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Potential Research Areas in Residential Energy Storage for NIST's Engineering Laboratory

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ABSTRACT

This paper recommends research that is required to develop and, thus, enable cost effective, residential electricity storage systems for renewable energy. As residential electricity generation from renewable sources becomes more prevalent, residential energy storage will become an important factor in ensuring the stability of the electrical grid; grid operators will be able to time-shift demand to smooth peaks and match supply capacity. However, local storage of excess energy from renewable sources is currently not economically attractive due to the long payback period required to recover capital costs. NIST Engineering Laboratory is well positioned to make significant contributions to the relatively neglected field of residential energy storage. Possession of the NIST's Net-Zero Energy Residential Test Facility makes it possible to work collaboratively with other laboratories within NIST to demonstrate field performance of new ideas in energy storage technologies such as batteries, super capacitors, superconducting magnets, and hydrogen storage. In addition, EL staff and facilities are well matched to projects in Phase Change Material (PCM) facades and PCM evaporators, pumped hydro, solar water heaters and cost/benefit analyses. Potential project ideas are provided for these areas of research.

Keywords: electricity, energy storage, residential

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INTRODUCTION

Compared to residential electricity generation from photovoltaic (PV) systems and wind turbines, residential electricity energy storage is essentially non-existent. As long as utilities buy excess renewable electricity generation from residences at supply prices, a practice called net metering, there is little incentive for home owners to consider energy storage to handle their excess electricity production. However, as renewables energy generation becomes more prevalent, it is not expected that power companies will continue net metering without transferring some of the grid maintenance costs to the PV homeowner to ensure that they pay their fair share (CPUCED, 2005). Furthermore, in the event of high market penetration of residential renewable energy, on-site generation would no longer be welcomed nor fully used by the existing utility grid (Pless and Torcellini, 2010). The reason for this is that excess electricity from renewables may cause grid instabilities (Scaini, 2012) and blackouts due to low demand and insufficient electricity storage capacity (Bruch et al., 2011). Excess electricity from renewable resources makes it difficult for grid operators to balance electricity supply and demand. The effects of variable renewable electricity generation have already been seen in European markets, most notably in Germany, which forced *negative* pricing of conventionally-produced electricity during certain times of the day due to high renewable output and low demand (DGE, 2012). Local electricity storage could reduce the strains on a utility's reserve capacity by providing electrical power at or near the source of use thus eliminating the inefficiencies of ramping fossil fuel based generation capacity, and of transmitting the power during periods of high demand. Both the phase-down of net metering and the need for greater grid stability will drive demand for residential energy storage. However, local storage of excess electrical energy from renewable electricity sources is currently not economically attractive due to the long payback period required to recover capital costs. Electricity Storage (ES) capital costs are well above the $100/kWh (IREA, 2012) that the United States Department of Energy has determined would make a system economically attractive. Reaching the target of $100/kWh could be accelerated by focusing future research on the most viable technologies and concepts.

Electrical grid supply/demand mismatch, as well as peak demand shaving, can also be addressed by thermal energy storage. Thermal energy storage is attractive because it can be used to reduce energy use by taking advantage of cooler ambient temperatures at night and warmer ambient temperatures during the day. Heating and/or cooling energy can be stored during times of excess renewable resource or favorable outdoor conditions, and then used during peak grid demand or when renewable resources are not available. Thermal storage can effectively be used to store both thermal (e.g. solar thermal) and electrical (e.g. PV or wind turbine driven heat pump hot water heater) energy. Unlike electricity, a utility does not exist that will purchase a homeowner's low grade thermal energy at generated value. Consequently, thermal energy storage is likely to appear more appealing than electrical storage as a residential capital investment at the present time. In fact, Hudon et al. (2012) report that solar water heaters are on their way to becoming cost-competitive with conventional natural gas water heaters in most regions of the United States.

Considering the National Institute of Standards and Technology's (NIST's) mission of "enhanc[ing] economic security and improve[ing the] quality of life" by "advancing measurement science, standards, and technology" there is a clear fit/justification for NIST bringing its expertise to bear on the problem of cost-effective residential energy storage. The question is what research should NIST be focused on that will result in the greatest impact for the U.S. consumer while remaining within the realm of NIST's charter. NIST research is confined to measurement science that falls within one of the following categories:

(1) The development of performance metrics, measurement and testing methods, predictive modeling and simulation tools, knowledge modeling, protocols, technical data, and reference materials and artifacts.
(2) The conduct of inter-comparison studies and calibrations
(3) The evaluation and/or assessment of technologies, systems, and practices including uncertainty analysis.
(4) The development of the technical basis for standards, codes, and practices—in many instances via testbeds, consortia, standards development organizations, and/or other partnerships with industry and academia

Accordingly, this paper identifies research that can facilitate the commercialization of residential energy storage while conforming to one of the above four measurement science categories.

GENERAL RESEARCH NEEDS FOR VARIOUS ENERGY STORAGE METHODS

Figure 1 taken from the Fraunhofer Institute for Solar Energy Systems shows the five different classifications of electrical energy storage systems: (1) mechanical, (2) electrochemical, (3) chemical, (4) electrical, and (5) thermal. Mechanical energy storage includes pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheel energy storage (FES). Electrochemical energy storage includes secondary batteries and flow batteries. Chemical energy storage is primarily focused on using electricity to produce hydrogen. Electrical energy storage includes double-layer capacitors and superconducting magnetic coils. Thermal energy storage includes sensible heat storage and latent heat storage (not shown in Fig. 1).

Mechanical Energy Storage

Pumped hydro: Pumped hydro is used to store over four-fifths of the world's renewable electricity (IRENA, 2012). However, commercial PHS for residential storage does not presently exist. Typical PHS consists of two bodies of water at different elevations. Electricity is stored by pumping water from the lower reservoir to the upper reservoir. The electricity is retrieved when the water is allowed to flow back down from the upper reservoir through a turbine and into the lower reservoir. The turbine operates a generator that produces electricity. The efficiency of a PHS ranges between 70 % and 85 % (IEC, 2011).

No commercial residential PHS exist because the cost effectiveness of PHS increases with the size of the system and the traditional system requires two large bodies of water separated by 100 m or more in elevation. Therefore, working towards a smaller PHS that is suitable for the home is counterintuitive. In addition, most homes do not have the hilly topography that is required of traditional PHS. However, rather than having a lake on top of a small mountain above a damned river, the elevation difference for residential PHS could be achieved with alternate reservoirs. For example, Martin and Baines (2007) suggest that PHS which would consist of drilling a well and galleries as an underground lower reservoir, with an integrated pump/turbine at the surface or just below the upper reservoir at ground level. The required depth of the well could be reduced by using compressed air and/or a piston weight. Advocates for smaller PHS, like Islam (2012), argue that PHS will have a greater overall efficiency than most technologies and can be maintained using local technical expertise. An additional advantage of PHS is that it can be sized to meet a few days' energy requirements of a particular home by selecting the correct diameter and depth of the well. Otherwise, a community PHS may also be an option if smaller systems cannot be made cost effective.

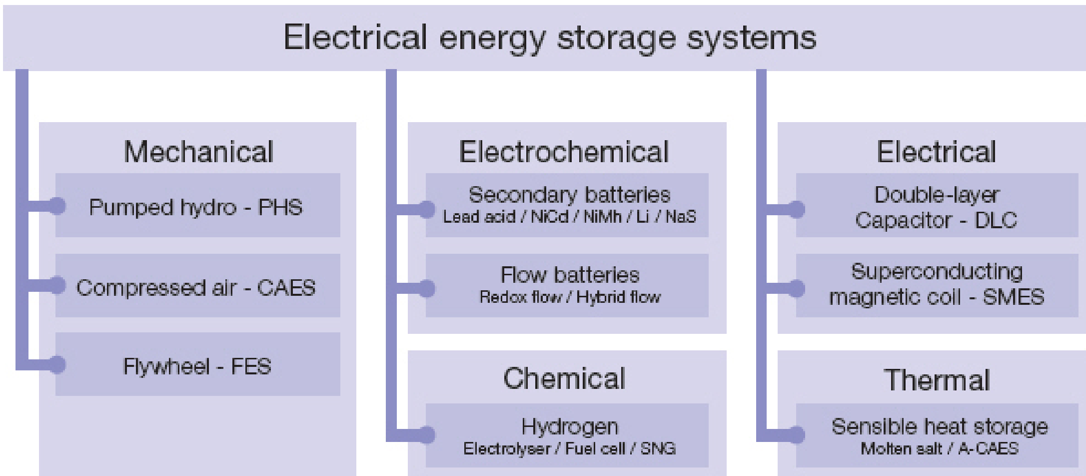

Figure 1 Fraunhofer ISE classification of electrical energy storage systems according to energy form (IEC, 2011)

Compressed air: CAES stores energy in tanks or caverns in the form of compressed air. Energy is retrieved by expanding the compressed air through a turbine to produce electricity. According to Zhai et al. (2013), CAES are reliable, have negligible self-discharge, are non-toxic, and have very long lifetimes. One disadvantage of CAES is that it has a low thermodynamic efficiency because there is a rise in temperature of the air during compression, which causes heat to be lost to the surroundings. In addition, the air has to be heated during expansion (Zhai et al., 2013). Recuperators can be used to improve the efficiency by exchanging heat between the compressed and expanded air (IEC, 2011). Havel (2103) suggests that further improvements in efficiency and cost reductions can be achieved by using non-underground nano-porous material for compressed air storage. Similar to PHS, CAES can be sized for residential use (Kim and Favrat, 2008).

Flywheel: FES is currently used as relatively short discharge time by power plants for load leveling and as uninterruptible power supply (UPS) devices. Flywheels store electricity from a motor as kinetic energy in the form of a spinning disk of significant mass. The energy is retrieved from the flywheel when it is used to drive the motor as a generator. The amount of energy stored depends upon the speed and the mass of the disk (Reading, 2004). Short discharge time flywheels are used for stabilizing voltage and frequency, while longer duration flywheels are suitable for damping load fluctuations (Deal et al., 2010). According to Reading (2004), flywheels are most suitable to discharge times in the order of seconds to a few minutes. Consequently, FES appears not to be suitable for residential energy storage. However, potential research areas could focus on extending the discharge duration and evaluation tests.

