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# THERMAL ENERGY STORAGE AND COOLING LOAD RESPONSE

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## Abstract

Thermal Energy Storage (TES) and Demand Response (DR) offer unique benefits to reducing the electricity consumption, carbon emission, investment, and operational cost of generating cooling energy by bridging the gap between cooling energy demand and production. To provide comprehensive guidance to policymakers, system planners, investors, clean energy advocates, and other relevant parties to accelerate the development of TES and DR technologies, this paper provides a comprehensive overview of the most common TES and DR strategies for cooling purposes, covering the working principles, advantages, development stages, technical limitations, suitable applications, and potential growth opportunities in the transition towards low carbon economy. The research directions and policy recommendations are also discussed for better TES and DR development and deployment, especially in Asia. Energy users and system planners can choose the most suitable TES and DR technology to reduce electricity consumption and carbon emissions for their energy systems, while policymakers, investors, and clean energy advocates can contribute to removing the economic, regulatory, or customer-related barriers to TES and DR deployment, which will jointly help fully release the enormous economic and environmental potential of TES and DR technologies.

**Keywords:** thermal energy storage, demand response, phase change materials, low carbon, clean energy

**JEL Classification:** O, O3, O31

# Contents

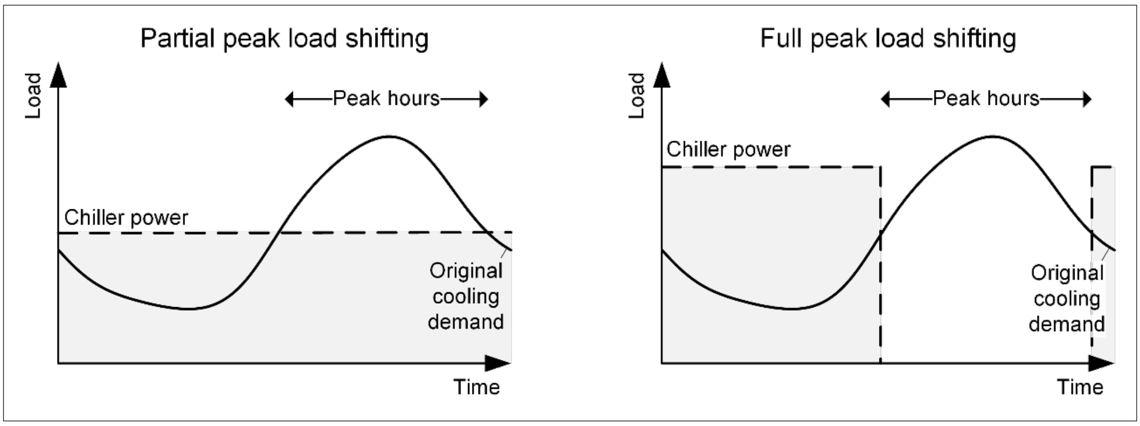
# 1. INTRODUCTION

Besides reducing cooling demand, improving cooling efficiency, and searching for alternative resources for cooling, another important method to reduce the electricity consumption, cooling emissions, investment, and operational cost of generating cooling energy is to bridge the gap between cooling energy demand and production.

Mainly dependent on the environmental temperature and user activities, cooling demand varies hourly, daily, and seasonally. This variable demand requires chillers to operate during peak hours when the electricity tariff is higher, and efficiency is lower due to higher environmental temperatures, which leads to higher operational costs, strain on the utility grid, and more carbon emissions. In some extreme cases, unexpected climate incidents such as extreme heat waves can cause excessive cooling demand and lead to blackouts in the utility grid (California ISO 2021). Moreover, the total capacity of the chiller should be sized according to the peak demand, which leads to higher investment costs and possible low-efficiency operations.

Without sacrificing thermal comfort, demand side energy management tactics can be used to reduce the costs and emissions caused by varying cooling energy demands. By reducing only 10% of the peak demand for 60 hours a year, 5,000 megawatts or 50 100-megawatt peak demand power plants can be saved in the United States, which is either unused or operates inefficiently during off-design working conditions most of the time (Hirsch et al. 2011). This is equivalent to around 0.5% of the total power generation capacity in the United States and 5% of peak demand. The primary tactic suitable for cooling is peak load shifting. In general, peak load shifting strategies try to smooth the load profiles, reduce chiller power during peak periods, and operate the chillers during off-peak periods when the electricity tariff is lower and chiller efficiency is higher. As shown in Figure 1, peak load shifting can be partial or full, depending on whether or not the chiller is operated during peak hours. These strategies can be achieved through 1) thermal energy storage (TES), by generating cold energy during off-peak hours, storing the cold energy, and using the cold energy to meet cooling demand during peak hours; or 2) through demand response (DR) by mitigating the cooling demand profile and moving some demand from peak hours to off-peak hours.

**Figure 1: Peak Load Shifting Strategies: Partial (*left*) and Full (*right*)**



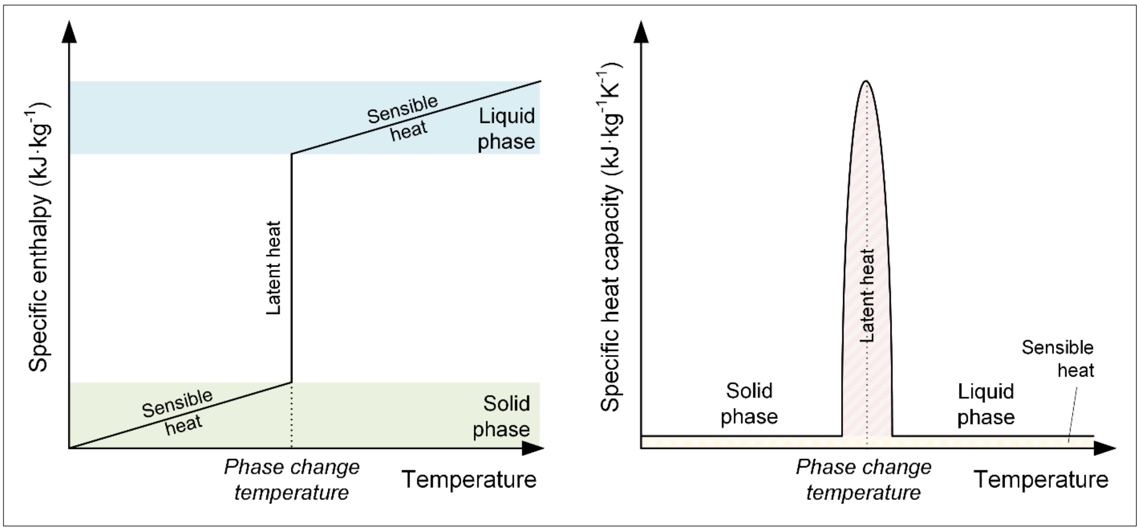
Note: The solid lines represent the original cooling demand profiles. The dashed lines and shaded areas denote the actual chiller power. By using thermal energy storage or demand response strategies, the cooling load during peak hours can be partially or fully shifted to off-peak hours. Thus, part or all of the cooling energy can be produced when the electricity tariff is lower and chiller efficiency is higher, without sacrificing user welfare.

## 1.1 Thermal Energy Storage

TES stores heat and cold energy in the form of sensible, latent, and thermochemical heat or couples with mechanical systems (such as turbines and compressors) to store electricity. Compared to electrochemical energy storage technologies, such as Li-ion batteries and flow batteries, thermal energy storage offers a more cost effective and direct solution in terms of storing heat and cold, which represents the largest share of global final energy consumption (around 50%) and energy-related carbon emissions (around 40%) (International Renewable Energy Agency [IRENA] et al. 2020). The global installed TES capacity is expected to increase threefold by 2030 due to its unique benefits of seasonal capability, large storage capacity, the potential for higher round trip efficiency, and longer life cycles (IRENA 2020).

