The State of Art of Heat-Pump integrated Thermal Energy Storage for Demand Response

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Heat pump integrated thermal energy storage is analyzed for demand response in grid-interactive buildings. We have reviewed various configurations presented in the literature, in both active and passive storage, and analyzed the reported demand impact, energy savings, and cost savings.

Introduction

Buildings are responsible for about 40% of the total energy consumed in the U.S. [1], accounting for 75% of the total electricity consumption, and 78% of the 2–8 PM peak period electricity use [2]. Heating, ventilation, and air conditioning (HVAC) loads account for nearly half of the building electricity consumption and exacerbate demand issues.

Thermal Energy Storage (TES) has been identified as a key enabler to reduce peak energy demands and grid stress through demand response strategies as described in the Department of Energy's Grid-Interactive Efficient Buildings (GEB) report [2]. TES may even allow refrigeration or HVAC systems to operate during outages, though this requires larger storage capacities than a system strictly intended for diurnal load shifting [2].

TES technology with greater flexibility presents research and development opportunities in materials, configurations, and controls: novel TES materials can be developed to increase energy storage density, many configurations can be explored to reduce installation complexities and TES footprint, and TES operation can be optimized through controls for demand response in grid-interactive buildings to offer greater energy and demand reduction potential.

More than 44% of the houses in the U.S. were built before 1970 [3] based on outdated building codes. Typically, in US residential buildings, there is no mechanical outdoor air exchange, or cross ventilation using natural resources, therefore, heat pumps are important to regulate the humidity inside the house as well as the indoor temperature. Thus, retrofit technologies are needed for a rapid transition to heat pump integrated storage.

It is often cost-prohibitive to rebuild houses or update the conventional air conditioning methods, but heat pump systems can be made smart to respond to peak demand. Today's high-efficiency HVAC and appliance products can provide energy savings, but do not generally help with demand management and grid stress.

Thermal energy storage can provide benefits when integrated with the heat pump components. TES materials can be charged and discharged to store and release energy, respectively, thus reducing the time and shifting heating or cooling energy demand. Despite diurnal changes in outdoor temperatures, the high-thermal-mass buildings can maintain inside temperature in a comfortable range without expending an excessive amount of HVAC energy.

Path Forward

This article summarizes the state of art of heat pumps integrated with thermal energy storage. Phase change materials (PCMs) are thermal storage materials that can be embedded into heat pump equipment or building envelope. Research has explored a wide variety of methods to incorporate PCM into systems for space heating and cooling, in both active and passive storage, as well as being incorporated into buildings using various configurations.

The majority of the existing commercial PCMs are incorporated in passive storage and they charge and discharge depending on the ambient temperature. In passive storage, PCM can be installed in the building envelope such as walls, ceiling, windows, or embedded directly into the building material such as concrete. Ideally, the materials in passive configuration can offset the peak demand by shifting loads, but they are unable to control the charging or discharging operation to optimize grid benefits.

Active TES systems on the other hand use mechanical work to transfer heat between the space and the PCM, hence there is some control over when the TES system is charged and discharged. Examples of this setup are a standalone storage tank system with an integrated heat exchanger coupled to the building's ventilation system or a vapor compression system. The TES system may be separate and removed from the space. One advantage of these active configurations is the ability to add these systems to existing building infrastructure without significant construction.

For grid-interactive buildings, a demand response strategy can be designed for building load and grid stress management. The utility providers may define peak hours and off-peak hours of operations based on a

