

TES for Residential Settings

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In this column, we shall address two forms of Thermal Energy Storage (TES) that are matched to residential settings. The first, electric thermal storage (ETS), is a mature technology. As with the cool storage technologies, notable current developments include smarter controls and tighter demand-response integration with the electric grid. The second is the incorporation of phase change materials (PCMs) into building components in both envelope and interior. Last reviewed by Emerging Technologies in July 2007,¹ PCMs show promise for energy savings but still face cost and performance barriers to adoption.

Technology Overview

Electric thermal storage (ETS) systems have been commercially available for decades, with total installed capacity in the U.S. now about 1,000 MW.² Typically, ETS uses an insulated bank of ceramic bricks. During system charge, electric resistance elements heat up the bricks. During discharge, air (in the case of room units or centrally ducted forced hot air systems) or water (in hydronic heating systems) is passed through the hot brick array and on to the heating load. While the core technology behind ETS is mature and fairly static, associated control technology has seen recent advances.

One Internet-enabled ETS controller, compatible with both new and existing units, has been introduced by a demand-response (DR) services company. Controllers attempt to optimize ETS operation based on weather and electricity pricing information, but they also can be remotely commanded by the DR company. This allows aggregation of many ETS units into substantial DR resources that can be called upon by utilities in real time. Concord Electric Light in Massachusetts and PPL Electric Utilities in Pennsylvania are early adopters of this Internet-enabled technology.

A very different form of TES involves incorporating solid-liquid phase change materials (PCMs) into building components, e.g., insulation, wallboard, or as a dedicated layer. Because of the high latent heat of the phase change, PCMs can add significant thermal mass without substantially increasing building envelope weight or volume. Assuming ambient outdoor temperatures cycle diurnally around the phase change point, including a PCM

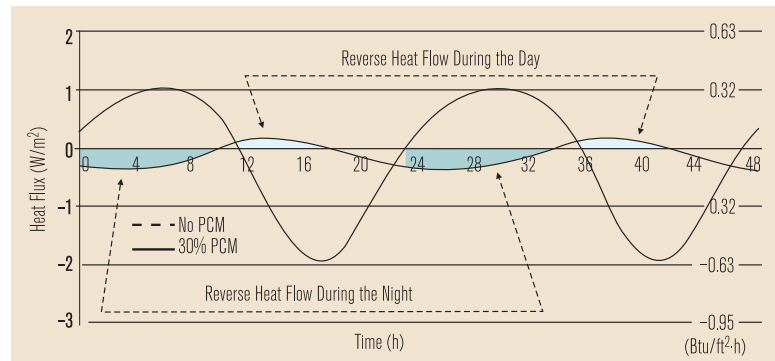


Figure 1: Passive heating/cooling effect arising from delay and attenuation of temperature variation (simulation of a constant-temperature space with 0.3 m-(1 ft.) thick PCM-enhanced fiber insulation)³

effectively delays and attenuates temperature swings. Generally, inclusion of more PCM means more delay and more attenuation. Under the right conditions, the delay can be advantageous from a time-of-use standpoint, shifting load into off-peak hours, while the attenuation can reduce heating/cooling energy consumption and peak loads. Under certain conditions, the combination of attenuation and delay can provide a passive cooling and heating effect (Figure 1).

The concept of using phase change materials in building envelopes is not new, but practical implementation still presents significant challenges. The ideal building PCM is low-cost, fire-resistant, inert, non-toxic, stable over a long lifetime, with a high energy storage density, and an easily engineered phase transition point that is near room temperature and exhibits minimal hysteresis, i.e., through complete heating and cooling cycles, the PCM exhibits melting and a freezing temperatures that are essentially the same, a necessary condition for predictable and consistent heat transfer. While various PCM-containing building materials have been installed in pilot projects, no product has yet achieved sustained commercial success. Both organic and inorganic compounds

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have been explored as building PCMs. Among organic materials, petroleum-derived paraffins have historically been the most common. More recently, bio-derived organic PCMs have risen in prominence. One technology company offers vegetable-based PCMs at a wide range of transition temperatures. One problem with organic materials is their inherent flammability. Current efforts have emphasized formulas and packaging techniques that result in PCM-based building components that meet applicable code requirements for fire resistance.