Electrochemical Energy Storage

Battery: Batteries are one of the most popular areas of research for energy storage because they are very efficient and have a large power output. However, battery capacity diminishes over time, they experience self-discharge, and they typically use toxic and/or flammable materials (Zhai et al., 2013). Most of the current research is focused on ways to make batteries safer and cheaper via lower-cost materials and chemistries.

NIST's Center for Nanoscale Science and Technology is currently using nanowires to investigate how to improve the performance of lithium-ion batteries.[2] The nanowire is being used as a tag so that changes in the micro-structure of the battery during charging and recharging can be visualized. Similarly, NIST's Material Measurement Laboratory researchers have collaboratively developed a promising lithium-sulfur (Li-S) battery that weighs roughly half as much but contains twice as many ions as a lithium-ion battery (Simmonds et al., 2014). The battery is expected to be less expensive than the lithium-ion battery and survive the same number of recharging cycles. The Engineering Laboratory could work with both or either of these projects to demonstrate the improved batteries as used in residential energy storage applications.

Chemical Energy Storage (CES)

Hydrogen: Electricity can be used to produce hydrogen from water with conventional electrolysis. Electrolysis is done by passing a direct current through a dilute water solution of an electrically conductive acid or base (Pilar, 1979). The process separates water into gaseous hydrogen and oxygen that collect at the cathode and anode, respectively. The hydrogen can be stored and used to operate engines, fuel cells, or other devices that use hydrogen as fuel. Electricity may be retrieved from the hydrogen by using a fuel cell, which is essentially electrolysis in reverse. A fuel cell converts hydrogen and oxygen into electricity by ionizing the elements in the presence of an electrolyte. Like a battery, a fuel cell is an electrochemical energy conversion device, but rather than storing energy it converts it.

In one type of fuel cell, the hydrogen ions flow to the cathode inducing a flow of electrons, i.e., current flow, from the anode to the cathode. Most fuel cell research is done to improve the efficiency of the use of hydrogen because the efficiency of the conversion of electricity to hydrogen and back to electricity via a fuel cell is only around 20 %[3]. For example, NIST's Center for Nanoscale Science and Technology is currently working on improving the efficiency of the catalysts used in the water-splitting process with additives in iron oxide (Bohn et al., 2012). However, despite low efficiency, hydrogen could achieve low and attractive costs[3].

There are several projects being conducted in NIST's Material Measurement Laboratory (MML) dealing with improving materials for containing hydrogen and the efficiency of fuel cells that use hydrogen. Research on materials for use with hydrogen is important because hydrogen can penetrate and embrittle some metals and alloys. One project in MML has developed a facility

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[2] http://www.nist.gov/cnst/erg/nanowire_li_ion_battery.cfm

[3] http://ec.europa.eu/energy/infrastructure/doc/energy-storage/2013/energy_storage.pdf

for testing the suitability of pipes, valves, fittings and pumps for transporting and delivering hydrogen.[4] In addition, the Materials Measurement Science Division of MML is working on solar-powered hydrogen generation as a cost-effective way to generate hydrogen directly from water and sunlight with a silicon-based device (Esposito et al., 2013). The Engineering Laboratory (EL) could work with both or either of these projects to demonstrate the use of hydrogen in residential energy storage applications. The concepts for improving the efficiency of fuel cells could be examined with the fuel cell rating procedure that was developed in EL by Davis et al. (2006). In addition, basic characteristics and concept testing of CES components and systems including technical evaluation (capacity, power, discharge time, lifetime, etc.) could lead to guides for implementation of CES.

As Figure 2 from the Fraunhofer Institute for Solar Energy Systems shows, hydrogen has the potential for the highest energy content and power of most of the energy storage technologies. In addition, the Fraunhofer report shows that the most research is needed in this area to get it to product and to increase efficiencies from the present values of 35 % to 45 %. Possible areas of research include methods to enhance performance and lower costs of electrolysis, and to develop underground and solid storage. Otherwise, hydrogen stored as vapor requires large tanks, while hydrogen stored as liquid requires cryogenic temperatures and energy to achieve the low temperatures.

Electrical Energy Storage

Double-Layer Capacitor: The double-layer capacitor is also known as the super capacitor or the ultracapacitor. Like traditional capacitors, the double-layer capacitor is an electrical device that consists of two oppositely charged metal plates separated by an insulator. What makes a double-layer capacitor different is that the insulator is an ionic fluid that enables the capacitor to behave as two capacitors in series (Deal et al., 2010). Energy is stored in the capacitor by charge accumulation on the metal plates. Energy is discharged when the electric charges are released by the metal plates. Given that capacitors are suitable for short-duration applications as in providing backup power during brief interruptions, they are not really applicable to residential storage. However, EL could test super capacitor prototypes for use in residential applications. Currently, NIST's Electromagnetics Division in Boulder is researching ways in which to use graphene in the construction of super capacitors to extend the duration of energy release.

[4] http://www.nist.gov/mml/acmd/hydrogen_021610.cfm

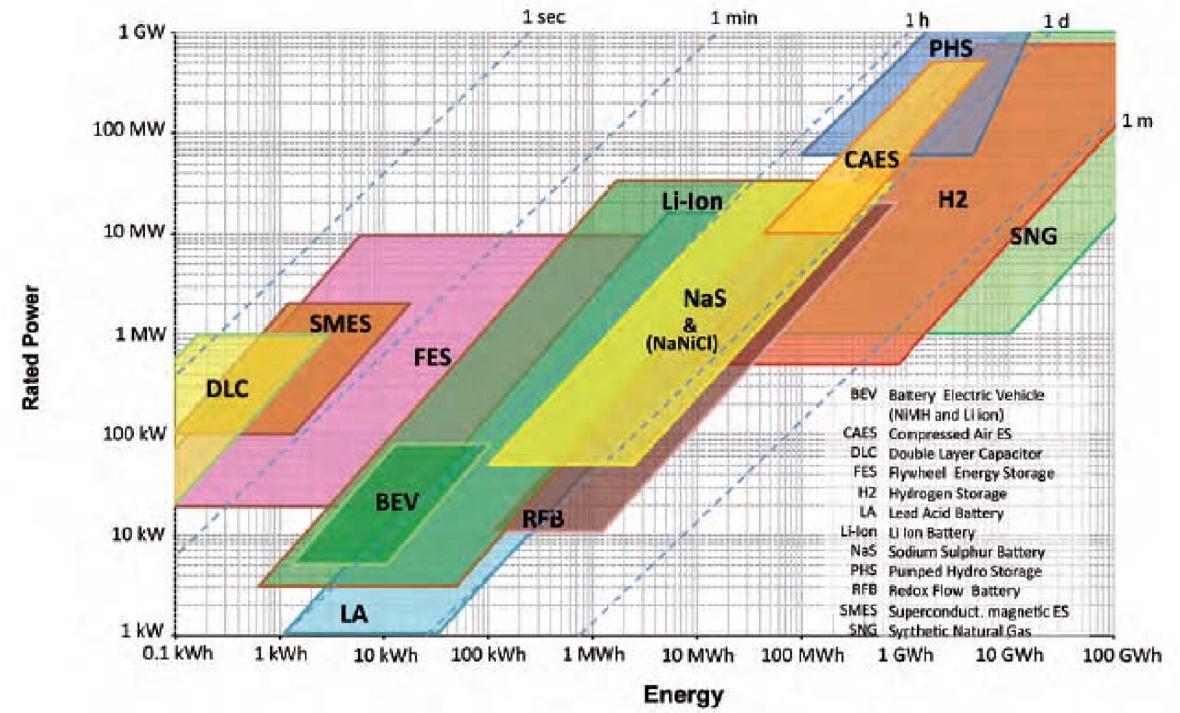

Figure 2 Fraunhofer ISE comparison of rated power, energy content and discharge time of different EES technologies (IEC, 2011)

Superconducting magnetic coil (Superconducting magnets): Superconducting magnetic energy storage ("SMES") stores energy in the magnetic field produced by a superconducting winding. One disadvantage of SMES is that the superconducting wire of the windings requires cryogenic refrigeration for the wire to function as a superconductor. Current research is focused on increasing the temperatures at which wire superconductivity can be achieved and increasing the duration of energy release (Deal et al., 2010).

NIST has been conducting superconductivity research since 1916 (Lundy et al., 1989). Several divisions at NIST have active material research for superconducting material that function at temperatures greater than 100 K. In general, because SMES only offer a few hours of storage, they have limited application to residential storage. However, there are opportunities for EL to work together with other NIST laboratories in their efforts to demonstrate extended duration and higher operating temperatures.

Thermal Energy Storage

Thermal energy storage can be integrated with both direct-thermal systems (e.g. solar thermal) and indirect-thermal (e.g. PV driven heat pump hot water heater). Similar to electrical storage, thermal energy storage time-shifts loads on electrically-driven thermal machinery (space-conditioning and water heating equipment) to minimize electricity import/export and peak demand; energy is stored during times of excess renewable resource, favorable outdoor temperatures, or low grid demand, and then utilized at the residence during peak load times. An additional benefit of thermal energy storage is that the peak capacity rating (and subsequently size, cost, and cycling inefficiencies) of thermal machinery can be reduced. A small thermal system can operate as a hybrid with the storage to provide peak loads, where during periods of low loads the thermal system can be charging the energy storage system.

Sensible heat storage: Electricity is used to either heat or cool a single phase fluid for later use for space heating or cooling, respectively. When electricity is used to heat a fluid it is called active heating. When heat is collected from the sun it is called passive solar heating. Generally, sensible heat storage (SHS) is done without re-electrification (Deal et al., 2010). Hot water tanks are used to store hot water produced by either electricity or solar energy (IRENA, 2013). The hot water can be used for either residential hot water usage or heating during the night.

Aquifer thermal energy storage can be used for both space heating and cooling by pumping ground water through a heat exchanger. In the summer, ground water is drawn from one side of the well to air condition. The warmed water from the air-conditioning heat exchanger is returned to a part of the well that is a sufficient distance from the pumped side of the well. The warmer water is stored until it is needed for heating in the winter. In winter, the direction of flow is reversed so that the cooled water is returned to the cooler side of the well. Significant research is done on ways to isolate the warm and cool sides of the aquifer in order to maintain temperature stratification (Zhai et al., 2013). Chung et al. (2008) have found that the degree of temperature stratification has a significant effect on the efficiency of the system. Stratification can be improved with properly designed shape and position of the suction and discharge to the aquifer, and other devices to reduce mixing.

