is high, simply speaking. For simplification, the ambient in an infinitely large temperature body whose temperature can fluctuate in time, is unaffected by the operation of the HP, and thermally interacts with the application. The efficiency of the HP to thermal condition the application is inversely correlated to the temperature difference between the application and the ambient, typically. Adding TES to a HP system provides a third temperature body with which to operate the HP. At any one time, the HP may only couple to two of the three temperature bodies.

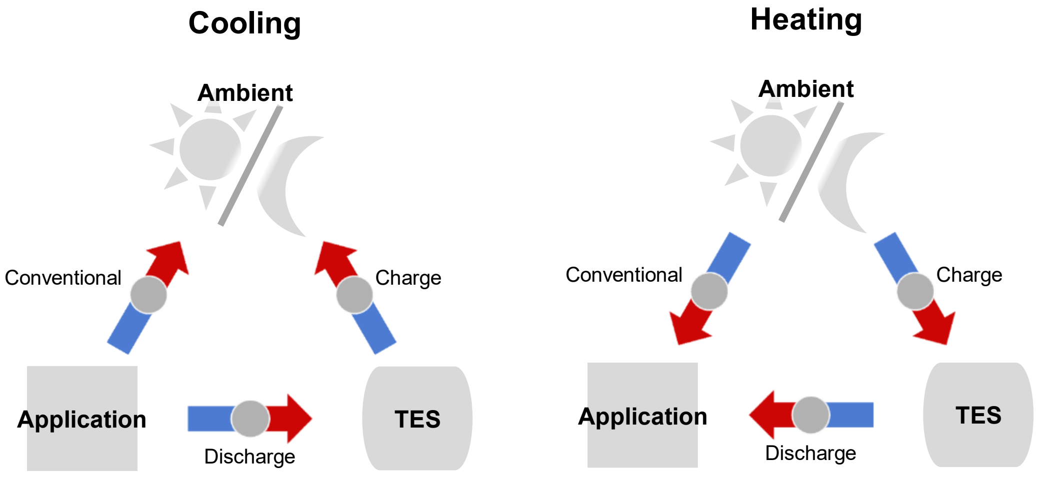

Fig. 1. Heat exchange between three temperature bodies in a HP-TES system.

If the TES is at a different temperature than the ambient, it may provide more advantageous HP operating conditions with which to heat or cool the application. Discharging mode is when the TES is used to provide thermal conditioning to the application and this mode nominally reduces the available energy stored within the TES. Simply speaking, operating in discharging mode is advantageous when the temperature difference between the application and TES is more favorable than the difference between the application and ambient for the thermal conditioning needed. For example, if the application requires cooling and the TES is at a lower temperature than the ambient, it may be more favorable to operate the HP in discharging mode than in conventional mode. If the ambient temperature experiences time-varying fluctuations, there may be an optimal time to operate in discharging mode based on the ambient temperature oscillation. However, the TES has finite energy storage capacity and once it is depleted, it must be returned to its original state before another discharging event can occur. In this system, this charging event is accomplished by thermally coupling the TES to the ambient via the HP, and the HP adds heat to or withdraws heat from the TES, depending on what is needed, to return the TES to its original state. Again, if the ambient temperature presents cyclic fluctuations and the TES temperature is constant, there may be an optimal time to charge the TES when the HP is most effective. Thus, HP-TES systems may shift bulk energy demand for peak heating and cooling loads of an application.

Another value proposition for HP-TES systems is the potential to downsize a HP. Typically, a HP is sized for the most extreme heat load the application might experience, often called the design condition. But most conditions experienced by the application are less extreme than the design condition and thus the HP is oversized for most of its regular use. If instead TES is designed to be utilized during the most extreme conditions by providing more favorable HP operating conditions, a smaller HP, more appropriately sized for a less extreme condition, can be used effectively. In essence, the TES increases the apparent capacity of the HP by providing more favorable HP operating conditions during extreme conditions and thus the requisite heat delivered to the application is met with a nominally smaller HP.

Some published research has examined HP sizing with integrated TES. However, most studies focus on the sizing of the TES storage capacity to meet the thermal loads of a certain event while fewer leverage the TES to reduce HP size. A summary of the reports found in literature follows, first those that include HP sizing then those that exclusively focus on TES capacity sizing. Many also report on the TES storage temperature, but this is often predetermined or chosen from a narrow set of preselected temperatures. It is observed that the approaches to integrate TES into a HP system differ significantly between studies, and the criterion by which the value of TES or downsized HP vary. Many studies focus on building technologies and systems, but HP-TES can be used in many applications.

Renaldi *et al.* (2017) performed a cost optimization of an integrated HP system to meet indoor heating demands and domestic hot water production in the United Kingdom [1]. The authors explore four HPs that were modeled using regression fits from manufacturer data and six TES capacities each modeled with two storage temperatures, 35°C and 50°C. The TES is modeled as a typical domestic hot water tank which was used for either space heating through radiators and underfloor heating, or for providing domestic hot water. The authors reported HP-TES as compared to gas boilers and concluded that the HP-TES system is not cost effective, even when subsidized. The authors include a baseline HP system without TES in a summary figure, and it is observed that the TES can reduce the operational cost of the HP by approximately 50% with the largest TES size studied. However, the baseline HP and the HP in the HP-TES system are identically sized, therefore it is inferred that the authors found no advantage or mechanism by which the TES reduces the HP size. Furthermore, the authors mention that smaller HPs can lead to increased cost by way of increased energy consumption from auxiliary backup heating systems if the smaller capacity cannot meet all the heating demands even with TES. In the scenario studied, no HP downsizing potential was viable.