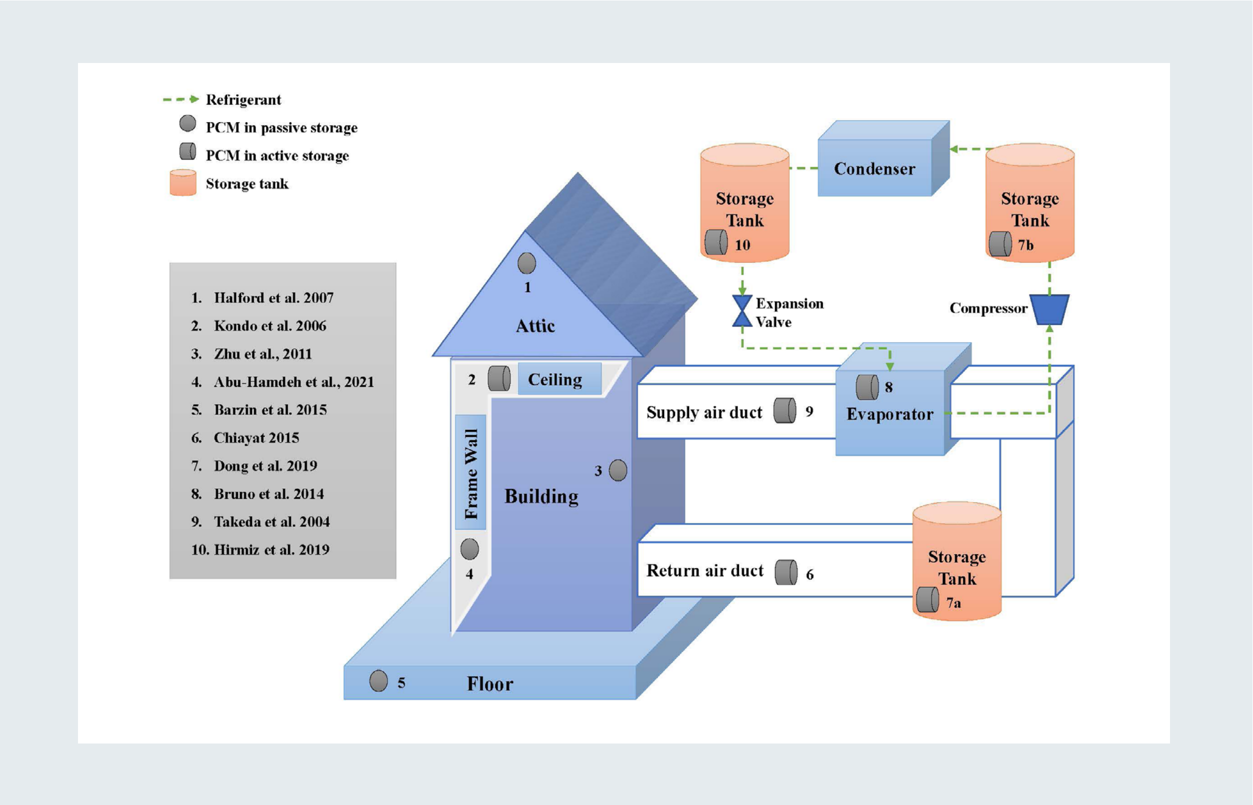

Figure 1: Ten ways to integrate TES with heat pump were identified in the literature, as summarized here.

pre-determined schedule or a high demand-based charge schedule. During the time of high demand or peak hours, the utility rate tends to be higher than what is normally charged to customers during normal or off-peak hours. Load shifting can manage the demand by shifting peak load to off-peak or normal operating hours, hence reducing the utility cost and grid stress.

When properly controlled, thermal storage can be useful in an economic or behavioral curtailment scenario for demand response. Major factors influencing an appropriate TES system's choice include the energy storage period and duration, cost and economic feasibility, and operational conditions. The key to using this technology to provide grid benefits is the development of materials or packaging in an active storage configuration that allows real-time control of the charging and discharging processes for grid-interactive operation. The energy savings and grid benefits in such configurations would be particularly significant in regions of high peak demand [2].

The use of phase change materials as TES has its advantages reported in the literature. Researchers have used various demand management systems to take advantage of lower utility rates during the off-peak hours and used TES in various configurations for storing the energy to be used later during peak hours, as shown in Table 1 and Figure 1.

A selection of ten references is shown here to represent the state of art available in the literature, with one reference chosen to represent each configuration type. The figure shows building and heat pump components with embedded TES in various possible configurations. Some are used in passive configurations and installed in building envelopes like frame walls, ceilings, floorboards, and attic insulation. The passive configurations included are connected to the air conditioning system and the effect of air conditioning load reduction is studied.
The active configurations reported here are the ones integrated with air conditioning or heat pumps. Most researchers have commonly used a standalone storage tank containing a PCM and heat exchanger, while others have incorporated PCM into heat pump system components like the supply and return air ducts, and evaporator. Another common practice is to use two storage tanks for both cold and heat dissipation (see 7a and 7b in the figure).