Research needs for sensible heat storage would include ways to enhance the single-phase heat transfer of water and secondary fluids. Enhancement techniques would include passive internal tube flow enhancements like those shown in Webb and Kim (2005) and the use of nanofluids as recommended by Kedzierski (2013). Similarly, Fox et al. (2011) showed the benefit of nanofluids as nanoparticle-enhanced ionic liquids (NEILs) for increasing the energy stored per volume in concentrated solar power units.

Latent heat storage: Latent heat storage (LHS) uses phase change materials (PCMs) to store thermal energy. According to Sharma et al. (2009), most PCMs are designed to release heat when they change from liquid to solid and to store heat when they change from a solid to liquid having 5 to 14 times more heat per unit volume than liquid water. PCMs are advantageous compared to sensible heat storage because of high energy density, and, the nearly constant discharging temperature (Dincer and Rosen, 2002). PCMs more typically phase change between solid and liquid, but liquid-gas PCMs exist. PCMs are used to reduce peak-hour cooling loads. According to Kośny et al. (2008), PCMs have been used in buildings for at least 40 years. PCMs can be classified as organic (fatty acids, eutectic mixtures, fatty alcohols, neopentyl glycol, and paraffinic hydrocarbons, alkanes) or inorganic (salt hydrates) (Pinel et al., 2011 and Kośny et al., 2008). Water is also considered to be a PCM when it is used in ice storage.

Passive solar heating collects heat from the sun and stores it in a PCM. For active heating, the PCM is heated by electrically driven machinery. The heat is released at night when it is cooler. PCMs can also be used to store energy at cooler night temperatures for cooling during the day.

Significant material research is done to find organic and inorganic PCMs at specific design working temperatures, to have large heat of fusion, high thermal conductivity, low toxicity, low corrosiveness, and distinctive phase separation characteristics. PCMs other than water are necessary to store energy for heating so that the phase change occurs near the heating application temperature. Baetensa et al. (2010) state that only a few materials are known to transition around the comfort temperature, and these have a relatively low heat of fusion. NIST is not currently conducting research on PCMs for energy storage. However, the National Renewable Energy Laboratory (NREL) has an extensive research program on the subject (NREL, 2011). NREL's research on new PCMs is focused on characterizing the melting point temperature, the chemically stable working temperature range, the chemical compatibility with materials, the heat capacity, the latent heat, the thermal conductivity, the viscosity, the liquid and solid densities, and the cost.

PCMs can be integrated into residential thermal conditioning systems in several different configurations. For example, PCMs can be used in heat exchangers where the PCM is pumped to another (sink) heat exchanger for use; alternatively, a secondary fluid can be pumped between the PCM source and sink heat exchangers. Another option includes using PCMs as part of the construction material of the walls of the home. For example, small pellets of PCM material can be embedded in the gypsum of drywall that forms the interior wall of a home, and/or the PCM material can be a full layer in the wall construction as done in advanced façade construction (Zhai et al., 2013).

PCMs can be used strictly to store and reuse thermal energy (Heller, 2013), or they can be used to generate electricity with concentrated solar power (CSP), a steam generator and a turbine (Kotzé1 et al., 2011). Whether the PCM is used to store thermal energy or to make electricity, heat transfer research is required to adequately size and rate the heat exchanger and improve the efficiency of the heat transfer.

Using stored ice as a PCM is a popular way to provide air conditioning for large buildings. The benefit is that ice is made during the night when commercial electricity rates are significantly lower than during the day when the demand for electricity is high. In addition, chillers for making ice can be smaller than those large enough to meet the building's immediate cooling demand because the smaller chillers can operate continuously throughout the night to make enough ice for the peak day's use (ASHRAE, 2012). Residential electricity rates typically do not vary with the time of day, so making ice with imported energy during the night has limited application to the home. However, ice storage can provide an alternative to exporting excess renewable electricity to the grid. As an example a wind turbine that produces more electricity during the night than during the day could be used to drive an ice-making machine for storage. Ice made at night would be done at greater or comparable system efficiency due to lower outdoor air/condensing temperatures as compared to daytime temperatures (ASHRAE, 2012). The home might require two separate systems for cooling: a relatively small chiller for making ice and a heat pump to meet the cooling demands when there is no stored ice. Ice slurry and melt-ice-on-coil heat transfer studies like those done by Kumano et al. (2014) and Lo´pez-Navarro et al. (2013), respectively, would have to be either adapted or re-done for residential applications.

Combined Energy Storage Methods

Combined Technologies: Energy storage technologies are combined in an attempt to mitigate the shortcomings of a particular technology. Most of the combined technologies currently in the literature involve compressed air systems. For example, Bi et al. (2013) and Wang et al. (2013) have investigated combining pumped hydro with compressed air, i.e., PHCA. The advantage of the PHCA system is that it avoids the inefficiencies of adding heat during the expansion process of the compressed air system. As shown on the left of Fig. 3, rather than using the compressed air to run a turbine, the air is use to pressurize water that is used to drive a pump. Wang et al. (2013) have calculated that a tank pressure (*P*) of 5 MPa is equivalent to a dam with a height (*h*) of 500 m as shown on the right side of Fig. 3.

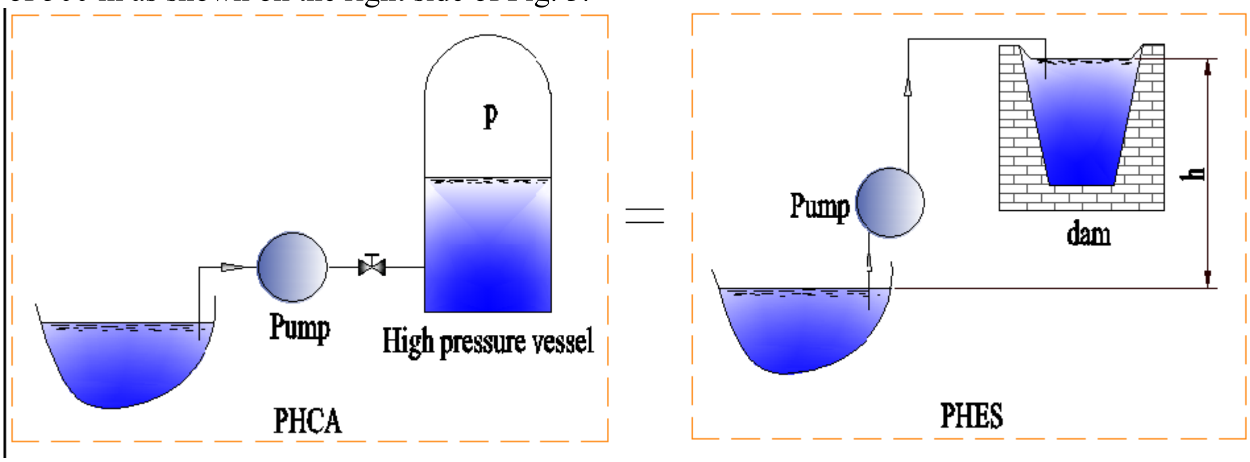

Figure 3 Comparison of PHCA to equivalent PHES system (Wang et al., 2013)

Lemofouet and Rufer (2005) show that combining compressed air with supercapacitors improves the flexibility and the dynamic performances of the storage system without the need for fuel to reheat air. The supercapacitors serve to increase the stability and "smoothness" of the variable output of the system and result in efficiency improvements.

Havel (2013) reduces the required pressures of CAES by adsorbing the air in nano-porous materials. Adsorption of the air provides an equivalent air density of 100 bar at less than 20 bar. The modified energy storage system is temperature rather than pressure controlled and as a result is less costly and more efficient than traditional CAES.

POTENTIAL ENERGY STORAGE RESEARCH

This section highlights projects that might be particularly successful in the EL laboratory because they capitalize on existing strengths of the organization.

PCM Facades

Figure 4 shows a passive cooling of a room with external walls containing phase change material, i.e., PCM facades (IRENA, 2013). PCMs make it possible to turn the inconvenience of outdoor temperatures transitioning from too hot to too cold into a means for energy conservation. During the day when the incident sun causes the temperature of the outside wall of a home to increase, the insulation and the wall materials act to delay the increase in temperature of the wall inside the house. The specific heat and the thermal conductivity of the insulation and the wall materials determine how quickly the inside wall temperature increases for given outside conditions. A wall with a large specific heat and a small thermal conductivity exhibits inside temperatures that respond more slowly to the outside temperature and incident sun than otherwise. The use of PCMs significantly increases the response time of the inside wall temperature by adding an additional energy storage term (heat of fusion) to the wall's effective heat capacitance. If the melting point of the PCM is chosen correctly, it will be near the desired room temperature and solid when the outside temperature begins to increase. Because the PCM typically melts at a constant temperature, the increase in the outdoor temperature acts to melt the PCM at T_{PC}. As long as some solid PCM remains, the hotter outside temperature is prohibited from increasing the inside wall temperature greater than T_{PC}. Rather, the energy incident from the outside is stored in the PCM as a higher energy state, i.e., liquid. During the night the PCM in liquid form works to keep the house warm by remaining at a constant, comfortable temperature as the night air freezes the PCM. Likewise, as long as some liquid remains in the PCM, the colder outside temperature is not seen by the inside of the house. Baetensa et al. (2010) state the above more succinctly: "the principle behind phase change materials is excess energy at elevated temperatures is stored and given back at a certain temperature, resulting in an increased thermal mass in a narrow temperature range."