The most mature and widely used TES solutions can be divided into two categories depending on the storage material used, which may or may not change phase. The first category uses the sensible heat of materials, where the cold is stored and released when the temperature of the material decreases and increases without changing phase—that is, without freezing/melting or evaporating/condensing. The energy stored in the material is the production of the material mass, temperature change, and specific heat capacity. The most common examples of sensible heat storage materials are chilled water, rocks, concrete, and building mass. The second category of TES for cooling uses latent heat, which is the energy stored and released during the material phase change, especially between the solid and liquid phases. Latent heat TES uses phase change materials (PCMs), such as ice, water salt solutions, and organic eutectics. As illustrated in Figure 2, the temperature stays approximately constant during phase change, and the energy that can be stored or released during the phase change is significantly higher than the sensible heat. Hence, latent heat TES generally has a larger energy density, while sensible heat TES is simpler in construction and operation.

**Figure 2: An Illustration of the Working Principle of a Solid–Liquid PCM with the Specific Enthalpy in kJ·kg$^{-1}$ (*left*) and Heat Capacity in kJ·kg$^{-1}$K$^{-1}$ (*right*) with Respect to the Temperature**



Note: In the diagram on the right, the peak curve indicates the phase-changing process. The integration area (pink) beneath the peak curve is the latent heat of fusion during the phase-changing process. As can be seen in both diagrams, the latent heat is significantly larger than the sensible heat.

## 1.2 Demand Response

While TES shifts cooling energy production and does not affect the demand profile of the users, the users of DR can manually adjust or willingly permit automated shifts in their demand profiles in return for lower energy costs or cash incentives (Clean Energy Ministerial 2014; Segu 2012). DR relies on the premise that the users need cooling services instead of the cooling energy itself. Because it takes time for the temperature of the indoor environment and cold storage facilities to increase, the thermal inertia of the building mass and the insulation layers of cooling devices are used as a buffer when shifting cooling demands without compromising cooling service levels.

TES and DR can also work together. For example, when grid strains are in high demand for air-conditioning during the summer, DR programs pay facilities to reduce peak energy consumption. With a TES supplying the cold energy that is stored during off-peak hours, the unused peak-hour electricity capacity can be sold back to the grid. Therefore, the combined forces of TES facilities storing cold energy and DR programs controlling cold demand form a virtual power plant, so building occupants can stay cool and comfortable while lowering peak energy use on the grid. This encourages less energy use during peak times, leads to lower energy bills, and generates profits. Moreover, shifting the cooling loads can result in better utilization of highly intermittent renewable power sources such as photovoltaic and wind for cold energy production. As described by IRENA (2020), by decoupling cold energy production from utilization through hourly, daily, and even seasonal load shifting, more renewable sources can be connected to the power grid without causing grid congestion and extra infrastructure investment. TES and DR can thus help realize a smooth transition towards future energy systems with a higher share of renewables in the energy mix.

This paper introduces the most common TES and DR technologies for cooling purposes, including chilled water, ice, other PCMs, building mass, and cryogenic energy storage technologies, as well as cooling load response technologies and applications, covering the basic working principles, advantages, development stages, technical limitations, research directions, suitable applications, and potential growth opportunities in the transition towards a low carbon economy in Asia.

# 2. CHILLED WATER STORAGE

Chilled water storage is the simplest and most widely used form of TES for demand side cooling energy management. This mature and proven technology has been developed for over 30 years worldwide. Chilled water storage uses the sensible heat of water to absorb and release cold energy. The high specific heat capacity (around $4.2\ \mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$) and low cost of water make it an ideal sensible TES material for cooling applications.

Compared to the other TES technologies, chilled water storage has several obvious advantages. First, chilled water storage is compatible with all types of chillers, so long as its operating temperature is above 0°C. Because it is a sensible TES technology, the temperature of chilled water storage can be adjusted according to user requirements, so it is compatible with most conventional water chillers and district cooling systems. Generally, chilled water is stored at around 5°C, with a return temperature at around 15°C, and a higher return temperature is always desirable to increase the temperature difference and reduce the storage tank size (Pacific Gas & Electric Company 1997).

Second, chilled water is widely used as the heat transfer fluid (HTF) for air conditioning systems in large-scale applications, such as commercial and industrial facilities, the central cooling systems of buildings, data centers, and district cooling systems. Installing a secondary heat transfer loop and retrofitting the chillers can be avoided by directly storing the HTF. Moreover, saving time in overcoming the thermal inertia of a second HTF enables chilled water storage to have a short response time and discharge rate, making it especially suitable for shorter duration applications (30 minutes to 2 hours) (Valenta 2021).

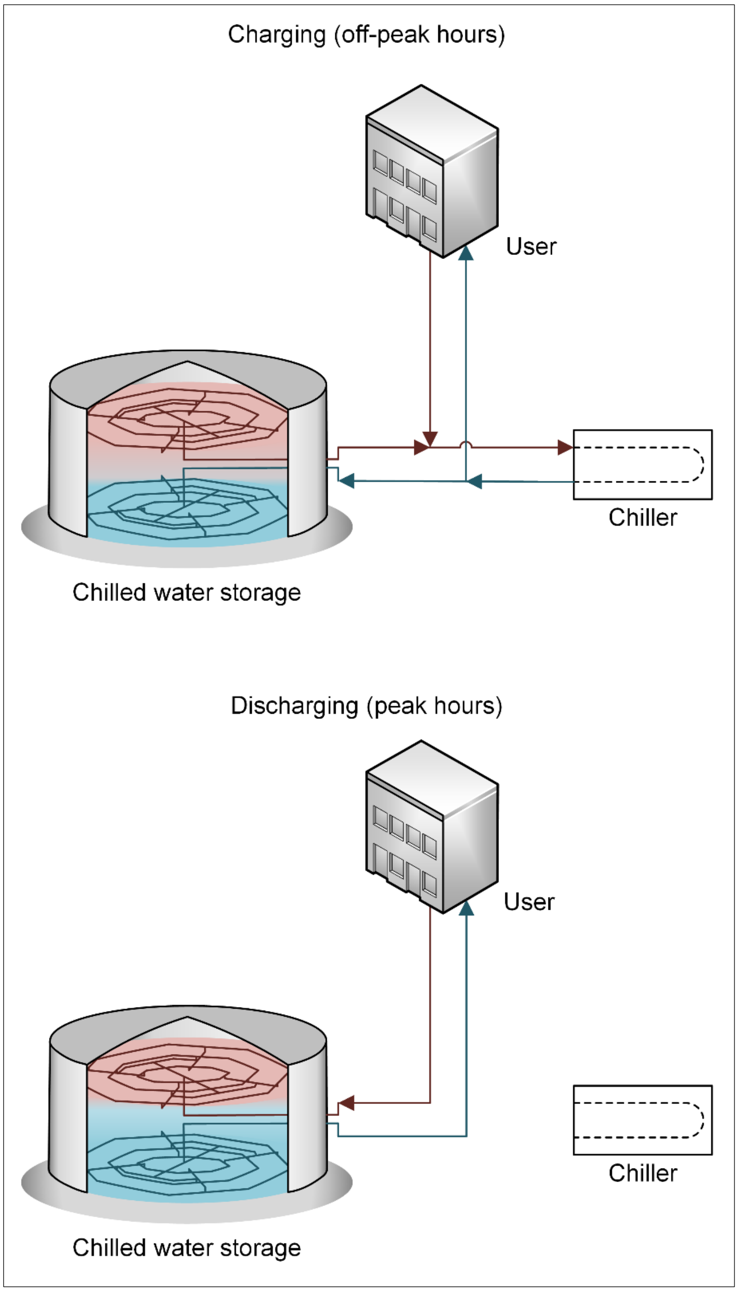
A base-load chiller unit for chilled water production for district cooling. Chilled water storage can directly be connected to the unit without extra retrofitting (*image courtesy of Jianping Fu, Shenzhen Qianhai Energy Technology Development Co., Ltd.*).