Aljehani *et al.* (2018) evaluated a 4-6°C TES system for air conditioning [2]. The TES was coupled to the HP refrigerant loop and the duct air via an ethylene glycol loop. The HP was used to charge the TES, and the temperature difference between the air and TES allowed for direct discharging with a nonzero amount of work to circulate the ethylene glycol. The authors explain that in the conventional system, a 5 kW compressor is needed to meet the thermal loads during the six hour peak, but that it is oversized during off-peak hours. With the integrated TES system, a 2.5 kW compressor was sufficient in meeting peak loads and this size was sufficient for off-peak. Thus, the authors demonstrate a 50% reduction in HP compressor size with the inclusion of TES. Simulations then show that this system can reduce electricity consumption by 30%.

Lyu *et al.* (2022) evaluated the size of an air source HP and of a water tank TES unit for a residential house in Beijing, China [3]. The building model was built in TRNSYS based on measurement data. The water storage tank is modeled between 0.06 – 4.5 m^3, though this is not explicitly related to energy storage capacity. The TES temperature is studied with two setpoint temperatures: 45°C during the hottest 12 hours of the day and 35°C during the coldest 12 hours of the day. The HP size is varied from 80-100% of the HP sized for the design heating load of the building, and all could meet the thermal needs of the building with TES. The authors indicate that HP capacities lower than 80% of the design conditions led to an unacceptable loss of thermal comfort even with large TES. In addition, the authors investigated the startup losses associated with HP cycling. The authors explain that steady HP capacity may not be achieved until several minutes after startup, based on measurement data. Thus, some efficiency loss is observed during the transient startup period. The authors hypothesize that the larger HPs will have shorter operational times and therefore startup losses are more significant and will accumulate with repeated short cycling events. Comparatively the smaller HPs have longer operational times which leads to fewer startup events and therefore less accumulated startup losses. During startup, the TES acts as a buffer tank to compensate for the reduced capacity as described by Meng *et al.* (2021) [4]. Furthermore, the TES can be used to absorb excess heat during steady HP operation, prolonging its operating time and limiting loses due to short cycling. Thus, Lyu *et al.* (2022) conclude that even small TES can reduce HP startup losses compared to lone HP systems. Furthermore, Lyu *et al.* (2022) do not observe significant energy savings with the smaller HP and therefore conclude that the size of the HP has little effect when TES is present. Critically, however, the successful use of a smaller HP is enabled by the presence of the TES. And they note that a smaller HP can reduce the upfront investment. Findings indicate that the large TES sizes can lead to higher energy savings, upwards of 18%.

Marini *et al.* (2019) performed an analysis for the potential of HP-TES to replace existing gas boilers in the UK for space heating and domestic hot water [5]. Data from several residential building were collected operating with the existing gas equipment. A model was then built in TRNSYS to simulate each building with HP-TES equipment, over 400 scenarios in total. A process was used to select an appropriate HP size based on [6] such that the HP-TES thermal service provided to the building matched as closely as possible to the historical data. The HP selection process included information about each house analyzed, the load shifting strategy based on available utility tariffs, and the TES capacity modeled as a hot water tank with a setpoint temperature of 60°C. The authors show that larger TES systems required larger HPs – contrary to the hypothesis proposed that TES adds capacity and thus reduces HP size. However, little discussion was given to the HP selection process as the analysis focused on whether the HP-TES can meet or exceed the thermal conditioning service as compared to the extant gas equipment. It is speculated that the combination of large TES size and relatively high TES temperature requires a large HP to fully recharge. Furthermore, the approach to mirror historical heat loads with the HP-TES led to a bias towards big systems as there was little opportunity for the load shift flexibility of the HP-TES to be explored. From the data, a minimum TES size could be determined based on the building characteristics, the occupants' idiosyncratic behavior, and the utility tariff. The authors conclude that sizing such HP-TES systems might be specific to certain building and occupant characteristics, and that operational costs to maintain the same level of thermal comfort are likely the largest motivator for HP-TES systems.

Alimohammadisagvand *et al.* (2016) performed a cost optimization of a TES operating with a ground source HP for space heating in Finland [7]. The temperature of TES was evaluated between 55-95°C and the size the TES system varied between 0.3-1.5 m^3, but it is not said how TES physical size correlates to energy storage capacity. The HP and TES selected in this study are based on available products. The authors find that the smallest TES size led to the minimum life cycle cost. Moreover, the authors note that increasing the TES temperature does not lead to increased performance if the TES discharging capacity is sufficient for the application. The optimal TES size was determined by a cost minimization; there is no objective function which would size the TES to the expected heat loads or usage. The authors report the delivered energy from the TES. Unsurprisingly with this metric, the smallest TES unit delivered the lowest amount of energy therefore having the smallest impact of all systems analyzed. Moreover, this study evaluated a ground source HP which are not greatly influenced by the ambient conditions and often have more consistent operation compared to air source HPs. Therefore, without a cost objective related to load shift enabled by the TES, such as a time-of-use or other time varying utility tariff, or a HP that undergoes significant performance changes, it is unsurprising that a small TES tank was found to be cost optimal.