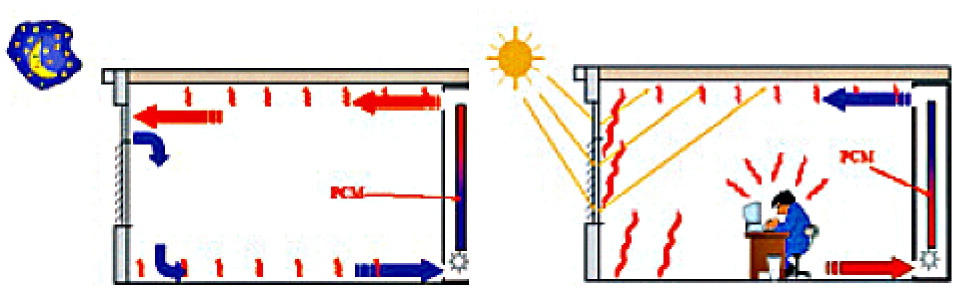

Figure 4 Passive cooling with external PCM wall (IRENA, 2013)

Figure 5 shows some of the many forms that PCM facades can take. Some facades have air cavities that can be selectively ventilated. The ventilation can be achieved with a blower (active ventilation) or by natural convection (passive ventilation). As shown in Fig. 5, Zhai et al. (2013) investigated several different multilayer walls, some with multilayer PCMs. They developed the Advanced Façade Systems "AdvFacSy" tool that models the heat transfer through various PCMs walls like those shown in Fig. 5. The AdvFacSy uses an enthalpy method with an iterative correction scheme to account for weather conditions and solar radiation.

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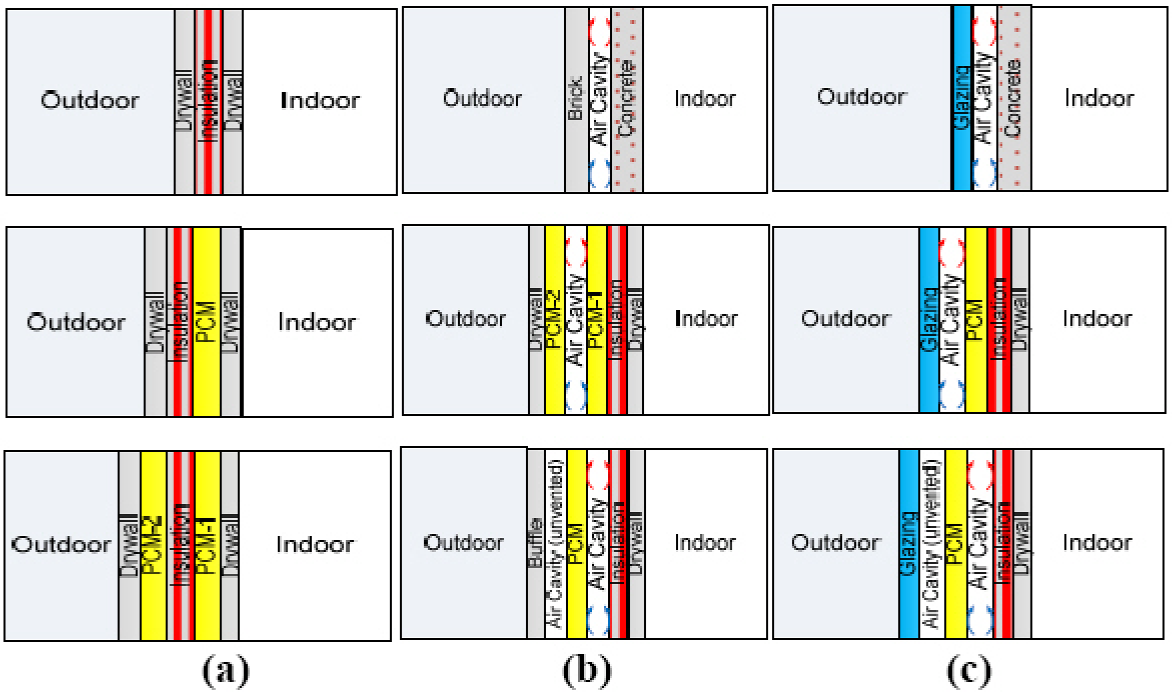

Figure 5 Classical and advanced façade designs with and without PCMs in "AdvFacSy" Toolbox [(a) Multi-layer wall; (b) Ventilated opaque multi-layer wall; (c) Ventilated transparent multi-layers walls] (Zhai et l., 2013)

Considering the above, the first area of potential research for EL in PCM facades is to build on the work of Zhai et al. (2013) toward determining the favorable design and material selection for PCMs in residential facades. Entire house simulations, like those done by EL's Office of Applied Economics (Kneifel, 2010), could then be done to determine which PCMs, and in what configuration are the best for a particular climate. Building cost databases for the various PCMs façades would have to be developed. These would serve as input for the whole building energy consumption simulations that are used to determine the life-cycle cost-effectiveness and carbon emissions of each design. NIST's Building for Environmental and Economic Sustainability (BEES) software (Lippiatt, 2007) could be used to compute the life-cycle costs analysis as was done by Kneifel (2010).

The second area of potential research in PCM facades would be to measure the performance of various PCM walls in a calibrated hot box. NIST has an extensive history using several versions of a calibrated hot box for measuring the heat transferred through compound walls (Zarr, 2001). Figure 6 shows a schematic of the cross section of the hot box envisioned by R. S. Dell and completed in 1937 (Whittemore et al., 1943). The wall specimen is shown sandwiched between a cold and a hot box. The hot box was heated by electric heaters and the power was measured with a watthour meter. A fan was used to gently mix the air so that the air temperature was nearly uniform. The cold side of the box was cooled by mechanical refrigeration. The outer walls of the cold box and the hot box were maintained at their respective air temperatures so as to minimize heat loss/gain from the surroundings.

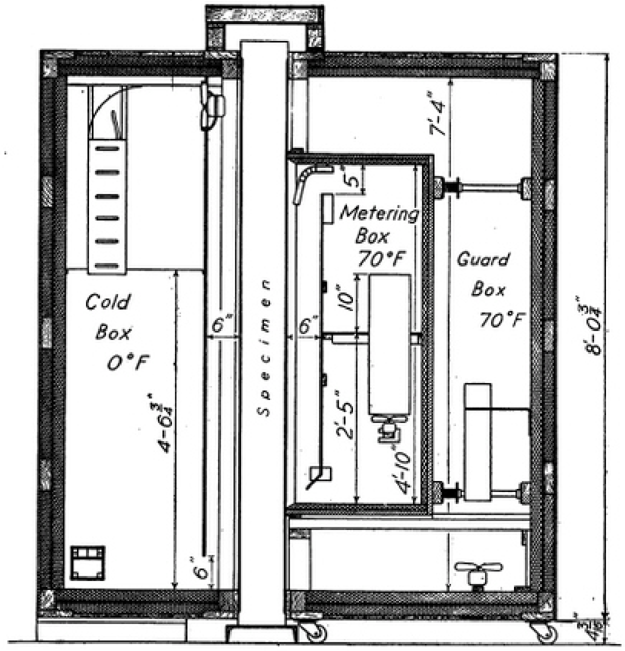

Figure 6 Cross-section of NBS hot box test apparatus 1937 – 1964 (Whittemore et al., 1943)

Figure 7 shows a photograph of the calibrated hot box that was in EL from 1967 to 1980. Currently, EL does not have a calibrated hot box. The advantage of this is being able to design a new hot box so that it is tailored for use with PCM facades. The calibrated hot box could be designed for measuring the heat, air, and moisture transfer of room-sized exterior wall specimens

Figure 7 NBS hot box test apparatus 1967 - 1980

under a range of simulated climatic conditions.

PCM Evaporator for Residential Air Conditioner

Integrated PCM

A new concept that EL could investigate is the direct expansion PCM evaporator for high-efficiency air conditioner shown in Fig. 8. The PCM evaporator resembles a conventional residential evaporator in that it is a tube-and-plate-fin geometry with air flowing between the aluminum plate fins and evaporating refrigerant flowing inside nominally 9 mm OD copper tubes. However, the refrigerant tubes are inside of a larger copper tube thus forming an annulus that is filled with PCM material. The melting temperature of the PCM material is proposed to be approximately 2 K less than the dew point of the humid air so that dehumidification occurs on the evaporator fins. The tubes are orientated nearly vertically to prevent voids in the PCM material from forming in the annulus so as to keep the outer wall of the annulus wetted with phase change material during the melting process. The PCM does not flow in the annulus, rather, each tube is closed on both ends. The tilt of the fins allows for condensate drainage from the fins to occur by gravity.

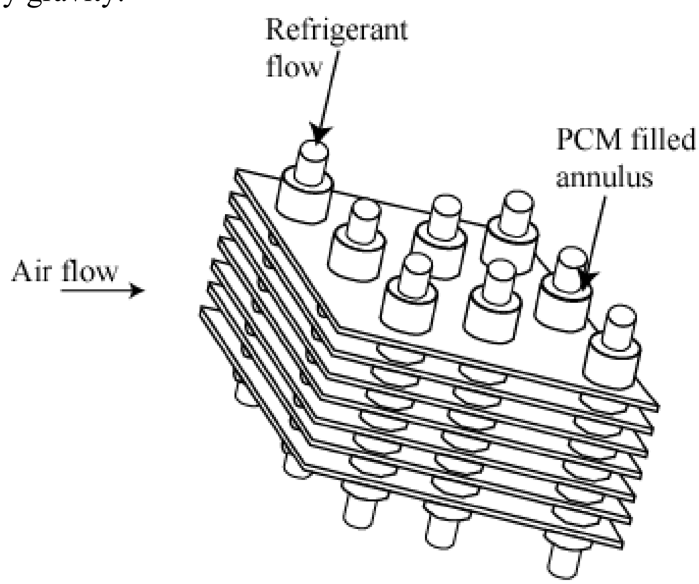

Figure 8 Proposed PCM evaporator for investigation

Use of a PCM evaporator will allow the air conditioning unit to be much smaller and operate more efficiently than the traditional unit. The required capacity is reduced because the peak load is met by the combined capacity of the mechanical air-conditioning and the melting of the PCM material. The efficiency is improved because the unit runs nearly continuously instead of cycling on and off to meet the load. Dampers would be required to close off the ducted air flow while the PCM was in recharge mode.