There is a large variation in the benefits provided by TES depending mainly on the system configuration, TES location, and TES type. Peak load reduction ranges from 12% to 57%, and electricity consumption savings ranged from 9% to 62%. In this work, we have tried to present a comprehensive review of various heat pump integrated PCM-based TES configurations with a demand impact and economic analysis.

The thermal energy storage systems (TES) incorporation with current cooling, heating, and ventilation systems has been shown to shift the load and energy use of the HVAC systems from on-peak to off-peak times to bypass the peak charges due to high demand. TES has also been shown to improve energy efficiency by controlling the energy supply and energy demand gaps. Active heat pump integrated TES configurations generally outperform passive TES-HP configurations because acti-

*Table 1: The ten representative heat pump integrated configurations included here have been shown to reduce peak load by 12% to 57%. *Calculated based on the data provided in the paper*

Reference	Configuration	TES Location	Outcomes
Halford et al., 2007	Passive	Modeled to be installed in the attic	19 - 57% peak load reduced
Zhu et al., 2011	Passive	In the walls to enhance envelope of air-conditioned PCM building	Daily electric consumption reduced by 10% 17-20% peak demand reduction 11% cost reduced
Barzin et al., 2015b	Passive	In wallboard with underfloor heating	44.4% energy savings 3-4 hr of Peak load shifted 35% cost savings
Abu-Hamdeh et al., 2021	Passive	In frame wall of air-conditioned building	11.25% energy savings Air handling unit's power usage decreased by 11.73% 18.6 years payback
Bruno et al., 2014	Active	In chiller used as evaporator	13% cooling energy savings
Takeda et al., 2004	Active	In supply air duct of ventilation system	42.8 to 62.8% ventilation load reduced
Kondo et al., 2006	Active	In ceiling board coupled with air handling unit	9.4% load reduction
Chaiyat, 2015	Active	In the return air duct coupled with evaporator	Cooling load decreased by 3.09 kWh/d 9.1% cost saved, 4.15 years payback
Hirmiz et al., 2019	Active	Integrated with heat pump via condenser storage tank	6 hr Load shift
Dong et al., 2019	Active	Direct coupling with the electrical heat pump via storage tanks	13% power savings 12.7% peak load shifted* 19% electricity cost savings

ve storage systems offer a high level of control of indoor conditions and improve heat energy storage.
A particularly promising configuration is the directly coupled active TES-HP configuration by Dong et al., which requires small modification and offers large performance improvement while reducing the TES footprint.

Challenges and Future Work

The HVAC system incorporating TES is beneficial to both residential and commercial buildings by providing grid value, though the residential system requires more installation costs making it challenging for many consumers to adopt this technology. The end-user would need to purchase the equipment for new construction, replacement of an old heating/cooling system, or retrofit applications. The most financially motivated users tend to be the consumers paying demand charges or on tariffs like Time-Of-Use (TOU) rates, as TES is ideal to shift the predictable daily load for demand response. The performance of active TES systems can be optimized by taking advantage of favorable environmental conditions and pre-scheduled utility tariffs to charge the storage medium efficiently. However, careful scheduling is required to maximize the benefit to avoid round-trip energy losses.

Conclusions

This article reviews the state of art of heat pump integrated TES in grid-interactive buildings. Various configurations are reviewed and active storage is found to be more beneficial for daily load shifting, where PCMs can be charged for generation during off-peak hours.

TES has been shown to reduce building energy consumption from 9% to 62% and building peak load from 12% to 57%.

Heat pump integrated TES allows the use of already established technology and resources, with minimal equipment that can reduce the installation complexity. Heat pump-integrated TES equipment is also programmable with the thermostat for demand response and can provide building flexibility. With the number of possibilities, novel configurations can be explored that offer maximum benefits to both consumer and grid, while minimizing the TES footprint.

Research is needed in controls to optimize performance under various utility tariffs for demand response as well as develop novel directly coupled configurations to reduce the TES footprint.

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