Third, water is hazard-free to the environment. The leakage of water from the heat transfer or storage systems will not pose extra environmental or human health threats. Moreover, if the purity of the water can be properly controlled (especially in terms of the reduction of chloride ions), water is less corrosive to the piping and containment materials than other TES materials, especially eutectic salt solutions.

Finally, water is among the most affordable TES materials. The cost of chilled water storage facilities can be even lower if constructed at large scales. It is thus especially suitable for large-scale applications, such as data centers that have sufficient space for a large tank (Valenta 2021). Chilled water storage can also be used to supply redundant cooling capacity during emergency issues for data centers, which require non-stop operation during its service time.

However, the disadvantages of chilled water storage are equally manifest. The energy density of chilled water storage is about 8 to 10 times smaller than for latent heat TES technologies. Chilled water storage thus has to come with much larger storage facilities. The volume of a typical chilled water storage tank can be thousands of cubic meters and beyond, causing a significant footprint (approaching 10 or more meters in height) that is also quite heavy (thousands of tons), which makes them less movable and leads to longer installation times (Valenta 2021). Because they operate in atmospheric pressure, chilled water storage also faces challenges in working with pressurized pipes in high-rise buildings. Chilled water storage is thus less suitable for densely populated areas, such as metropolitan districts with less storage outdoor space, and for small-scale applications, such as household roof-top installations.

**Figure 3: Operation of a Chilled Water Storage System (Full Peak Load Shifting)**



These disadvantages may form pose challenges when deploying chilled water storage, especially for large Asian cities with tens of millions of people or in dry environments where water resources are scarce. However, it is one of the most cost-effective storage technologies for industrial parks and rural areas. With continued population growth and economic development, especially in the developing countries of Southeast Asia, significant growth in chilled water storage facilities can be foreseen in the near future with the rapidly growing cooling demand.

The operation of chilled water storage is similar to that of other TES technologies, except that because chilled water is used as both the HTF and the TES material, there is no need to deploy an extra heat exchanger. For example, in full peak load shifting mode, during off-peak hours, the chillers produce cold energy and supply the chilled water to users. Excess chilled water production is stored in the chilled water storage tanks. This process is also called the charging phase for the storage tanks. During peak hours, the chillers are turned off, and the chilled water stored in the storage tanks is discharged from the storage tanks to meet users' cooling demand.

As summarized in Tables 1 and 2, various types of chilled water storage tanks have been developed in the past decades, from various containment materials. Most chilled water storage tanks are deployed outdoors, either above or underground; the tops of the outdoor storage tanks can even be used to host photovoltaic panels (Valenta 2021). The major difference in storage tank types is how to separate the cold water ready to supply the users with the return water from the user. Because chilled water storage tanks are usually considered to be permanent installations compatible with consistent cold demand for the foreseeable future (Valenta 2021), the design of a storage tank should be durable throughout the service time, with low maintenance costs. The most favorable and widely adopted tank type is the thermally stratified tank (also called a thermocline tank) due to its simplicity and low cost. The design of the thermally stratified tank takes advantage of the thermocline effect, which uses natural stratification to separate hot and cold water from each other. The density of the colder water is higher than that of the hotter water. Hence, as illustrated in the tank schematics in Figure 3, the cold supply water stays at the bottom of the tank, and the hot return water remains at the top. However, internal flow between the top and bottom parts, which mixes the hot and cold water, may still equalize the temperature distribution, increasing the temperature of the chilled water and causing the usable energy stored in the tank to decrease. To overcome this problem of storage density degradation, specially designed diffusers (illustrated in the spider net–shaped pipes in Figure 3) are often used to gradually charge and discharge the water with a low flow velocity in the vertical direction (Pacific Gas & Electric Company 1997). This can minimize mixing and allow the thermocline to be kept.

Due to the high mutuality of chilled water storage tanks, future research can focus more on their applications in modern energy systems, especially in district cooling systems for industrial, commercial, and residential areas. For countries with significant seasonal temperature variations, studies about combining chilled water storage for the summer with hot water storage for the winter can be carried out. Long-distance transportation of chilled water is also worth investigating, particularly for using alternative sources to supply cold energy, such as that currently wasted during the regasification of liquefied natural gas (LNG), as shown in the following case study.

### Table 1: Chilled Water Storage Tank Types

| Chilled Water Storage Tank Type | Description |
|---|---|
| Thermally Stratified (or Thermocline Tank) | A thermally stratified tank is the most common design used for chilled water storage. Thermal stratification relies on the difference in density between the cool supply water (high density, bottom of tank) and the warm return water (low density, top of tank) to maintain the separation of the two temperature zones with no physical barrier. The separation zone is characterized by a sharp temperature gradient or thermocline. |
| Membrane or Diaphragm Separation | This design uses a flexible membrane to separate the cool supply water and the warm return water. The membrane, or diaphragm, moves up and down during charging and discharging. This design is prone to mechanical problems such as jamming of the diaphragm. |
| Empty Tank (or Two-Tank) | A simple empty tank configuration consists of two tanks: one to hold cool supply water and one to hold warm return water. In a two-tank design, both tanks need to be sized to hold the entire water capacity. Two-tank designs thus require more space and are more expensive than a single thermally stratified tank design. Multiple-tank designs have also been used. |
| Labyrinth Tank | Labyrinth tanks use multiple compartments in a horizontal configuration, with water flowing from cell to cell. Labyrinth tanks are most common in high-rise buildings that can incorporate the tanks in the foundation. A drawback of labyrinth tanks is that temperature mixing occurs between the warm return water and the cool supply water. |
| Baffle-and-Weir | These tanks consist of internal walls with water flowing over a wall to one cell, and then under a wall to the next cell. A drawback of baffle-and-weir tanks is that temperature mixing occurs between the warm return water and the cool supply water. |

Source: Adapted from Lindsay et al. (2019) and US Department of Energy (2016).

### Table 2: Containment Materials for Chilled Water Storage Tanks

| Containment Material | Advantages | Disadvantages |
|---|---|---|
| Welded Steel | • Low initial cost | • High maintenance costs<br>• Corrosion issues<br>• Out of service time |
| Conventionally Reinforced Concrete | • More adaptable with water<br>• High availability of the material<br>• Widely used in the area | • Concrete in tension<br>• Congestion of rebar<br>• Liners and coatings<br>• Rectangular shapes |
| Internal Post-Tensioned Concrete | • Concrete in compression | • Tendon ducts<br>• Base joints<br>• Liners<br>• Repair is difficult |
| External Pre-stressed Concrete | • Lowest total cost of ownership<br>• Complete compression<br>• No maintenance<br>• High speed of construction | • Potential for higher initial cost |

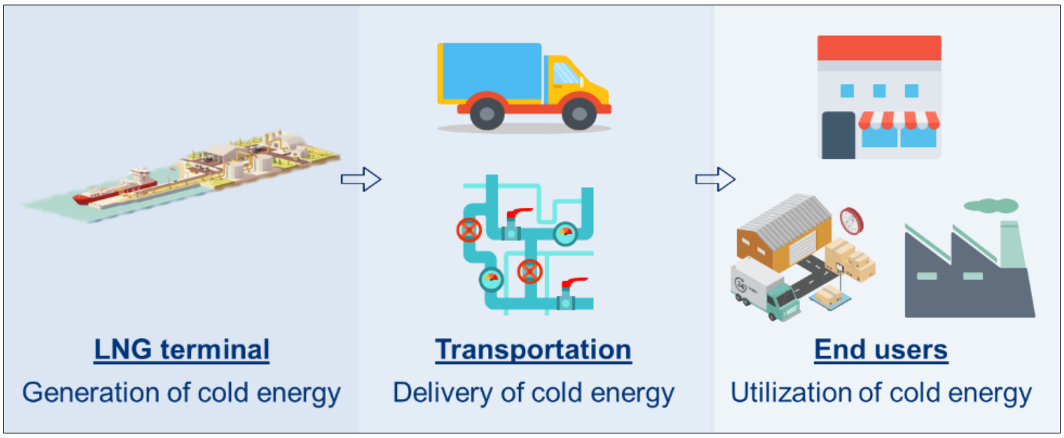
Source: Adapted from Somarriba (2012).