The previous studies evaluate specific building technologies in specific climates to ascertain HP sizing or requisite TES capacity. Many studies focus on operational or life cycle cost to determine an optimal solution. And it is well understood that consumer facing products heavily factor cost into success and deployment. However, the approaches used in determining the equipment size and TES temperature vary considerably between studies and result in some conflicting conclusions. A more methodical approach for determining the potential of TES and its effect on HP size is warranted.

This paper explores the potential of an isothermal TES system to reduce nominal HP size and presents a methodology by which HP and TES size, and TES temperature can be determined for an application. First the method is explained in general terms as it might apply to any application. Then the method is demonstrated using empirical HP data for a building cooling application.

2. Methodology

The method by which TES can reduce HP size is shown here using general terms such that it can be applied to any application. Fig. 2 shows the process flow for determining the downsizing HP for an application in generalized terms. The follow sections provide more detail to how this process is utilized for an application. In Section 2.1, the method is explained as to provide heating to the application, but an identical approach can be used for cooling applications, curtly discussed in Section 2.2.

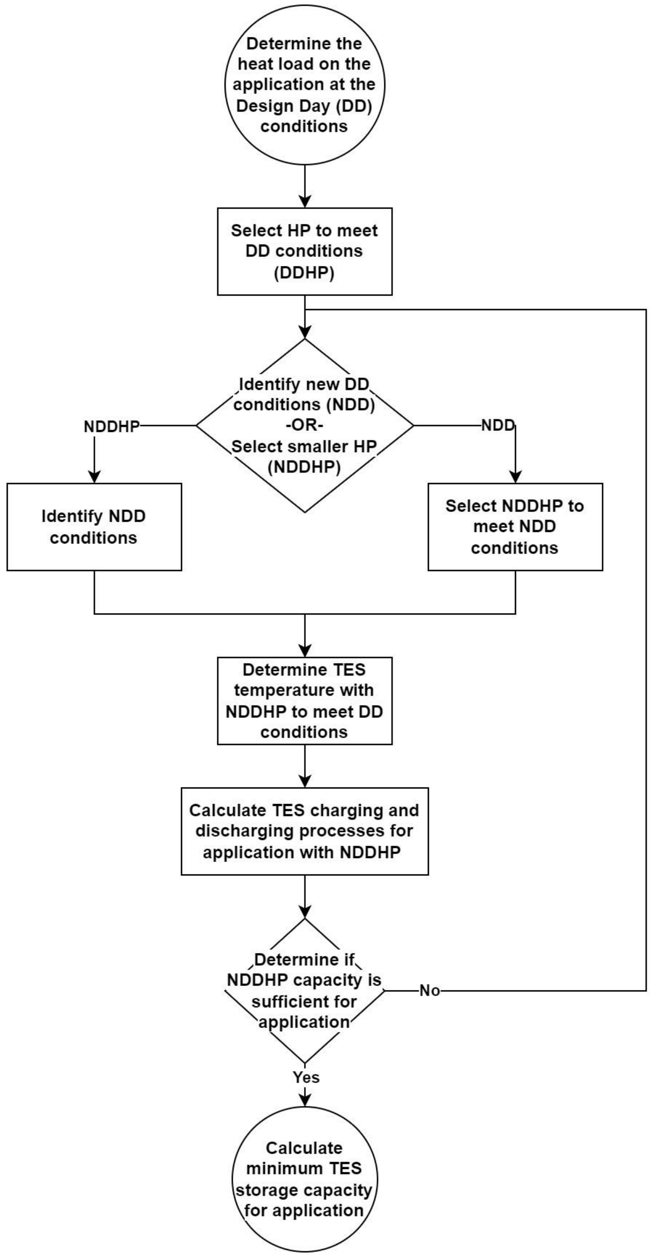

Fig. 2. Generalized HP downsizing with TES approach

2.1. Heating Application

For a heating application it is assumed that a HP provides all heating and no backup heating systems are used. First, the design condition, or design day temperature, $T_{H,DD}$, and associated design heat load on the application, $\dot{H}_{H,DD}$, are determined. For buildings, this could be determined from ACCA Manual J, ASHRAE Standards, or through building energy modeling. Other applications might require unique calculation procedures to determine heating loads against some design conditions. It is uncommon to determine the heating loads for all conditions and commonly, even for real systems. The heating load curve, $\dot{H}_H$, is thus a linear interpolation between the design conditions and the application's balance point temperature, T_{BP}. For applications with special considerations, the heating load might yield a nonlinear curve, but this would be specific to that application and circumstances. But to keep the method general, intermediate heating loads at some ambient temperature, T_O, between T_{BP} and $T_{H,DD}$ the curve is interpolated on the load curve, $\dot{H}_H(T_O)$.