The first phase of the project should be to design the evaporator for the correct size and the correct total mass of PCM for a given cooling duty. The evaporator should have four rows and the space between the annulus should be large enough so that there is sufficient PCM to remain solid through the peak demand time. Preliminary measurements from the NIST net-zero house show that an additional 4 kWh to 6 kWh of cooling would be required to "shave" the peak load. Using the latent heat of fusion of a commercially available PCM (PureTemp 8)[5,6]of 180 kJ/kg with a density of 860 kg/m3, it would require approximately 120 kg of PCM to meet 6 kWh. A typical residential air conditioner has approximately 40 m of evaporator tubing. Assuming that the diameter of the inner refrigerant tube of the PCM evaporator shown in Fig. 8 is 9 mm, the outer diameter would need to be approximately 67 mm to hold 120 kg of PCM within the annulus. This outer tube diameter is physically possible but can be reduced by using a PCM of a larger heat of fusion or more tubing length. In addition, geometries other than that shown in Fig. 8 can be investigated that result in smaller evaporators. Other investigated geometries could include remote PCM storage tanks where the evaporator refrigerant is circulated through peak loads.

The second phase of the project should be to characterize the heat transfer of the PCM in a simplified version of the evaporator in the laboratory. Heat transfer coefficients as a function of the percent solid mass of PCM should be developed in order to calculate the transient heat transfer of the evaporator. The third phase of the project should be to manufacture a PCM evaporator and install it in a residential unit and evaluate the performance in the environmental chambers. The fourth phase of the project should be to install the PCM evaporator in the NIST's Net-Zero Energy Residential Test Facility (net-zero house) (Fanney et al., 2014) for field testing. The final phase of the project should be to explore ways that the same PCM heat exchange could be used in heating as well as cooling as is done in a residential heat pump. A possible technique to make a PCM-integrated heat exchanger both an evaporator and a condenser would be to charge the PCM annuli with equal parts heating and cooling PCM. Alternatively, a PCM mixture that is capable of shifting composition and thus melting temperatures could be used for both heating and cooling modes. The composition shift could be achieved by distillation, filtering as in a reverse osmosis system, or by shifting the water content of a salt hydrate PCM.

All in all, the PCM evaporator is expected to be a worthwhile project to pursue. Support of this premise was found when the authors were able to find a prototype PCM evaporator for automotive air conditioning. Figure 9 shows an automotive PCM evaporator currently under development; in 2012 it was expected to be in production by the year 2015[7]. The automotive PCM evaporator is expected to be lower cost and more efficient than a traditional system. In addition, EL has experienced staff and facilities for testing heat pumps and novel heat transfer devices and surfaces.

<u>Discrete PCM</u>

A second concept for the PCM evaporator locates the PCM external to the air handler within its own heat exchanger. Storing the PCM external to the evaporator eliminates the concern of having sufficient PCM mass within a limited evaporator volume and footprint, but adds some complexity as additional valves are needed for control.

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[5] http://www.puretemp.com/technology.html

[6] Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor does it imply that the products are necessarily the best available for the purpose.

[7] http://johndayautomotivelectronics.com/delphi-air-conditioning-technology-with-pcm-evaporator-keeps-start-stop-vehicles-cooler-longer/

Figure 9 Delphi Automotive PCM evaporator

One possible configuration for this system is shown in Fig. 10. The system is comprised of two evaporator coils with an intermediate PCM heat exchanger, two electronic expansion valve (EXVs), and a bypass valve. Using EXVs, rather than thermostatic expansion valves (TXVs), allows the system to use control logic to completely close the EXV when a particular refrigerant circuit is not needed. Depending on the current and anticipated loads, the system would operate in three modes: charge, release, and normal. The only difference between the modes is which heat exchanger acts as the evaporator load for the rest of the air-conditioning system. For example, for the charge mode, only the PCM heat exchanger provides a cooling load for the system. Similarly, evaporator coils 1 and 2 act as the evaporator for the normal mode with the PCM heat exchanger bypassed. In the release mode, all three heat exchangers are used.

In the charge mode, the PCM is cooled and solidified by the refrigerant flowing from the condenser with its mass flow controlled by a dedicated expansion valve (EXV2 in Fig. 10). No air flows in the air handler during the charge mode. In the release mode, the refrigerant flows from the condenser and through the EXV1, both evaporator coils, and the PCM tank. The refrigerant evaporates in the first evaporator coil, re-condenses in the PCM heat exchanger, and then evaporates again in the second evaporator coil. The release mode combines the capacity of the air conditioner with that of the PCM to temporarily increase the system cooling potential. The system would run in the normal mode when the PCM is fully charged or when predicted future loading conditions do not require the extra energy stored in the PCM material. The PCM tank is bypassed in the normal mode to reduce losses related to the pressure drop and the heat leak through the PCM tank. Normal mode uses both coils, which is a large heat exchange surface relative to the capacity of the heat pump alone (i.e. without the PCM). This results in a higher air-side pressure drop than would occur if just the first coil was used. Additional fan

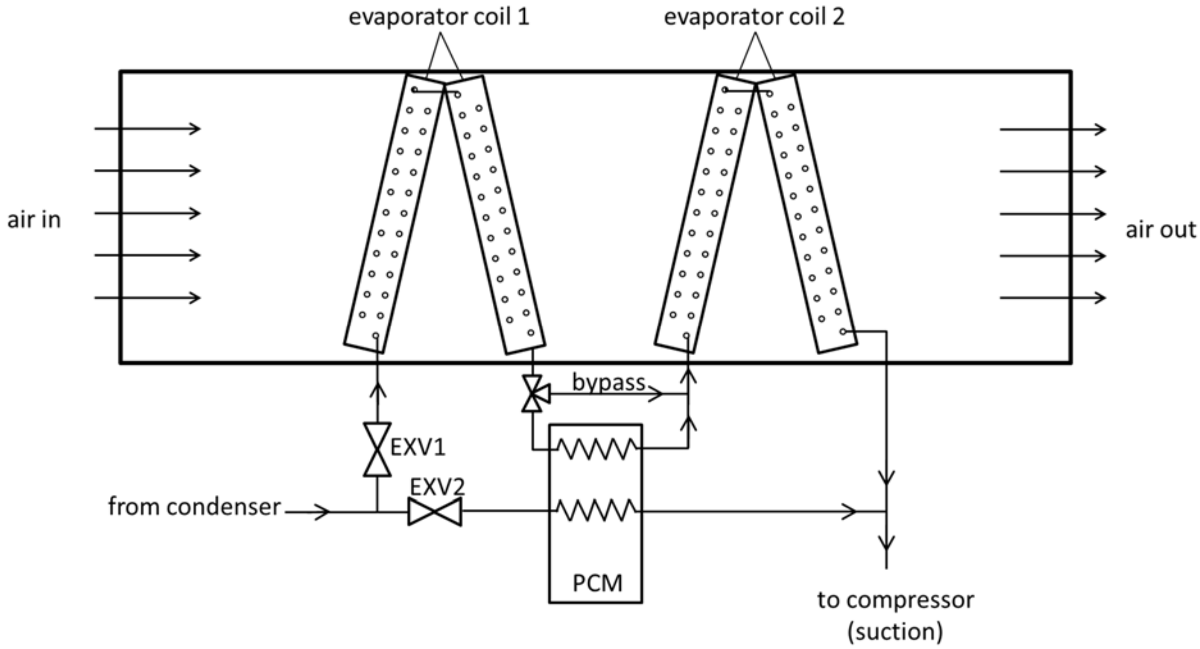

Figure 10 External PCM evaporator where PCM re-condenses refrigerant before the refrigerant enters the second evaporator coil

power would be required to overcome the pressure drop; however, these losses would at least partially be offset by the compressor efficiency gains related to higher saturation temperature (achieved via the larger evaporator surface area).

The system shown in Fig. 10 would require a phase transition temperature below the evaporation temperature of the refrigerant (about 7 °C (45 °F)) in order to re-condense the refrigerant exiting the first evaporator coil. When the PCM material is being charged, the refrigerant saturation temperature must be even lower than the PCM transition temperature; therefore the charging process will occur at a reduced COP relative to normal operation. Furthermore, the insulation losses in the PCM tank will be higher because of the low storage temperature.

Figure 11 shows another possible configuration for a discrete/external PCM evaporator, where the PCM is pumped through an evaporator coil as a slurry to cool the air. The system features two evaporator coils, two independent EXVs to control the PCM and the second evaporator coil circuits; and the pump to circulate the PCM slurry, respectively. This system can be operated in four modes including normal, charge, release, and combination. In the normal mode, the refrigerant flows only through EXV2 and the second evaporator coil. During charging, refrigerant cools the PCM after expanding in EXV1. The maximum system capacity is achieved in release mode, where the PCM slurry is circulated through the first evaporator coil, and the refrigerant is circulated through EXV2 and the second evaporator coil. Finally, the system can operate in a combined mode where both EXVs are open. Here, the refrigerant simultaneously cools the second evaporator coil and the PCM material.

The PCM material can operate with a higher phase transition temperature than the normal refrigerant saturation temperature (about 7 °C (45 °F)) in this configuration because it is used to directly cool the air, rather than to re-condense the refrigerant as it does in the Fig. 10 configuration. The PCM evaporator effectively pre-cools the air for the refrigerant evaporator

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coil. The PCM evaporator provides mostly sensible cooling, whereas the colder refrigerant evaporator coil provides both sensible and latent cooling.

The Fig. 11 configuration offers two distinct advantages compared to the Fig. 10 configuration, including the higher PCM transition temperature (which allows the charge mode to operate with a higher COP), as well as the ability to operate in combination mode. However, the PCM evaporator restricts the airflow even when not in use, and provides no offsetting benefit.