## Box 1: Case Study: Chilled Water Production Using LNG Cold Energy

After extraction, natural gas is processed and transported from the production wells to the end users. Most of natural gas is transported in gaseous form via pipelines or in liquid form via LNG vessels. After being liquefied to around −162°C, the volume of natural gas can be reduced by several hundredfold. LNG is thus a low-cost and safe method for natural gas transportation and storage (US DOE n.d.) that is particularly suitable for international energy trade. Mainly driven by the strong increase in LNG demand in Europe and Asia, the International Energy Agency (IEA 2019) and Royal Dutch Shell (2021) estimate that the global LNG trade may overtake pipelines to become the major form of natural gas transportation in less than ten years, and increase by around 100% within twenty years from now.

Once arriving at the receiver terminal, LNG needs to be regasified back into its gaseous form at ambient temperature. The heat sources for regasification are often ambient air or saltwater. The high-grade cold energy of LNG (about 830 $kJ \cdot kg^{-1}$ of LNG) is generally wasted. If the cold energy could be harvested at the LNG terminals and transported to cold energy end users through pipelines or trucks, it could be utilized for a variety of purposes, such as cryogenic power production, space and industrial process cooling, cold supply chain, air separation, seawater desalination, and waste treatment (Hirakawa and Kosugi 1981; Kanbur et al. 2017; He et al. 2019), leading to a novel concept of an LNG-based cold economy, as illustrated in the figure (L. Yang, Villalobos, et al. 2021).

### Figure: Concept for an LNG-Based Cold Economy



The most straightforward way to use LNG cold energy is to connect the LNG terminal, where the cold energy is generated, to the end users via chilled water energy storage systems. LNG cold energy could be used to produce the chilled water instead of the chillers in a conventional cooling system involving chilled storage, as illustrated in Figure 3. Because LNG supply profiles vary drastically (Xiao et al. 2022), chilled water storage can compensate for the mismatch between the LNG cold energy supply and user cooling demand, which would allow for users to fully use the available LNG cold energy. The system, when combined with chilled water pipes, could also be transformed into a district cooling system, supplying low-emission and nearly free cold energy to industrial, commercial, and residential users. This concept could also be applied to harvest and utilize the cold energy in future liquid hydrogen (LH2) energy systems.

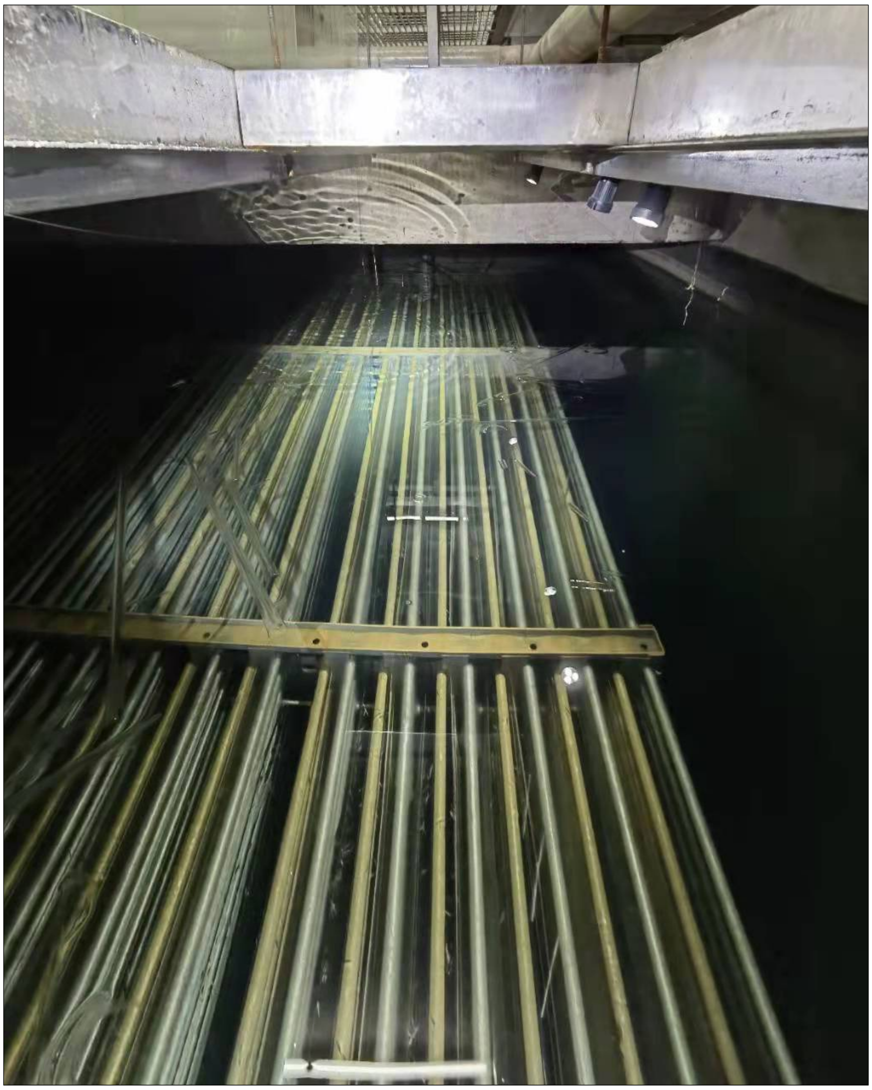
# 3. ICE STORAGE

Both ice and chilled water are excellent TES materials. However, a chilled water system would be better choice in buildings such as data centers have loads with a very short duration (30 minutes to 2 hours) due to the faster discharge rates. Ice storage systems have a much higher heat absorption capacity as an efficient cooling storage medium in applications with longer loads duration, such as large and taller multi-story buildings. Ice is a PCM. Cold TES systems applying ice can store and release 334 $kJ \cdot kg^{-1}$ during a cycle of melting and freezing, whereas chilled water systems can store only about 80 $kJ \cdot kg^{-1}$ of energy considering a temperature difference of 20°C. Therefore, ice storage tanks are usually 8–10 times smaller than chilled water storage tanks, making them modular, re-deployable, and more suitable for small capacity applications, where the tanks can be installed on roofs, indoors, in basements, or outdoors (Valenta 2021). In most ice storage systems, only a simple shift (one-third of the cooling requirements) can reduce bills by up to 40%, because off-peak electricity prices have not increased in the last 40 years in the United States when converted to today's dollars (Sharma et al. 2009).

These merits make ice storage an ideal solution for small scale applications in Asia, especially for metropolitan areas with tens of millions of people and limited living spaces. The payback period for an ice storage system can be as short as three to five years (Valenta 2021). Due to the rapid increase in demand for cooling and more renewables in Asian power grids, a new wave of deployment in ice storage can be expected. However, the designer or the user of the ice storage system should pay more attention to real-time electricity price signals if operating the system for peak load shifting. Because ice storage requires lower temperature and higher energy cost, incorrect operation strategies can lead to higher operation costs and longer payback periods.

Ice stores and releases the cold energy at around 0°C. If using ice storage for indoor cooling purposes requires a chilled water supply at around 6°C–12°C, the chiller has to operate in a lower temperature to charge the ice storage, thus resulting in less efficient operation and high electricity consumption. In some systems, a dual working-condition chiller is employed to simultaneously produce chilled water at 6°C–12°C and HTFs at sub-zero temperatures to charge the ice storage tanks with high efficiency. The demand for dual working-condition chillers and HTFs leads to an increase in the cost of investment.