Among inorganic materials, hydrated salts have shown the most promise for building PCMs. Hydrated salts were the first PCMs to be used for building applications. While comparatively low cost and nonflammable, they can be difficult to encapsulate and often have large phase change hysteresis. Recent development efforts have focused on additives to mitigate these weaknesses, with some success.⁴

To be used in buildings, PCMs must be packaged, or encapsulated, in a form that does not leak and is easy to handle and install. "Macro-encapsulation" commonly involves bulk PCM contained in pouches or packets. One company has developed sheets or mats of macro-encapsulated bio-based PCM for use behind wallboard and under roofs.⁵ "Micro-encapsulation" traps tiny quantities of PCM in polymer shells, which are then incorporated into materials such as thin laminated panels,⁶ foam, fiberglass, or cellulose insulation,³ or gypsum wallboard.⁷

Energy Savings

ETS does not save energy at the site of use, although, compared to an electric heating system without ETS, it may save energy at the electricity generation source. Charging periods for residential ETS systems can be managed remotely by the utility, enabling the lowest possible electricity cost to homeowners. Electricity generated offpeak usually consumes less primary energy per kWh as compared to on-peak electricity.

From a sustainability standpoint, however, the merits of ETS (and electric heat in general) depend strongly on the regional electricity mix. If regional generation is predominantly fossil-based, the carbon footprint of electric heat (with or without ETS) is larger than that of gas heat.

The efficiency of a state-of-the-art natural gas fueled combined cycle power plant (~50%) is still far less than the efficiency of an in-home gas boiler or furnace (~90%). However, if the regional grid is weighted toward nuclear and hydropower, and/or if oil (which, in addition to being more expensive than gas, has a higher carbon footprint per Btu) is the only available heating fuel, the sustainability case for electric heat becomes somewhat more attractive. With very high penetrations of wind power, ETS is appealing in that it could be used to absorb intermittent surpluses of wind-generated power overnight.

In addition to saving energy at the source through time-of-use delay, PCMs also save energy on site. A 2013 report⁴ published by the DOE Office of Energy Efficiency and Renewable Energy (EERE) reviewed experimental studies of cooling load reduction from PCM applications. Cooling load savings ranged from 9% to 25%,

with in-wall PCM loadings of 10 to 45 Btu/ft² (0.11 to 0.51 MJ/m²).

The energy savings achieved by using PCMs, however, are highly dependent on the climate and season, as well as on the specifics of wall design, internal temperature setpoint, and phase transition temperature. For example, to function as thermal storage, a PCM must experience temperature cycles that span the phase transition point (near room temperature). A hot summer night may never allow the PCM to solidify, thus rendering it ineffective. There are other, more subtle relationships at work as well. A 2012 simulation study by Oak Ridge National Labs⁸ found that an effective PCM phase transition temperature could be selected for either the cooling season or the heating season, but not both.

Market Potential

Because of the primary energy efficiency advantages of natural gas heat (which translates approximately into cost advantage), ETS is unlikely to displace gas heat at scale in the near term. Neither is ETS likely to be attractive in mild climates with low heating costs. The 2009 Residential Energy Consumption Survey⁹ estimates that in "cold" or "very cold" U.S. climate regions there are about 6 million homes with electric heat and 4 million homes with oil heat, suggesting an addressable market for ETS of about 10 million homes. The rate and extent of penetration of ETS into this addressable market, however, is likely to be determined by the extent to which it is incentivized by utilities, directly through rebates and/or indirectly through time-of-use or real-time electricity pricing.

The market potential of PCMs for building materials depends strongly on product cost. A U.S. DOE Energy Efficiency and Renewable Energy (EERE) study included a cost viability case analysis for microencapsulated organic PCMs in wall and attic insulation applications, considering the effects of climate, electricity pricing structure, and PCM cost. Phoenix was the most favorable case examined, with large diurnal temperature swings and strong time-of-use electricity rate schedule. Under these assumptions, the PCM price point to achieve a 10-year payback period was estimated at approximately \$0.05/Btu (\$0.05/kJ).⁴ It remains to be seen whether products currently under development can meet a sufficiently low price point to achieve widespread adoption.

Most of the current market demand for PCM products comes from building and construction applications, with total global demand estimated to be about \$460 million.¹⁰ Energy-saving performance and environment-friendly products are expected to help drive global demand to about \$1 billion in 2018. According to MarketsandMarkets, the U.S. accounts for only a small fraction of that demand, with 2013 PCM revenues of \$15 million from building and construction, growing to an estimated \$36 million by 2018.¹¹ Low natural gas prices are already negatively affecting the PCM market in the U.S., making European and Asian markets more lucrative for the companies providing PCM building components.

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