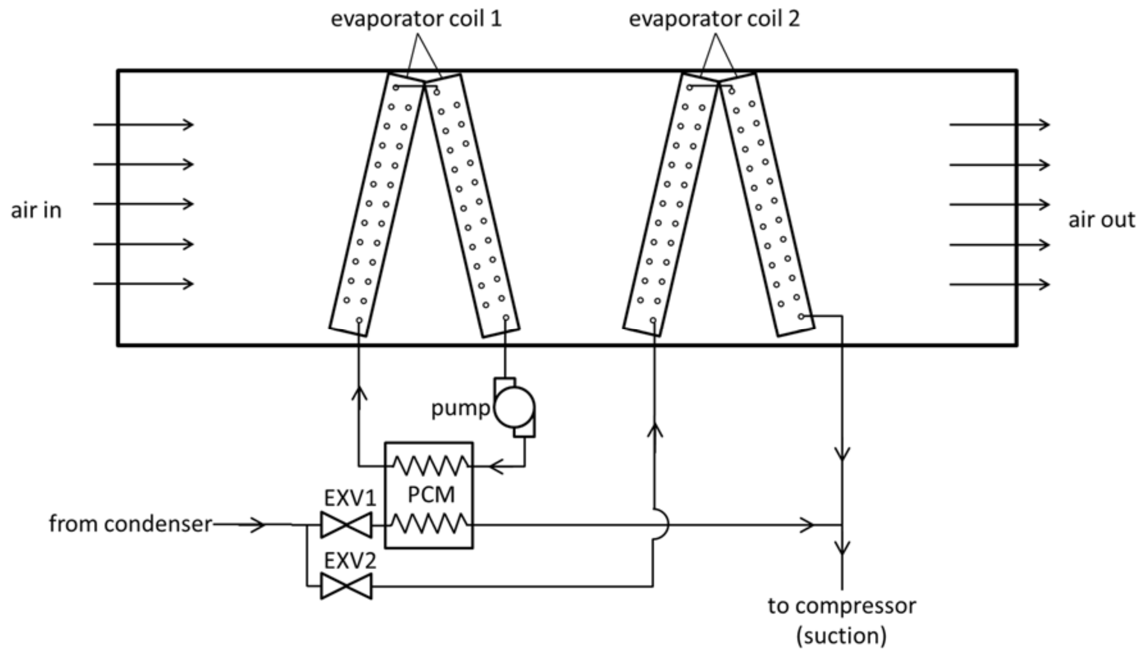

Figure 11 External PCM evaporator where the PCM is pumped through the first evaporator coil

The storage needs and development cycle for the external PCM evaporator are very similar to the annulus-filled PCM evaporator described in the preceding "PCM Evaporator for Residential Air Conditioner - evaporator-integrated PCM" section. The storage needs to meet the peak would be approximately 4 kWh to 6 kWh of energy stored in 120 kg of PCM.

The development of this system would begin with a modeling study of the system to determine feasibility and optimization of the system. A system prototype can be constructed and tested in the environmental chambers, as well as the NIST net-zero house.

Pumped Hydro

Figure 12 shows a model of the existing structure of the plumbing tower in EL. The overall height of the tallest portion of the tower is approximately 18 m. The EL plumbing tower could be used to test scaled versions of advanced pumped hydro with/out compressed air for residential applications. Chanson (1999) provides guidance on how to properly scale a physical hydraulic model with consideration given to the boundary and flow conditions. According to Chanson (1999) physical hydraulic models are used to optimize hydraulic systems and to guide design decisions.

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A prototype of the full-scale PHS would allow the exploration of the value of adding compressed air to the system and other hybrid techniques. In the meantime, the tests would be considerably less expensive than a full scale test and could be done under controlled laboratory conditions and allow for the development of concise predictive models.

Figure 12 Model of NIST plumbing tower

Water Heaters

EL has studied water heater performance for more than a decade (Fanney et al., 2000, Healy et al., 2003, and Healy et al., 2011). The NIST studies deal with general thermal performance, efficiency, and rating methodologies for water heaters. These skills could be used to investigate solar water heaters (SWHs) and heat pump water heaters (HPWH).

Solar water heaters use energy from the sun to directly or indirectly heat water. Indirect water heating requires a secondary heat transfer fluid to travel between the solar heat exchanger and the water heater tank. A PCM may be used as a stationary "secondary fluid." Sharma et al. (2009) state that research is needed to improve the heat exchange between the PCM and the water. EL has the personnel and the laboratory experience to carry out the necessary studies that would be required to characterize the fundamental heat transfer characteristics of PCM as secondary fluids. According to Hudon et al. (2012), another crucial area of research for SWHs is to enable operation in cold climates. In addition, Hudon et al. (2012) claim that SWH systems can already meet the hot water demand for a typical household, but that the major barrier to achieving significant market acceptance is the capital cost (Sharma et al., 2009).

Heat pump water heaters use a heat pump to assist electric resistance heating elements to heat water in a tank. Hudon et al. (2012) note that commercially available HPWHs operate more efficiently in warmer climates. Zimmerman (1986) states that HPWHs have been manufactured since the late 1950's. Consequently, there may be fewer research opportunities for advancing HPWH technology as compared to that for the SWH.

Radiant Floor Heating

Radiant floor heating and cooling is done by pumping a heat transfer fluid through tubing. Some systems circulate water in heat exchanger panels while others directly condition either the floor or the ceiling slabs. PCM plates with polystyrene insulation can be used below the floor instead of tubing (Sharma et al., 2009). Feng et al. (2013) measured the performance of radiant cooling panels in an environmental chamber. EL has the capabilities for conducting similar studies using its environmental chambers. In addition, the basement slab of the NIST's net-zero house has a 9-circuit radiant floor heating system (Fanney et al., 2014) that is available for field testing.

Field Testing

Evaluation of the performance of residential energy storage systems in a real home is intended to result in valuable practical information to facilitate the commercialization of residential EES. NIST's net-zero home is well suited for the evaluation of the EES projects recommended in this manuscript. In addition, the load simulator developed by NIST (Guo et al. 2014) could be an integral part of the field testing by making it easy to simulate loads that EES should expect to meet. NIST's new load simulator can simulate appliances by consuming electricity as scheduled according to typical load profiles with programmable power, power factor and operating time. In addition, the load simulator can be used to properly size and select the EES that has the desired compromise between performance and capital costs.

Smart Grid

Energy storage will naturally become an integral part of the Smart Grid. Bi-directional power flow, which is an essential consideration for the Smart Grid, can be significantly influenced by energy storage. Nationally, Smart Grid research funding significantly exceeds that for energy storage (SBC, 2013). Below are three of many NIST Smart Grid research projects that would benefit from energy storage research:

1) Power Conditioning Systems for Renewables, Storage, and Microgrids project under the Smart Grid Project[8]: advanced smart grid-interactive Power Conditioning System (PCS)-based generator and microgrid functions developed as a result of this project enable solutions to these and many other issues and will enable distributed generators to provide grid interactive functions that increase their value proposition.
2) Smart Grid Communication Networks Project[9]: develop communication standards for smart grid interaction between houses, power plants, and renewable energy sources.
3) Smart Grid System Testbed Facility Project[10]: the testbed will implement network communication by way of a home microgrid protocol and the Building Automation and Controls Network (BACnet) data protocol.

[8] https://eli.nist.gov/program/PROGRAM_PROJECTS/Project_48.aspx
[9] https://eli.nist.gov/program/PROGRAM_PROJECTS/Project_62.aspx
[10] https://eli.nist.gov/program/PROGRAM_PROJECTS/Project_64.aspx

EES Cost and Benefits

An EL project could be developed to compare the costs and benefits of various types of EES. This would require a cost-benefit methodology for EES to be developed by possibly modifying or applying the cost analysis given in Zheng et al. (2014). It would have to define, quantify and monetize the full range of EES costs and benefits. According to Pedram et al. (2010), in order to achieve high energy cost savings, an ideal EES system should possess many features such as high charge/discharge efficiency, high energy density, low cost per unit capacity and long cycle life.

SIZE OF RESIDENTIAL ENERGY STORAGE SYSTEM

The storage capacity, in kWh, of a residential energy storage system (Q_s) is directly proportional to the capital cost of the energy storage system. The size of the system determines how much of the unused residential electricity generation is captured and saved. A system designed large enough to store all of the excess electricity produced may be too expensive and physically too large to build on a residential site. Consequently, the energy storage system must be sized with the trade-off between storing as much energy as possible and the system cost in mind. This engineering calculation requires the net electricity generation/usage characteristics of the house in question such as that shown in Fig. 13.

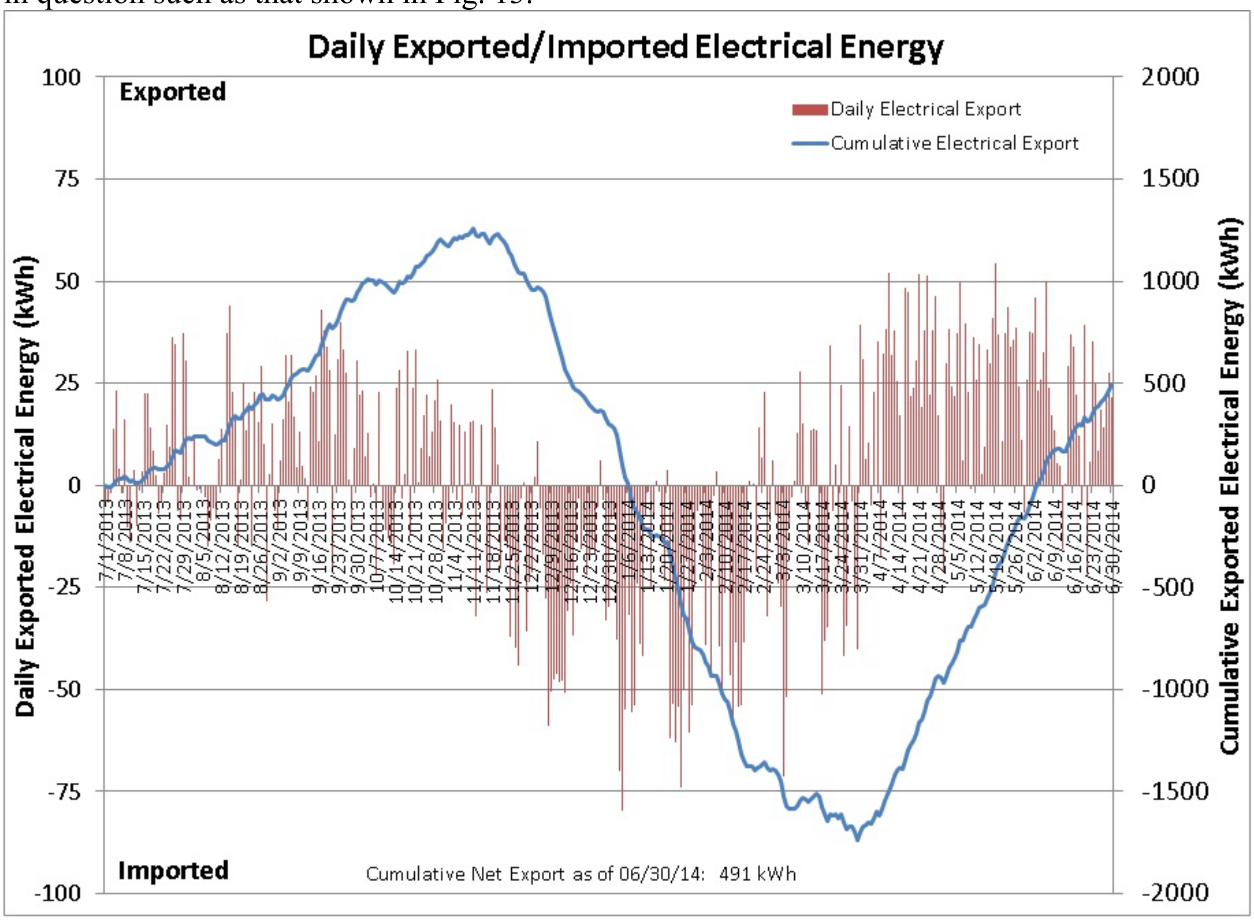

Figure 13 Net zero house electricity net generation and usage (Fanney et al., 2014)