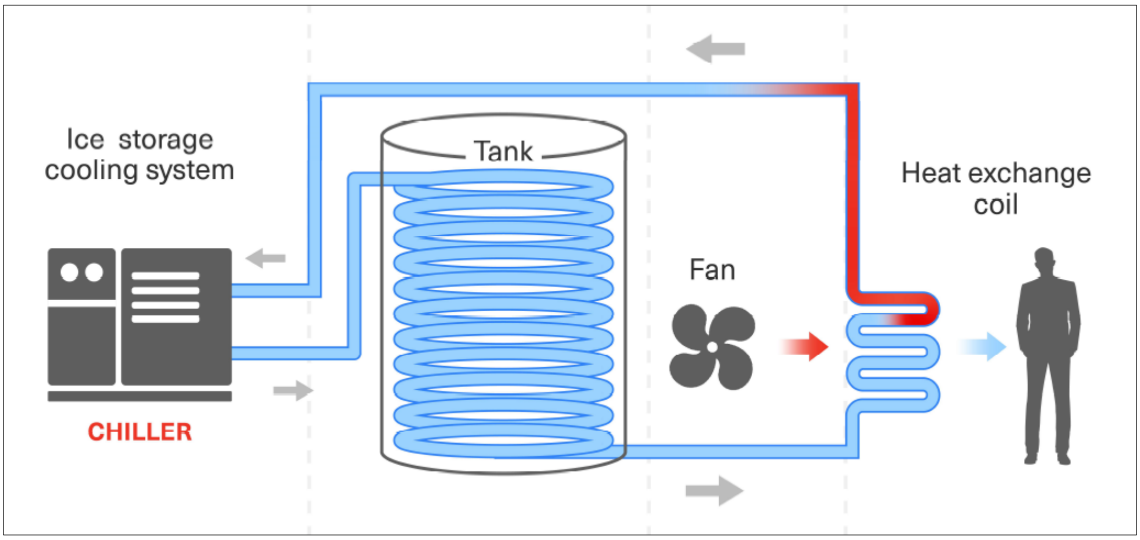
There are various ice storage technologies such as ice-on-coil, ice slurries, ice banks, and ice packs. In the ice slurry technology, the ice is part of the HTF, and the main part of the heat stored is transferred out of the storage facility. In this case, the heat storage and heat transfer medium become one fluid that is always liquid and has a component that stores latent heat. In another technique, the bulk storage system of encapsulation consists of using tank heat exchangers for ice. The problem with ice bulk systems is the need for an extensive heat transfer area between the PCM (ice) and the HTF. Inserting fins or using high conductivity particles, metal structures, or fibers in the PCM (ice) side or direct contact heat exchangers are solutions to moderate this problem.



Ice storage facility for district cooling (*image courtesy of Jianping Fu, Shenzhen Qianhai Energy Technology Development Co., Ltd.*).

Ice banks, or ice-on-coil systems, are one of the most efficient thermal energy storage technologies applied in many building air-conditioning systems. During off-peak hours, typically during the nighttime, a solution of water ethylene or propylene glycol is cooled by a chiller, and the thermal battery is charged. There is a heat exchanger within the ice bank in which the solution circulates, as shown in the figure. Most of the water surrounding the heat exchanger inside the tank is frozen. The water surrounding the heat exchanger never leaves the tank. As the uniform ice forms inside the ice-bank tank via counter-flow-heat exchanger tubes, water still moves freely. That is the key to preventing damage to the tank. The full charging of a typical ice-bank system takes from 6 to 12 hours (Trane 2020). During daytime peak hours, the water-glycol solution circulates through the ice storage tanks and transfers the cold temperature to the building. In the final step, a fan blows air over the coils to deliver cooling to the building.

**Figure 4: Ice Storage Cooling System, Ice Bank**



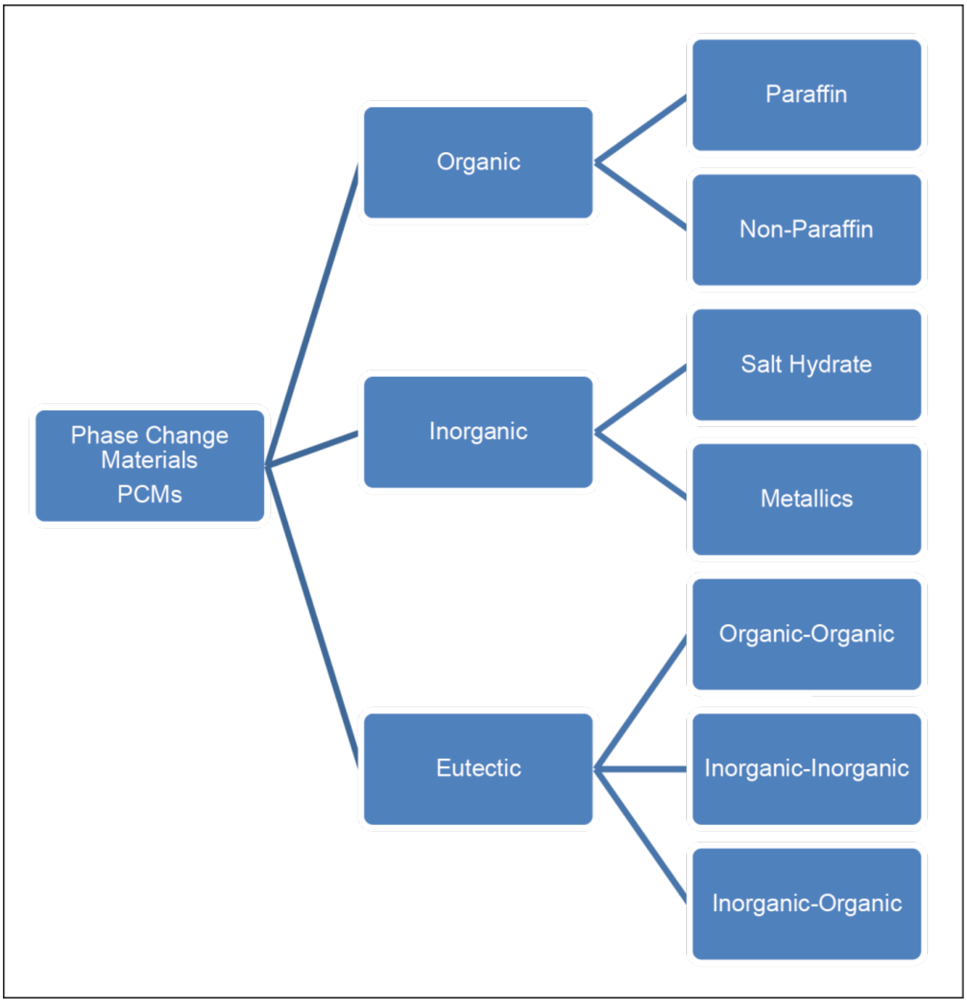
Source: Image courtesy of CALMAC®.

Similar to chilled water storage tanks, ice storage is also highly mature. Future research could focus on improving the storage system design to minimize the cost of investment, reduce the storage volume, enhance heat transfer, reduce the temperature difference between the HTF and the ice melting point, and combine the system with ice slurry facilities. More studies could also look at expanding its applications to more modern energy systems, especially in recovering the waste cold energy from cryogenic sources, such as the LNG and liquefied hydrogen.