For a heating application, the HP hot side is connected to the application temperature body, T_{app}, which is often at a higher temperature than T_{BP}. The heat might be delivered with some approach temperature above the application temperature, T_{app}^{+} (the approach temperature denoted as a plus sign for brevity). The notation for HP capacity will be $\dot{Q}(T_{cold\ side}, T_{hot\ side})$. A subscript *H* will indicate HP heating, a *C* will indicate cooling. Additional subscripts will identify the HP design conditions.

The ACCA Manual S includes a methodology for sizing the HP to the design conditions of a building [8]. Other methodologies for sizing the HP might be used, including those that are "tricks of the trade" of contractors, but generally, the HP is sized to meet the design day conditions with some safety factor, f_S. The capacity of the design day HP, *DDHP*, is sized for these conditions: $\dot{Q}_{H,DD}(T_{H,DD}, T^+_{app}) = f_s\dot{H}_{H,DD}$

Next, either a smaller HP or a new design day temperature is selected – these are intrinsically linked. If a smaller HP is selected, its maximum capacity, $\dot{Q}_{H,NDD}$, will identify the new design day temperature, $T_{H,NDD}$, to meet the thermal conditioning needs at this temperature. Or if a new design day temperature is identified, the same HP sizing procedures and standards as before may be used to identify a properly sized, presumably smaller, *NDDHP*. The result of both processes yield a *NDDHP* and $T_{H,NDD}$ such that $\dot{Q}_{H,NDD}\left(T_{H,NDD}, T^+_{app}\right) = f_s\dot{H}_{H,NDD} = f_s\dot{H}_H(T_{H,NDD})$. This process can be done iteratively based on available HP devices and the conditions experienced by the application. Once the *NDDHP* and $T_{H,NDD}$ are determined, the TES temperature, $T_{H,TES}$, is identified as the operating temperature at which the *NDDHP* can supply the heating capacity equal to the design day heat load, $\dot{Q}_{H,NDD}(T_{H,TES}, T^+_{app}) = f_s\dot{H}_{H,DD}$. For simplicity, the TES will be used for discharging only when the ambient temperature, T_O, is less than $T_{H,NDD}$, and despite the safety factor included in its sizing. The safety factor will be dropped from further discussion and equations.

The ambient temperature is a function of time, $T_O(t)$, and may take a periodic waveform. Thus, to determine the time spent discharging during a single event, $t_{H,dis}$, information about the amount of time and the magnitude by which the ambient temperature is below $T_{H,NDD}$ is needed for each discharging event. This information will be specific to the application, location of the system, and the previous decisions made to determine $T_{H,NDD}$. An energy balance is then performed such that the time spent discharging at the constant *NDDHP* discharging heating capacity, $\dot{Q}_{H,NDD}(T_{H,TES}, T^+_{app})$, is equal to the cumulative heating loads from the ambient during this time, $t_{H,-}$, below $T_{H,NDD}$, Eq. 1 This ignores temperature fluctuations or gradients in the application or the TES as these are considered small compared to the ambient temperature fluctuations. Also note that Eq. 1 is calculated for each discrete discharging event, not cumulatively.

$$t_{H,dis} \cdot \dot{Q}_{H,NDD}(T_{H,TES}, T^+_{app}) = \int_0^{t_{H,-}} \dot{H}_H\big(T_O(\tau)\big)d\tau \text{ when } T_O < T_{H,NDD} \tag{1}$$

When the ambient temperature returns above the new design day temperature condition, $T_O \geq T_{H,NDD}$, the *NDDHP* may spend some time heating the application normally, t_{heat}, such that the cumulative heating delivered by the *NDDHP* equals the sum of the heating loads from the ambient conditions. To determine t_{heat}, the amount of time, $t_{H,+}$, and magnitude by which $T_O(t) \geq T_{H,NDD}$ is needed for the period immediately succeeding a discharging event and before the next discharging event. Unlike in Eq. 1, the heating capacity of the *NDDHP* is not constant as it couples between the time-varying ambient and application. Eq. 2 shows the energy balance of the NDDHP to meet the heat loads from the ambient in conventional mode.

$$\int_0^{t_{heat}} \dot{Q}_{H,NDD}(T_O(\tau), T^+_{app})d\tau = \int_0^{t_{H,+}} \dot{H}_H\big(T_O(\tau)\big)d\tau \text{ when } T_O \geq T_{H,NDD} \tag{2}$$

Any time not spent directly heating the application can be used to charge the TES, $t_{H,chg,available} = t_{H,+} - t_{heat}$. As the TES is discharged for heating the application, the TES experiences a cooling load from the *NDDHP* and receives some amount of cooling energy for the duration of discharging, depleting the stored energy by an amount $E_{H,dis}$, Eq. 3. The TES must receive an equal amount of cumulative heating energy to fully charge, $E_{H,chg}$, for the next discharging event, Eq. 4.

$$E_{H,dis} = t_{H,dis} \cdot \dot{Q}_{C,NDD}\left(T_{H,TES}, T^+_{app}\right) \text{ when } T_O < T_{H,NDD} \tag{3}$$

$$E_{H,chg} = \int_0^{t_{H,chg,min}} \dot{Q}_{H,NDD}\big(T_O(\tau), T_{H,TES}\big)d\tau \text{ when } T_O \geq T_{H,NDD} \tag{4}$$

Equating Eqs. 3 & 4 informs of the minimum time required to fully charge the TES after a discharging event, $t_{H,chg,min}$, based on the ambient conditions and where $t_{H,dis}$ is determined from Eq. 1. The charging procedure must satisfy the two constraints: 1) $E_{H,chg} = E_{H,dis}$, and 2) $t_{H,chg,min} \leq t_{H,chg,available}$. Failure to satisfy both is ultimately attributed to a lack of available time to complete the charging process before the next discharging process occurs which is related to the ambient conditions, and the combination of the new design day conditions and the capacity of the *NDDHP*.