Figure 13 shows the daily and cumulative net electricity excess-generation/deficit-usage of NIST's net-zero home (Fanney et al., 2014). The facility is a 223 m^2, two-story residential home that is fully instrumented to measure its energy consumption. Figure 13 shows the house's net generation/usage for each day over a year where a positive value indicates that the PV of the house produced more electricity than that required by the house for that day. Negative values indicate that the PV did not produce enough electricity to meet that day's electricity needs. Figure 13 shows measurements from July 2013 through June 2014 where the house produced 378 kWh more electrical energy than it consumed.

The net electricity measurements of Fig. 13 were used to illustrate, in Fig. 14, the required size of an energy storage system (Q_s) for NIST's house. Figure 12 shows the fraction of the total excess electricity generated in a year (Q_g) that was stored in an energy storage system over that same year (Q_y). The fraction of excess electricity stored is shown as a function of the size of the storage system. In general, larger energy storage systems can be used to store a larger fraction of the excess generation. Solid lines, in Fig. 14, represent energy storage starting in July (consistent with Fig. 13) while dashed lines represent energy storage starting in October. Comparison of the solid and dashed lines show that more energy can be stored in a year for a given system size if storage begins in the summer as compared to the fall. The lower two curves of Fig. 14 show that a 25 kWh and a 250 kWh storage system are able to store approximately 15 % and 30 % of excess generation in a year, respectively. For this case, storing twice as much energy in a year requires an order-of-magnitude larger energy storage system. As Fig. 13 shows, the PV for the test house was oversized considering that it produced more electricity than it used in a year. In

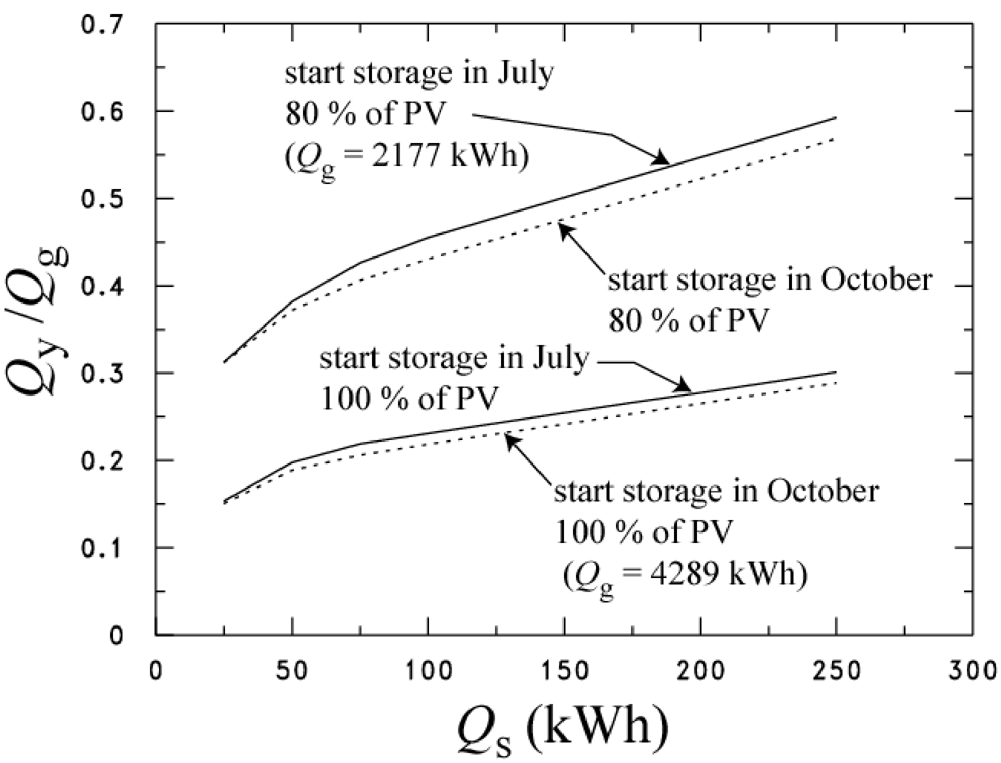

Figure 14 Fraction of excess electricity stored as a function of the size of the storage system

order to understand the energy storage size requirements for a house with less PV, the two upper curves of Fig. 14 show these characteristics for 80 % of the PV shown in Fig. 13 but with the electricity usage requirements unchanged. For this case, a 25 kWh and a 250 kWh storage system are able to store approximately 30 % and 60 % of excess generation in a year, respectively. Consequently, the size of the PV should be designed with consideration of the size of the energy storage system and vice versa. Otherwise, a significant amount of PV electricity generation may go unused if it cannot be put on the grid.

CONCLUSIONS

NIST Engineering Laboratory is well positioned to make significant contributions to the relatively neglected field of residential energy storage. Possession of the NIST's Net-Zero Energy Residential Test Facility makes it possible to work collaboratively with other laboratories within NIST to demonstrate new ideas in energy storage including batteries, super capacitors, superconducting magnets and hydrogen storage.

In addition, EL staff and facilities are well matched to projects in Phase Change Material (PCM) facades and PCM evaporators, pumped hydro, solar water heaters, and cost/benefit analysis. Accordingly, new heat exchanger and system designs with PCMs were proposed for investigation. The PCM investigation would require both heat transfer and system performance measurements. In addition, it was proposed to use the existing EL plumbing tower for hydro storage studies and to rebuild a calibrated hot box for PCM façade investigations. Other potential project ideas were also provided for these areas of research.

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NOMENCLATURE

English symbols

h	height (m)
P	pressure (Pa)
T	temperature (K)
Q	energy (W)

Greek symbols

ΔP	pressure drop (kPa)

Subscripts

g	excess generation
PC	phase change
s	storage system
y	excess electricity over a year

Abbreviations

AC	Air Conditioning
AdvFacSy	Advanced Façade Systems
BACnet	Building Automation and Control network
BEES	Building for Environmental and Economic Sustainability
CAES	Compressed Air Energy Storage
CES	Chemical Energy Storage
CSP	Concentrated Solar Power
DLC	Double Layer Capacitor
EES	Electrical Energy Storage
EL	Engineering Laboratory (laboratory within NIST)
ES	Electricity Storage
EXV	Electronic eXpansion Valve
FES	Flywheel Energy Storage
HPWH	Heat Pump Water Heater
ID	Inner Diameter
LHS	Latent Heat Storage
Li-S	Lithium-Sulfur (battery)
MES	Mechanical Energy Storage
MML	Material Measurement Laboratory (laboratory within NIST)
NBS	National Bureau of Standards (now called NIST)
NEIL	Nanoparticle-Enhanced Ionic Liquids
NIST	National Institute of Standards and Technology (in US Department of Commerce)
NREL	National Renewable Energy Laboratory
OD	Outer Diameter
PC	Phase Change
PCHA	Pumped Hydro with Compressed Air
PCM	Phase Change Material
PCS	Power Conditioning System
PHS	Pumped Hydro Storage
PV	Photovoltaic

SHS	Sensible Heat Storage
SMES	Superconducting Magnetic Energy Storage
SWH	Solar Water Heaters
TES	Thermal Energy Storage
TXV	Thermostatic eXpansion Valve
UPS	Uninterruptible Power Supply
U.S.	United States

REFERENCES

ASHRAE, 2012, 2012 ASHRAE Handbook -HVAC Systems and Equipment, Chapter 51, Atlanta, GA, p. 51-1.

Baetensa, R., Jelle, B. P., and Gustavsend, A., 2010, "Phase change materials for building applications: A state-of-the-art review," Energy and Buildings, Vol. 42, pp. 1361–1368.

Bi, J., Jiang, T., Chen, W., and Ma, X., 2013, "Research on Storage Capacity of Compressed Air Pumped Hydro Energy Storage Equipment*, *Energy and Power Engineering*, Vol 5, 26-30.

Bohn, C. D., Agrawal, A. K., Walter, V. M., Vaudin, V. A., Herzing, A., Haney, P. M., Talin, A. A., and Szalai, V. A., 2012, "Effect of tin doping on α-Fe2O3 photoanodes for water splitting," The Journal of Physical Chemistry, Vol. 116, pp. 15290–15296.

Bruch, M., Münch, V., Aichinger, M., Kuhn, M., Weymann, M., Schmid, G., 2011, "Power Blackout Risks Risk Management Options Emerging Risk Initiative – Position Paper," CRO briefing on Power Blackout Risks, p. 6.

Chanson, H , 1999, "Physical Modelling of Hydraulics. In Chanson, H., Hydraulics of Open Channel Flow: an Introduction, Edward Arnold, 1st ed., London, UK, pp. 261-283.

Chung, J. D., Cho, S. H., Tae, C. S., and Yoo, H., 2008, "The effect of diffuser configuration on thermal stratification in a rectangular storage tank," Renewable Energy, vol. 33, no. 10, pp. 2236–2245.

CPUCED (California Public Utilities Commission Energy Division), 2005, "Update On Determining The Costs And Benefits Of California's Net Metering Program As Required By Assembly Bill 58"

Davis, M. W, Ellis, M. W., Dougherty, B. P., 2006, "Proposed Test Methodology and Performance Rating Standard for Residential Fuel Cell Systems," NISTIR 7301, U.S. Department of Commerce, Washington, D.C.