# 4. OTHER PHASE CHANGE MATERIALS

Besides ice, various other PCMs with other phase change temperatures are also widely used for cooling purposes, and these represent another option to achieve better utilization of renewable energy and to improve energy efficiency (Chiu 2009; Sharma et al. 2009; Gao and Deng 2013). There are four general categories of PCMs according to phase change behavior: solid–solid, solid–liquid, solid–gas, and liquid–gas (L. Yang, Villalobos et al. 2021). The solid–liquid types are divided into organic, inorganic, and eutectic PCMs, as shown in Figure 5 (Chiu 2009; Sharma et al. 2009; Delgado et al. 2012; Gao and Deng 2013). Table 3 shows the comparison of these different kinds of PCMs (Sharma et al. 2009; Delgado et al. 2012; Gao and Deng 2013). In low-temperature industries, salt eutectic PCMs are applied for the temperature range of −60°C to 15°C. Organic PCMs, including paraffin and fatty acids (non-paraffin), have been applied for a temperature range of −110°C to 20°C (Socaciu et al. 2014; L. Yang, Villalobos et al. 2021). Figure 6 illustrates the heat of fusion, or the latent heat, of organic and inorganic PCMs according to the melting temperature ranges. In general, inorganic PCMs have a higher heat of fusion, while organic PCMs can reach colder temperatures. Among all types of PCMs, salt hydrates, eutectics, and paraffin are more applicable for refrigeration applications (Chiu 2009; Al-Abidi et al. 2012; Ling et al. 2014).

### Figure 5: Classification of PCMs

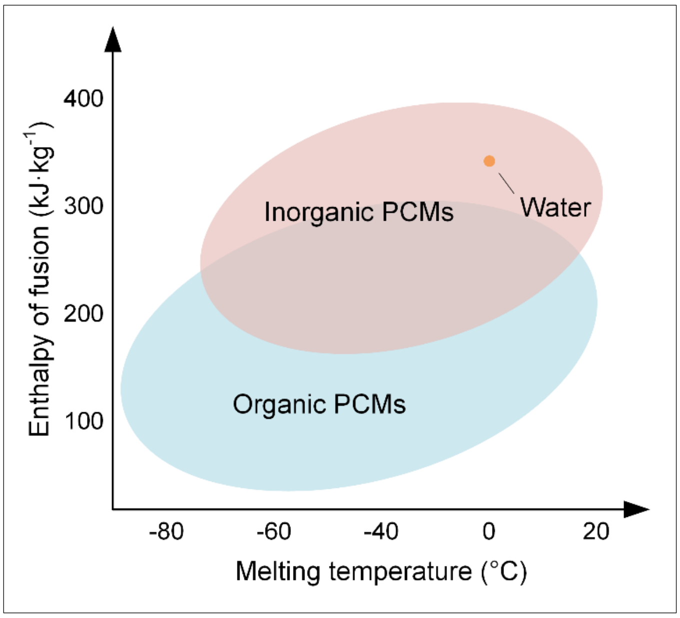


### Table 3: Comparison of Different Types of PCMs

| PCM Classification | Advantages | Disadvantages |
|---|---|---|
| Organic | Available in a large temperature range<br>Low or non-supercooling<br>Chemically stable and recyclable<br>Good compatibility with other materials | Low volumetric latent heat storage capacity<br>Low thermal conductivity<br>Relatively large volume change<br>Flammability |
| Inorganic | High heat of fusion<br>High thermal conductivity<br>Low volume change<br>Availability and cheapness | Supercooling<br>Phase separation<br>Lack of thermal stability<br>Corrosion |
| Eutectics | Sharp melting temperature<br>High volumetric thermal storage density | Lack of test datum for thermophysical properties |

Source: Chiu 2009; Sharma et al. 2009; Delgado et al. 2012.

### Figure 6: Latent Heat of Fusion and Melting Points of Low-Temperature PCMs



Note: In general, inorganic PCMs have higher enthalpies of fusion, while organic PCMs cover a wider temperature range.

Source: Adapted from Gao and Deng (2013) and Yang, Villalobos et al. (2021).

PCMs are widely applied in different areas, including thermal interface materials in electronic devices, heat exchangers, air conditioning, solar energy utilization, building energy-saving, medical applications, and textiles manufacturing (Farid et al. 2004; Delgado et al. 2011; Al-Abidi et al. 2012; Oró et al. 2012; Gao and Deng 2013). PCMs have recently attracted increasing attention in refrigeration and cooling applications, such as building air conditioning, process cooling, conservation and transportation of temperature-sensitive materials, food and pharmaceutical preservation in refrigerated trucks, cold stores, and storage warehouses (L. Yang et al. 2022). Because the food industry has a vital role in human health and is one of the largest electricity consumers, PCM application in TES in the frozen food storage industry is discussed in detail in the following case study. This application is novel throughout the world and is particularly suitable for developing Asian countries, where industries are growing rapidly.

### Box 2: Case Study: PCM Use in the Frozen Food Industry

In the warehouses of the frozen food industry, the sustainability and high performance of the refrigerated space used for the preservation of perishable products capitalize on conservation techniques that reduce environmental impact. This concept embraces a variety of techniques, including the replacement or supplementation of mechanical refrigeration systems by TES that incorporate PCMs and advanced refrigeration control. By using TES as a part of an integrated system, the overall efficiency can be improved, resulting in lower energy costs. In other words, TES systems integrate with existing refrigeration systems, controls, and racking structures. The technology is installed inside distribution centers, as well as commercial and industrial frozen food warehouses. The figure shows an installation of the Viking Cold Solutions Inc TES modules containing PCM above the storage racking in a food warehouse.

*continued on next page*

**Box 2** *continued*

TES modules containing PCM installed above food storage racking (*Viking Cold Solutions Inc. 2016*).

As shown in the figure, TES modules are installed above the product and inside the evaporator fans' air stream. This allows the heat to flow via convection to the TES when the air units are off. Once the TES modules reach their thermal capacity of absorbing heat, the airflow from the evaporator fans can efficiently and directly cool the cells back to solid state. The PCMs in the TES system provide latent heat capacity to the refrigerated environment, allowing the TES to absorb a large amount of thermal energy from the surrounding environment while remaining at the same temperature. These functions allow the refrigerated environment to maintain a cold operating temperature for an extended time without running mechanical systems. The freezer TES systems operate on a continuous 24-hour cycle. The latent heat capacity of the system reduces the frequency of compressor cycling by providing a larger heat sink on which the compressor can work while operating at a higher, more efficient suction pressure. This TES system absorbs and stabilizes up to 85% of the heat infiltration and allows refrigeration systems to be safely cycled off for up to 13 hours each day to avoid demand or time-of-use energy fees while maintaining stable temperatures. This technology reduces energy costs for cold storage operators by up to 50% (Viking Cold Solutions Inc. 2016).

In addition to this flexibility, TES systems increase refrigeration system efficiency by an average of 26% (Viking Cold Solutions Inc. 2016) by shifting the run time to the night and running compressors at maximum designed efficiency. This system improves temperature resiliency and stability in frozen food warehouses, reduces temperature fluctuations by half, and decreases temperature stratification. Furthermore, it has a three times longer temperature resiliency during power loss or equipment failure. PCM transfers heat in this system eight times faster than food, leading to minimization of micro-thawing and large crystal formation in the frozen food (Viking Cold Solutions Inc. 2016). This preserves food quality and shelf life. By utilizing TES, the room envelope efficiency is also effectively improved by limiting the impact of infiltration. Placing TES above the products, near the doorways, and along the ceilings or other sources of infiltration can reduce the impact of infiltration on stored product quality, as the TES absorbs infiltration more efficiently than the stored product.

A PCM product usually contains one or two base materials and a set of additives. The complexity in formulating and manufacturing can lead to more suitable phase change temperature ranges and even higher energy density than ice, but also to higher costs. Therefore, designing the storage facilities and energy systems associated with the PCMs should focus both on selecting the correct PCM and reducing the investment costs. The investment cost for the same TES unit can differ by up to three to four times due to differences in designs (L. Yang, Xu, et al. 2021). Future studies could focus on improving the design of PCM-based TES systems, as well as look for better applications and operation strategies.