For an application that experiences irregular periodic thermal heat loads from the ambient, the minimum energy storage capacity of the TES for heating the application, $E_{H,TES}$, should be equal to the maximum energy discharged, $E_{H,dis,max}$, in any one discharging event as determined by solving Eq. 3 for all events. A factor of safety might be added to the minimum determined TES capacity to provide additional resilience against extreme heating events.

This method might be done iteratively or with several different parameters to determine an array of feasible HP-TES systems for this application. Due to the relationship between the *NDDHP* capacity, TES temperature, and new design day temperature, decisions might percolate throughout the analysis and affect the result in unexpected ways. Furthermore, the availability of HPs might be limited or TES storage temperatures might be offered in discrete selections based on available TES materials or technologies. Therefore, if designing a HP-TES system some concessions might need to be made to the availability of products.

2.2. Cooling Application

The process for a cooling application follows the same approach as described by the heating application in Section 2.1. Dual heating and cooling applications are reserved for future work. To summarize the cooling application, like in the heating application, a design day condition, $T_{C,DD}$, is determined by conventional means based on the application. The design day heat loads are determined, and a linear heat load curve is drawn between the design conditions and the balance point temperature, T_{BP}, to calculate the heat loads as a function of ambient temperature, $\dot{H}_C(T_O)$. Note that for many applications, the balance point temperature might be the same for both heating and cooling. The *DDHP* is selected by conventional means. The *NDDHP* and $T_{C,NDD}$ are determined – these are intrinsically linked and choosing one will affect the other. The maximum TES temperature, $T_{C,TES}$, is identified by the conditions at which the *NDDHP* can provide the maximum heat load experienced by the application, $\dot{Q}_{C,NDD}(T_{app}^{-}, T_{C,TES}) = \dot{H}_{C,DD}$.

Fig. 3 demonstrates the approach graphically for a cooling application: 1) The design day heat load and temperature are determined. 2) A HP is selected to meet this design day load. Here, empirical HP compressor data is used to identify a suitable device, a nominal 3 ton HP. The published compressor map is used to plot its capacity as a function of condensing temperature which is related to outdoor temperature by a designated approach temperature. 3) A smaller HP is selected, a nominal 2.4 ton HP. Its capacity is determined from published compressor map information. Where its capacity intersects with the application's heat load curve is the temperature which describes the new design day conditions, $T_{C,NDD}$. 4) Where the *NDDHP* capacity is equal to the original design day heat load identifies the TES temperature necessary to provide thermal conditioning during the most extreme ambient conditions. Though this application and heat load curve is fictional, the HP compressor data is real and could be used in a similar way to size and design a HP-TES systems.

Like was explained for the heating application, the HP is responsible for cooling the application such that its time spent cooling multiplied by the HP discharging cooling capacity is equal to the heat loads experienced by the application from the ambient, Eq. 5. When the ambient temperature exceeds the $T_{C,NDD}$, discharging mode is activated, Eq. 6, as the *NDDHP* does not have enough capacity at these conditions to provide the necessary heat.

$$t_{C,dis} \cdot \dot{Q}_{C,NDD}\big(T_{app}^{-}, T_{C,TES}\big) = \int_0^{t_{C,+}} \dot{H}_C\big(T_O(\tau)\big)d\tau \text{ when } T_O > T_{C,NDD} \tag{5}$$

$$\int_0^{t_{cool}} \dot{Q}_{C,NDD}(T_{app}^{-}, T_O(\tau))d\tau = \int_0^{t_{C,-}} \dot{H}_C\big(T_O(\tau)\big)d\tau \text{ when } T_O \le T_{C,NDD} \tag{6}$$