Deal, M., Churchill, S., Chaset, L., and Villarreal C., 2010, "Electric Energy Storage: An Assessment of Potential Barriers and Opportunities," CPCU Policy and Planning Division Staff White Paper.

DGE, 2012, "Quarterly Report on European Electricity Markets," DG Energy, Market Observatory for Energy, Vol. 5, Issue: 1, January 2012 to March 2012, European Commission, Directorate-General for Energy.

Dincer, I., and Rosen, M. A., 2002, Thermal Energy Storage-Systems and Applications, Wiley, West Sussex, p. 1.

Esposito, D.V., Levin, I. T., I. Moffat I., and Talin A.A., 2013, "H_2 evolution at Si-based metal–insulator–semiconductor photoelectrodes enhanced by inversion channel charge collection and H spillover," Nature Materials, doi:10.1038/nmat3626.

Feng, J., Bauman, F., Schiavon, S., 2013, "Experimental comparison of zone cooling load between radiant and air systems," Energy and Buildings: HVAC Systems, October, http://escholarship.org/uc/item/9dq6p2j7

Fanney , A. H., Payne, V., Ullah, T., Ng, L., Boyd, M., Omar, F., Davis, M., Skye, H., Dougherty, B., Polidoro, B., Healy, W., Pettit, E., 2014," The National Institute of Standards and Technology's Net-Zero Energy Residential Test Facility," Submitted to Energy and Buildings

Fanney, A.H., Zarr, R.R., and Ketay-Paprocki, J.D, 2000,"Thermal Performance of Residential Electric Water Heaters Using Alternative Blowing Agents" ASHRAE Transactions 2000, Vol. 106, No. 2, 1-13.

Fox, E. B., Visser, A. E., Bridges, N., Gray, J. R., Garcia- Diaz, B., Maginn, E. J., and Khan, J. A., Report to DOE:Thermally-stable ionic liquid carriers for nanoparticle-based advanced heat transfer in concentrating solar energy applications,3rd quarter FY11 progress report, SRNL-STI-2011-00543, Savannah River National Laboratory, Aiken, SC,2011.

Havel, T. F., 2013, "Adsorption-Enhanced Compressed Air Energy Storage," *Proceedings of Electrical Energy Storage Applications and Technologies (EESAT) conference*, San Diego, CA.

Healy, W. M., Ullah, T, and Roller, J., 2011, "Input-Output Approach to Predicting the Energy Efficiency of Residential Water Heaters Testing of Gas Tankless and Electric Storage Water Heaters," ASHRAE Trans, Vol. 117.

Healy, W. M., Lutz, J. D., and Lekov, A. B., 2003, "Variability in Energy Factor Test Results for Residential Electric Water Heaters," HVAC&R Research Journal 9:4, pp. 435-449.

Heller, L., 2013,"Literature Review on Heat Transfer Fluids and Thermal Energy Storage Systems in CSP Plants," STERG Report

Hudon, K., Merrigan, T., Burch, J., Maguire, J., 2012, "Low-Cost Solar Water Heating Research and Development Roadmap," NREL Report No. TP-5500-54793.

Guo, W., Ullah, T., and Healy, W. M., 2014, "Deployment of a Load Simulator in Simulating Residential Household Appliances," IN WERB REVIEW

IEC, 2011, "Electrical Energy Storage," White Paper. http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf

IRENA, 2013, "Thermal Energy Storage," Technology Brief , E17, EA-ETSAP and IRENA, p. 6.

IRENA, 2012, "Renewable Energy Technologies: Cost Analysis Series," *Hydropower* Volume 1: Power Sector Issue 3/5.

IREA, 2012, "Electricity Storage and Renewables for Island Power: A Guide for Decision Makers," International Renewable Energy Agency, Issue 3/7.

Islam, S. M., 2012, "Increasing wind energy penetration level using pumped hydro storage in island micro-grid system," *Int. J. Energy and Environmental Engineering*, Vol. 3, 9.

Kedzierski, M. A., 2013, "Nanofluids, Heat-Transfer Equipment and Plain-Vanilla," Journal of Enhanced Heat Transfer, Vol. 20, No. 1, pp. 93-94.

Kim, Y. and Favrat, D., 2008, "Energy and Exergy Anaysis of a Micro Compressed Air Energy Storage and Air Cycle Heating and Cooling System," *International Refrigeration and Air Conditioning Conference at Purdue*, paper 2149.

Kneifel, J. D., 2010, "Cost-effectiveness of Energy Efficiency Measures Exceeding Current Standards in New Commercial Buildings," *Proceedings of the International Council for Research and Innovation in Building and Construction World Building Congress 2010 - Building a Better World*,

Kośny, J., Yarbrough, D., Miller, W., Petrie, T., Childs, P., Syed, A. M., and Leuthold, D., 2008, "PCM-Enhanced Building Envelopes in Current ORNL Research Projects," Oak Ridge National Laboratory Report ORNL/TM-2007/186.

Kotzé1, J. P., von Backström, T. W., and Erens, P. J., 2011, "A Combined Latent Thermal Energy Storage and Steam Generator Concept Using Metallic Phase Change Materials and Metallic Heat Transfer Fluids for Concentrated Solar Power," *Proceedings of SolarPACES*, Granada, Spain.

Kumano, H., Asaoka, T., and Sawada, S., 2014, "Effect of Initial Aqueous Solution Concentration and Heating Conditions on Heat Transfer Characteristics of Ice Slurry," Int. J. Refrigeration, Vol. 41, pp. 72-81.

Lemofouet, S., and Rufer, A., 2005, "Hybrid Energy Storage System based on Compressed Air and Super Capacitors with MEPT," *Proceedings of the International Power Electronics Conference*, pp. 461-468.

Lippiatt, B., 2007, *Building for Environmental and Economic Sustainability (BEES) 4.0 software*, National Institute of Standards and Technology, http://www.bfrl.nist.gov/oae/software/bees/.

Lo´pez-Navarro, A., Biosca-Taronger, J., Torregrosa-Jaime, B., Martı´nez-Galva´, I.,Corbera´ J. M., Esteban-Matı´ J.C., and Paya´, J., 2013, "Experimental Investigation of the Temperatures and Performance of a Commercial Ice-Storage Tank," Int. J. Refrigeration, Vol. 36, pp. 1313-1318.

Lundy, D. R., Swartzendruber, L. J., and Bennett, L. H., 1989, "A Brief Review of Recent Superconductivity Research at NIST," J. of Research of the National Institute of Standards and Technology, Vol 94, No 3, pp. 147-178.

Martin, G. D., and Barnes, F. S., 2007, "Aquifer Underground Pumped Hydroelectric Energy Storage," In Proceedings of the Electrical Energy Storage Applications & Technologies Conference, San Francisco.

Nguyen, T., and Savinell, R. F., 2010 "Flow Batteries," The Electrochemical Society Interface, fall issue, pp. 54-56.

Pedram, M., Chang, N., Kim, Y., Wang, Y., 2010, "Hybrid Electrical Energy Storage Systems", ISLPED, Proceedings of the 16th ACM/IEEE international symposium on Low power electronics and design, Pages 363-368, August 18-20, 2010, Austin, Texas USA.

Pilar, F. L., 1979, "Chemistry, the Universal Science," Addison Wesley, Reading, MA, p. 376.

Pinel, P., Cruickshank, C. A., Beausoleil-Morrison, I., and Wills, A., 2011, "A Review Of Available Methods For Seasonal Storage Of Solar Thermal Energy In Residential Applications," Renewable and Sustainable Energy Reviews, Vol. 15, No. 7, pp. 3341–3359.

Pless, S., and Torcellini, P., 2010, "Net-Zero Energy Buildings: A Classification System Based on Renewable Energy Supply Options," Technical Report NREL/TP-550-44586, p. 2.

Reading, M. M., 2004, "Flywheel Energy Storage System,' California Energy Commission, Sacramento, CA.

Scaini, V., 2012, "Grid Support Stability For Reliable, Renewable Power," White Paper WP083002EN.

Sharma, A, Tyagi, V.V., Chen, C.R., Buddhi, D., 2009, "Review on thermal energy storage with phase change materials and applications," Renewable and Sustainable Energy Reviews, Vol. 13, No. 22, pp. 318–345.

Simmonds, A. G., Griebel, J. J., Park, J., Kim, K. R., Chung, W. J., Oleshko, V. P., Kim, J., Kim, E. T., Glass, R. S., Soles, C. L., Sung, Y-E., Char, K., and Pyun P., 2014, "Inverse Vulcanization of Elemental Sulfur to Prepare Polymeric Electrode Materials for Li−S Batteries," ACS Macro Lett, 3, pp. 229−232.

Wang, H., Wang, L., Wang, X., and Yao, E., 2013, "A Novel Pumped Hydro Combined with Compressed Air Energy Storage System," Energies, Vol. 6, pp. 1554-1567.

Webb, R. L., and Kim, N-H., 2005, Principles of Enhanced Heat Transfer, 2nd ed., Taylor & Francis, New York.

Whittemore, H. L., Phelan, V., B., and Dill, R. S., 1943, "Structural and Heat-Transfer Properties of "Multiple Box-Girder Plywood Panels" for Walls, Floors, and Roofs Sponsored by Loren H. Wittner," Washington, D.C.: U.S. Dept. of Commerce, National Bureau of Standards.

Zarr, R. R., 2001, "A History of Testing Heat Insulators at the National Institute of Standards and Technology," ASHRAE Transactions, Vol. 107, Pt. 2.

Zhai, Z., Abarr,M. L., AL-Saadi, S., N., and Yate, P., 2013, "Energy Storage For Residential Buildings: Review And Advances," *APEC Conference on Low-carbon Towns and Physical Energy Storage*, Changsha, China Paper ID: ACLE2013-E08-10

Zheng, M., Meinrenken, C. J., and Lackner, K. S., 2014, "Electricity storage in buildings for residential sector demand response: Control algorithms and economic viability evaluation," NIST GCR in review, Washington D.C.

Zimmerman, K. H., 1986, "Heat Pump Water Heater Laboratory Test and Design Model Validation," Oak Ridge National Laboratory, ORNL/CON-173.