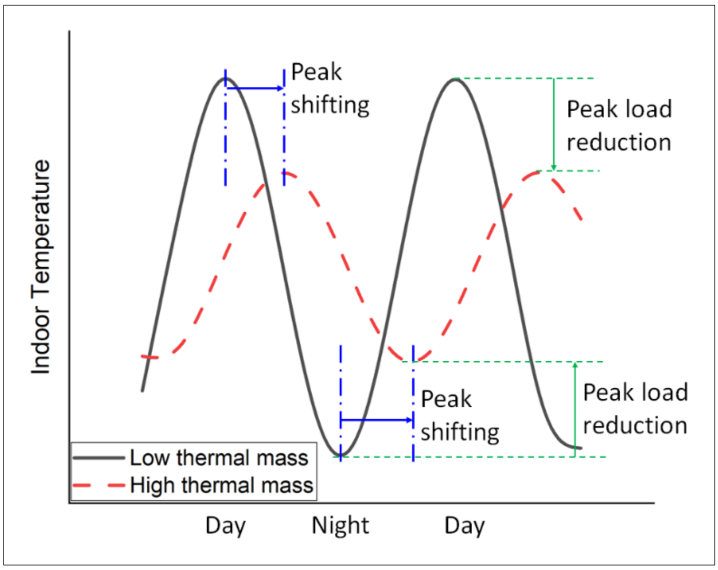
For deep-cold temperature ranges (below −60°C), the energy density and thermal conductivity of PCMs also decreases with the phase change temperatures, and many PCMs have corrosion, flammability, and even toxicity problems. More PCM formulas are therefore needed to increase the energy density and thermal conductivities, as well as to resolve health, safety, and corrosion issues (L. Yang, Villalobos et al. 2021).

# 5. BUILDING THERMAL MASS

Building thermal mass is the thermal inertia in building materials that can absorb, store, and release heat. These materials are heavy and dense or have high heat capacities. Common materials used for thermal mass include concrete, brick, or stone masonry, which are usually used in floors or walls. PCMs utilizing the high latent heat of fusion to store and release heat are considered a form of novel thermal mass for building applications, which can be used in floors, walls, or roofs.

To understand thermal mass, the concept of “thermal lag” needs to be introduced. Thermal lag is the rate of heat absorbed and released by a material. Materials with longer thermal lag times can absorb and release heat slowly. Larger thermal mass results in a longer thermal lag time (usually several hours, but less than half of a day), because thermal mass slows the material thermal response time. A large thermal mass can help shift and reduce peak loads for indoor temperature and thermal comfort control, as indicated in Figure 7.

**Figure 7: Indoor Peak Temperature Shifting and Reduction (Thermal Lag) Caused by High Building Thermal Mass**



Key factors affecting the performance of thermal mass materials are thermal conductivity, material thickness, density, and heat capacity (including the latent heat of fusion if PCMs are involved). In general, lower thermal conductivity, greater thickness, higher density, and larger heat capacity are preferred for thermal protection of the indoor environment. For example, lower thermal conductivity can result in a slower heat transfer rate for better insulation performance. A greater building thermal mass can store more heat and better protect the indoor thermal environment. The thickness of the building thermal mass also needs to be carefully designed. If the wall is too thin, it does not have enough mass to store and release heat, but if the wall is too thick, it may take too long to store heat and also increase the investment costs. Therefore, proper wall, floor, or roof thicknesses need to be optimized to achieve the best thermal protection performance instead of becoming a liability. Building thermal mass based on various types of sensible and latent heat materials is introduced in the following sections.

## 5.1 Cement, Masonry, and Wood

Conventional building construction materials, such as cement, masonry, and wood, have sensible heat storage capability, which can be affected by the moisture content, temperature, specific heat, and density of the material (Shafigh et al. 2018). Table 4 summarizes the thermal properties of some structural building materials. The specific heat of cement-based materials is higher than that of masonry materials and lower than that of wood. The density and thermal conductivity of wood are the lowest among these three types of building materials. Considering both heat transfer ($k$) and heat storage ($\rho c_p$) effects, the thermal diffusivity of wood is the lowest, which indicates the best thermal protection performance, although the thermal diffusivities of the three materials are in the same order of magnitude.

**Table 4: Thermal Properties of Structural Building Materials**

| | **Density ($kg \cdot m^{-3}$)** | **Specific eat ($J \cdot kg^{-1} \cdot K^{-1}$)** | **Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)** | **Thermal Diffusivity[a] ($m^2 \cdot s^{-1}$)** | **References** |
|---|---|---|---|---|---|
| Cement-based materials | 1,860–1,920 | 720–1,460 | 0.58–0.72 | $3.155 \times 10^{-7}$ | (Incropera et al. 2007; Shafigh et al. 2018) |
| Masonry | 1,860–2083 | 780–835 | 0.60–1.3 | $5.962 \times 10^{-7}$ | (Incropera et al. 2007) |
| Wood | 510–720 | 1,255–1,380 | 0.12–0.16 | $1.727 \times 10^{-7}$ | (Incropera et al. 2007) |

[a] Calculated based on the average $\rho$, $c_p$, $k$ values.

The moisture content in building construction material can also affect its specific heat value. The overall specific heat capacity includes the specific heat of the dry material and the heat capacity needed to drive off water content (Shafigh et al. 2018).

## 5.2 Water

Water has the highest specific heat among most materials and is substantially higher than conventional structural building materials (cement, masonry, and wood; see Table 4). Water can therefore be used as thermal mass in building to mitigate indoor temperature fluctuations remarkably. People have installed water-filled tubes in lightweight homes for micro-climate control. Because of the large heat capacity of the water storage medium, building masonry walls can have less mass and bulk, making the building more cost-effective (Australia Department of the Environment and Energy 2016).

## 5.3 PCMs

PCMs utilizing the latent heat of fusion during the phase changing process can significantly increase heat storage capacity compared to materials using sensible heat only (specific heat only, no phase change) for storage. Figure 2 illustrates the working principle for PCMs. The first documented use of a PCM for passive solar heating in a building took place in 1948 by Telkes (Kośny 2015). Since then, extensive studies have been reported on the incorporation of PCMs in building envelopes, such as walls, floors, ceilings, shutters, or windows, for better indoor thermal protection.

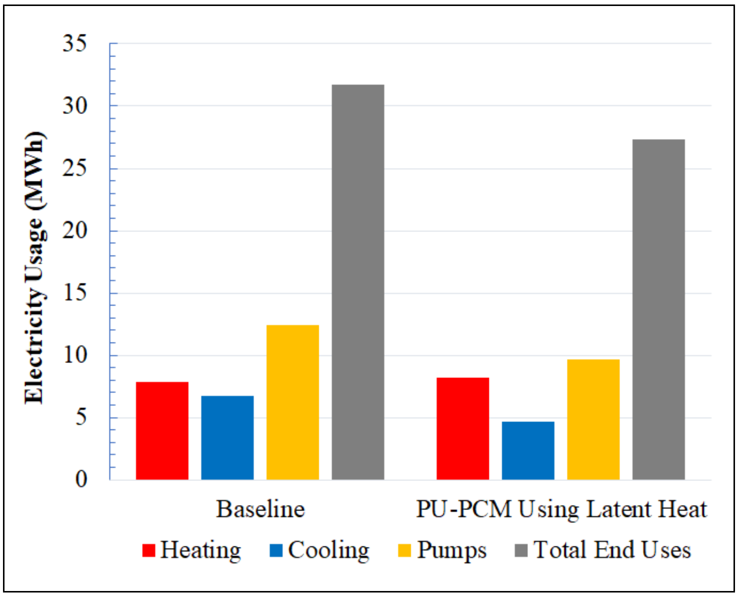
Generally speaking, conventional construction materials, such as gypsum board, concrete, cement, brick, plaster, and wood, can be used to hold PCMs (Kośny 2015; H. Yang et al. 2018). Panels made of other materials, such as polyvinyl chloride (PVC), honeycomb, plastic, stainless steel, and aluminum, can also be used to encapsulate PCMs (Kośny 2015). Other researchers have been studying the incorporation of PCM with insulation materials, such as polyurethane (PU) foam, fiberglass, cellulose fiber, and structural insulated panel (SIP), among others (MEDINA et al. 2008; Zhou et al. 2012; Kośny 2015). Several incorporation methods have been investigated and applied to incorporate PCMs with construction materials, including direct mixing PCM with building materials or immersion of building structure components in molten PCM; macroencapsulated, microencapsulated and nano-encapsulated PCM; and shape-stabilized PCM (Khudhair and Farid 2004; Raj and Velraj 2010; Kuznik et al. 2011; Zhou et al. 2012; Memon 2014).