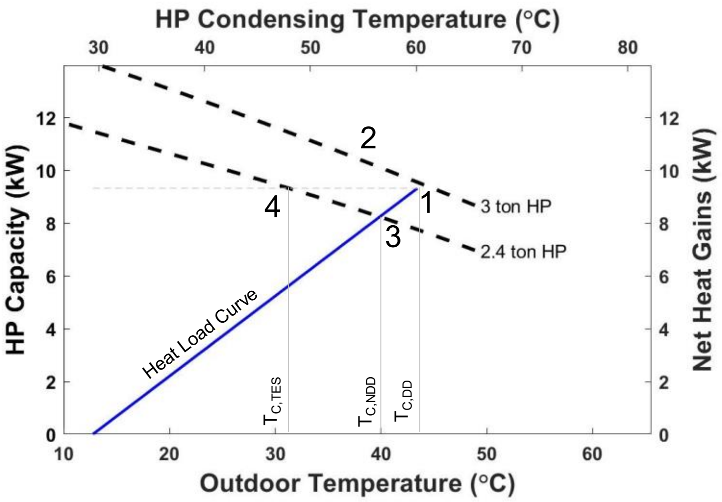

Fig. 3. Generalized HP downsizing with TES based on empirical HP data. 1) The outdoor design day temperature ($T_{C,DD}$) is determined for the application which determines the maximum heat load acting on the application. 2) A *DDHP* is identified to meet this maximum heat load at the $T_{C,DD}$ condition. 3) A smaller *NDDHP* is identified. The intersection of its capacity with the heat load curve indicates the new design day conditions ($T_{C,NDD}$). This can be done in reverse; $T_{C,NDD}$ identified and a *NDDHP* sized for this condition. 4) The temperature at which the *NDDHP* capacity equals the maximum heat load at the DD conditions indicates the TES temperature ($T_{C,TES}$) necessary to provide thermal conditioning at temperatures between T_{NDD} and T_{DD}.

Contrary to the heating application, the TES receives a heating load during discharging. Therefore, the delivered heat to the application is less than the heat stored in the TES; the efficiency of the HP implicitly affects the TES storage capacity which in turn is affected by the TES temperature. The energy depleted from the TES during discharging is shown in Eq. 7. After the discharging event, the TES is charged by coupling the TES to the ambient via the HP, Eq. 8. When charging, the HP still must provide cooling to the application if needed, but any time not spent directly cooling the application can be used for charging the TES, $t_{C,chg,available} = t_{C,-} - t_{cool}$. And likewise, the charging procedure must satisfy the two constraints: 1) $E_{C,chg} = E_{C,dis}$, and 2) $t_{C,chg,min} \leq t_{C,chg,available}$ for every discharge and charge cycle.

$$E_{C,dis} = t_{C,dis} \cdot \dot{Q}_{H,NDD}\left(T_{app}^{-}, T_{C,TES}\right) \text{ when } T_O > T_{H,NDD} \tag{7}$$

$$E_{C,chg} = \int_0^{t_{C,chg,min}} \dot{Q}_{C,NDD}\left(T_{C,TES}, T_O(\tau),\right) d\tau \text{ when } T_O \leq T_{H,NDD} \tag{8}$$

3. Demonstration of HP-TES Sizing

Fig. 3 only demonstrated the HP selection process, and the relationship between the *NDDHP* capacity, the new design conditions, and the TES temperature. However, to size the TES system and determine if the *NDDHP* is capable of supplying all thermal conditioning needs including conventional and charging modes, data on the fluctuating ambient temperature is needed. To demonstrate the approach outlined in Section 2.2 for a cooling application, the process is followed for a building application in Phoenix, Arizona. Typical Meteorological Year version 3 (TMY3) data is used [9]. The TMY3 data presents the median temperature for each hour of the year for building thermal energy simulations. In this analysis, the TMY3 data was interpolated and extrapolated to each minute of the year using Akima spline technique.

Fig. 3 shows the heat load curve for this building and two HP capacity curves calculated from empirical HP compressor data. The nominal 3 ton HP would be selected by conventional means for this building; this is the *DDHP*. Commonly for a building application, the *DDHP* is sized for the 0.4% design condition. The ASHRAE 0.4% design conditions for Phoenix is an ambient dry bulb temperature of 110.2°F (43.4°C). Using the interpolated 2020 TMY3 data, the 0.4% design temperature was identified as 45.2°C. For consistency with the dataset, the calculated 0.4% design condition from the TMY3 data is used. This building is assumed to experience a 9.3 kW net heat load at the 0.4% design condition. The balance point temperature is assumed as 12.8°C where it experiences 0 kW net heat load.

The 2.4 ton HP in Fig. 3 is the next model size smaller in the same family of HPs by the manufacturer; this is the *NDDHP* for this application. The *NDDHP* capacity intersects the heat load curve at 41.8°C, thus any ambient temperatures above this temperature will discharge using the TES; $T_{C,NDD}$ = 41.8°C. This temperature corresponds to the 3% design condition based on the TMY3 data. The TES temperature necessary to provide the necessary capacity at the design conditions is identified as 32°C.

Fig. 4 shows the TMY3 dry bulb temperature data, and 0.4% and 3% design conditions for Phoenix. Using the TMY3 data, all discharging events (when the outdoor temperature is greater than $T_{C,NDD}$) are identified. Then using Eq. 5, the time spent discharging is determined during each event is determined and the energy depleted from the TES found using Eq. 7. These are shown as green pins in Fig. 4 with the energy depleted from the TES for each discharging event on the right vertical axis. The maximum TES storage capacity is found to be 80.3 kWh for the discharging event on July 13 between 9:47am and 5:13pm – nearly 7.5 hours. For reference, if the density and phase change enthalpy of water/ice used, the volume of this TES is about 1 cubic meter or about slightly smaller than a typical domestic refrigerator; if the density and phase change enthalpy of sodium sulfate decahydrate (which has a melting temperature of 32.4°C), the volume of this TES would be approximately 1.5 cubic meters [10]. Note, the published compressor maps only include cooling capacity, thus as a proxy for heating capacity (*i.e.*, heat going into the TES and depleting its stored energy), the cooling capacity plus the electrical power consumed by the compressor was used. It is understood that this might not perfectly represent the heating capacity at the condenser, but from a crude energy balance, this method sufficed.

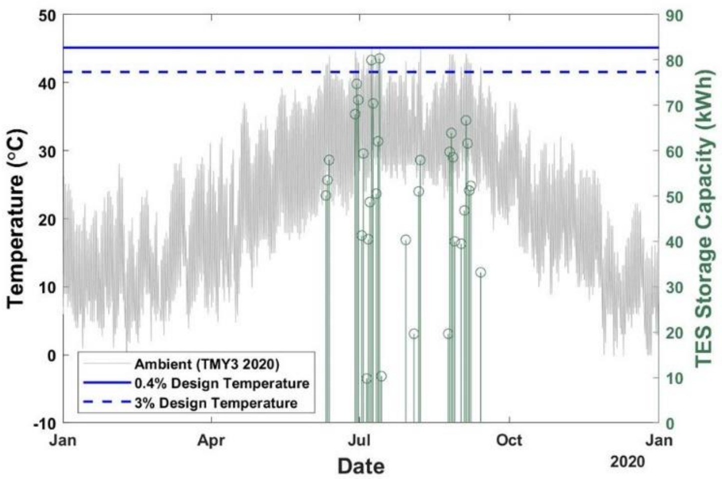

Fig. 4. A building cooling application modeled for Phoenix, AZ with a 2.4 ton HP and 32°C TES. The HP-TES allows for the system to be sized to the 3% design condition. The green pins indicate the 33 TES discharging events where the TES is needed to meet thermal loads greater than the HP capacity and where the HP can fully recharge the TES before the next discharging events.

Between each discharging event, the time required to cool the application in conventional mode was found from Eq. 6, which then informs on the available time to charge the TES. Note, these calculations do not include optimal HP timing to take advantage of diurnal ambient temperature extrema, but future versions and more rigorous simulations can include these considerations. Then by calculating Eq. 7 and comparing to the energy depleted from the previous discharging event, the feasibility of the *NDDHP* to fully recharge the TES was determined. For the conditions outlined, the *NDDHP* with TES can meet all thermal loads to cool the application and recharge the TES between discharging events, thus all discharging event pins in Fig. 4 are green.

As discussed, the performance of the HP is affected by the TES temperature for both charging and discharging. While a colder TES temperature is advantageous for discharging in cooling applications, it may present a larger temperature gradient for the HP to charge depending on the ambient temperature fluctuations. Fig. 5 shows the same building simulation in Phoenix, AZ except where the TES temperature is 25°C, only 7°C lower than in Fig. 4. Here, the necessary TES capacity is reduced to 77.1 kWh because there is a more favorable temperature gradient to cool the application. However, there are three events in which the *NDDHP* fails to fully recharge the TES between discharging events as shown by the red pins in Fig. 5. Thus, this combination of *NDDHP*, $T_{C,NDD}$, and $T_{C,TES}$ is not feasible for this application. This highlights the sensitivity of designing such HP-TES systems, and the interplay between the TES temperature, HP capacity, and ambient temperature conditions.

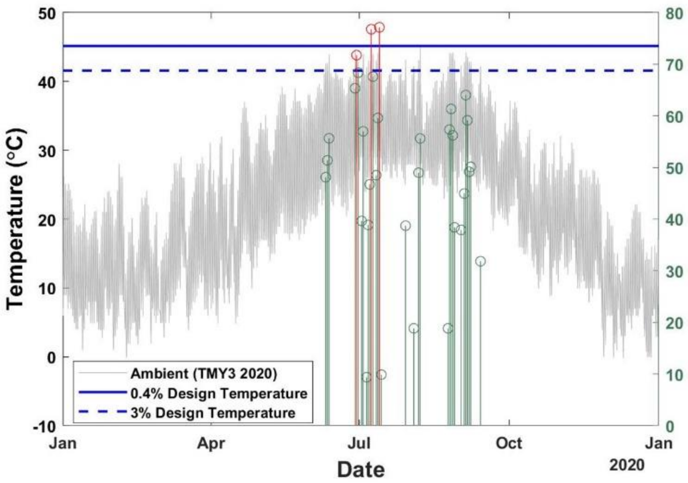

Fig. 5. A building cooling application modeled for Phoenix, AZ with a 2.4 ton HP and 25°C TES, identical conditions compared to Fig. 4 except for a colder TES. With the colder TES, the smaller HP cannot fully recharge the TES after each discharging event. This demonstrates the sensitivity of the HP-TES system; a colder TES provides more favorable cooling during discharging but presents too large a lift for the small HP to recharge.

Lastly, Fig. 6 shows the same building configuration with an even smaller *NDDHP*, nominal 2 ton capacity. From Fig. 6A, the $T_{C,NDD}$ is determined to be 38.1°C (a 6% design condition) and the required $T_{C,TES}$ is equal to 15°C. However, this *NDDHP* proves to be far too small to be effective even with the TES; there are discharging events over 12 hours long which leaves insufficient time to recharge the TES between discharging events with the smaller HP capacity as shown by the numerous red pins in Fig. 6B. This shows there are practical limits to downsizing with a HP-TES system. A HP-TES system with these conditions would need at least 170 kWh of storage to keep the system operational, bridging the gap between discharging events. During the height of the cooling season, the HP would be running continuously to either cool the building (conventional or discharging) or charge the TES, but it is still insufficient in supplying the necessary thermal loads.

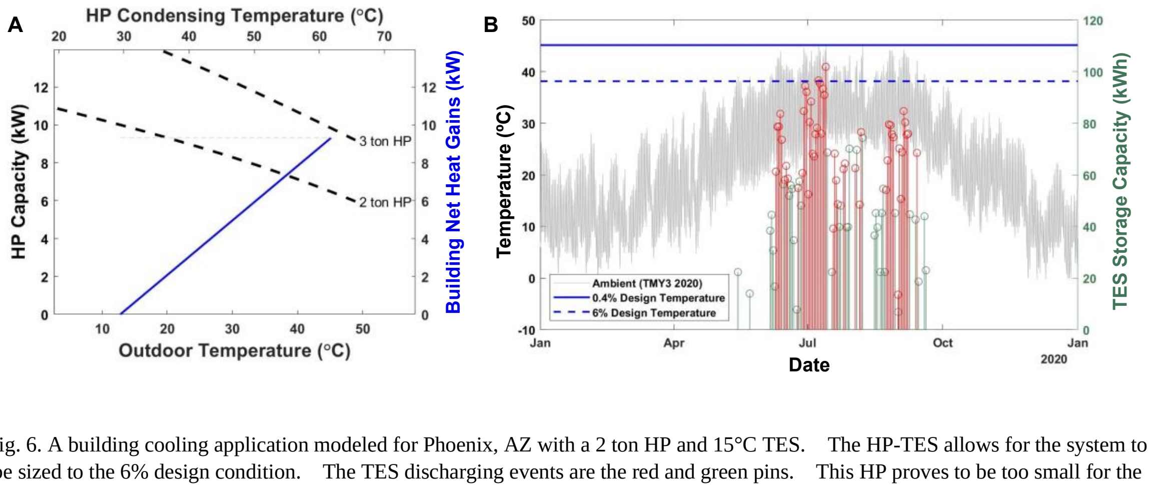

Fig. 6. A building cooling application modeled for Phoenix, AZ with a 2 ton HP and 15°C TES. The HP-TES allows for the system to be sized to the 6% design condition. The TES discharging events are the red and green pins. This HP proves to be too small for the application as the HP cannot fully recharge the TES before the next TES discharging event, evidenced by the red pins.

4. Discussion and Conclusion

This report presents a methodology by which a HP might be downsized when TES is integrated. Data on the specific application, its conventional operating conditions and heat loads, and climate-specific temperature fluctuations are needed. If this information is known for the HP-TES system to be installed, the TES temperature and its storage capacity can be determined as it relates to the smaller HP size. This report indicates the feasibility of HP compressor downsizing with empirical data but is not comprehensive. The approach can serve as a guideline for other applications or specific uses of HP-TES systems.

This procedure might be performed iteratively to identify an array of possible design conditions, HP equipment, and TES temperatures. HP sizes and TES storage temperatures might be available in discrete options, and thus the design of such systems is subject to these discrete variables. Once a HP-TES system is designed using the methodology outlined here, it might be evaluated in more rigorous simulations to determine the real-world feasibility of such HP-TES systems. Furthermore, more advanced HP-TES control strategies might enable more intelligent use of the TES. For example, simultaneous charging and conventional modes can more effectively utilize excess HP capacity and reduce short cycling, and forecasting heat loads might allow for a TES system to carry partial charges between discharging events while still providing the thermal conditioning necessary. Future work will also evaluate dual heating and cooling applications, and seek to identify HP-TES systems that benefit both modes.

The method was demonstrated on an example building cooling application in Phoenix, AZ with TMY3 weather data. It was shown that the HP could be downsized from a 3 ton system to a 2.4 ton system when TES was added. Furthermore, the TES enabled the HP to be sized based on the 3% design condition (compared to the 0.4% design condition). The HP-TES was shown to be sensitive to the TES temperature as the performance of the HP is affected by this temperature for both charging and discharging; a lower TES temperature is advantageous for cooling during discharging but presents a steeper thermal gradient to charge and thus the smaller HP capacity might be incapable of fully recharging the TES between discharging events.

HP-TES can be valuable for system retrofits. As global temperatures continue to rise due to anthropogenic climate change and thus the prevalence of air conditioning continues to grow, this methodology shows that integrating TES can increase apparent HP capacity. Therefore, adding TES to extant HPs might be a viable solution in applications where the extant HP is now undersized due to the locally changing climate. Thus, rather than replacing the HP, retrofitting with TES can extend its useful life and avoid costly system upgrades.

HP-TES systems are posed to play a critical role in the future of energy. The potential of HP-TES to reduce energy use and shift demand might be specific to the target application and its setting. Nevertheless, this analysis presents the opportunity for HP-TES to be designed more intelligently and reduce unwanted oversized systems. More work to realize these devices in real-world research settings.

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