Another novel approach is to increase the thermal mass of windows, by, for example applying PCMs, to further reduce the rate of heat loss or heat gain through the window (N. Soares et al. 2011, 2013; S. Li et al. 2013, 2014; Silva et al. 2016; Giovannini et al. 2017). By adding PCM (thermal mass) to the building envelope, around 1°C–5°C indoor peak temperature mitigation can be achieved (Schossig et al. 2005; Castell et al. 2010; Bragança et al. 2011; Hasan et al. 2016; Shi and Li 2021), a 2–3 hour delay for peak temperatures (Bragança et al. 2011; Hasan et al. 2016; Shi and Li 2021), and resulting building electrical energy savings of 15%–79% (Castell et al. 2010; Sayyar et al. 2014; Houl 2019) depending on the amount of PCM incorporated. Although the additional PCM could increase the initial capital cost of the building envelope, the payback period would be around five years based on the annual energy savings (Kosny et al. 2013).

## Box 3: Case Study: PCM in the Building Envelope

One case study is introduced to demonstrate how incorporating PCM in the building envelope promotes building energy savings. PCM (e.g., paraffin wax or fatty acids as bio-based PCM) was infiltrated in conventional building insulation material (such as PU foam) through a self-diffusion process. After the infiltration process, around 20 vol% of foam pores were occupied by PCM. The infiltrated PCM increased the thermal conductivity, but also significantly increased the heat capacity (thermal mass) due to the latent heat of fusion during the phase changing process. The large amount of latent heat could overcome the increased thermal conductivity of the composite material and remarkably slow down the heat transfer rate through insulation. The "effective" R-value (an indicator of the thermal resistance, defined as the thickness of the material divided by its "effective" thermal conductivity) was thus introduced to characterize the thermal performance of PCM-based insulation by considering the phase transition effect. With only 20 vol% of PCM infiltrated in the PU foam pores, an average "effective" R-value larger than 5.5 $m^2 \cdot K \cdot W^{-1}$ per 100-mm thickness could be achieved based on the thermal modeling for the PU-PCM composite–based SIP, which is higher than that of conventional PU foam without PCM (i.e., 3.3 $m^2 K \cdot W^{-1}$ per 100-mm thickness) (Houl 2019). Building energy modeling (BEM) was conducted for a 111 $m^2$ (1,200 $ft^2$) Zero-Energy (ZØE) lab building at the University of North Texas (Houl 2019) using the EnergyPlus simulation tool. This is an apartment-type building, and the PU-PCM composite was found to save around 30% of the annual cooling energy in the summer season, as shown in the figure. The heating energy usage did not, however, show a remarkable change when using PCM, because the melting point of the PCM was 25°C, which is suitable for peak temperature mitigation in the summer but is not applicable in winter. For winter, a PCM with a lower melting point is required.

**Figure: Annual Total Energy Consumption and HVAC Energy Consumption Breakdown in the ZØE Lab**



Note: Baseline: the current insulation in the ZØE building envelope, i.e., PU foam and batt insulation; PU-PCM Using Latent Heat: using PU-PCM composite to replace the current insulations in the ZØE lab (Houl 2019).

## 5.4 Current Challenges in a Deploying High Thermal Mass Building Envelope

A higher thermal mass in the building envelope can achieve more significant energy savings from heating/cooling loads, but high thermal mass materials result in increased costs, which is the main reason preventing their the wide usage in the building envelope, especially in developing Asian countries. PCMs have much higher volumetric enthalpy during phase changing process without significant temperature variation requirements, compared to other structural building materials and water storage mediums. The high volumetric latent enthalpy of PCM under melting/solidification leads to greater building thermal mass. Thermally speaking, PCM is a better building insulation material than other options; however, PCMs are expensive and subject to other technique issues when applied in the building envelope. Paraffin wax, for example, is a common organic PCM is produced from petroleum, which has negative impact on environment. Paraffin is also flammable, which prevents it from being widely usage in buildings. Obviously, paraffins are not a good choice.

Inorganic PCMs, such as hydrate salts, have potential in building applications because of their high volumetric latent heat, nonflammability, and low costs. However, hydrate salts have supercooling, phase separation, and corrosion problems and therefore require additional technologies to address these issues. It is possible to control the subcooling and phase separation problems by adding nucleate agents with a crystal structure similar to the corresponding PCM and thickening materials. Microencapsulated technology can also help mitigate these problems (Kosny et al. 2013). Hydrate salts can also be easily affected by moisture content in the environment because of their hydrophilic character. This could damage the material properties and cause severe mold and corrosion problems in the building envelope. To avoid direct contact with moist air, hydrate salts should be packed, vacuumed, and sealed or microencapsulated properly before being applied into the building envelope. These additional technologies could make the system complicated and therefore increase the cost of the final product. The development of low-cost, easy-to-manufacture, thermally and chemically stable additives and microencapsulation technology is vital for hydrate salts to be applicable in buildings (Kosny et al. 2013).

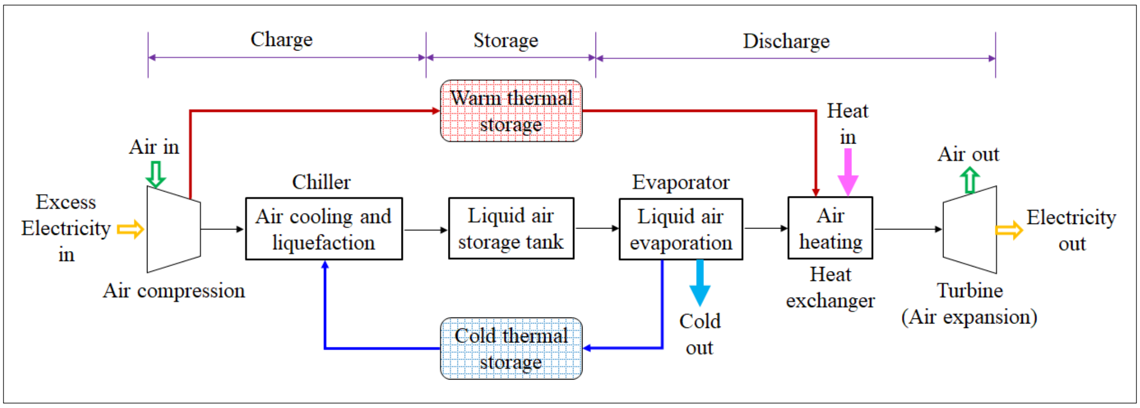
Bio-based PCMs, which are obtained from animal fat or plant oils, are renewable and sustainable products. They are environmentally friendly, nontoxic, thermally and chemically stable, have no corrosion issues, and have a greater degree of fire resistance. The authors therefore believe that bio-based PCMs are the most promising material for building thermal mass in the near future: they are great alternatives to paraffins and hydrate salts. Potential research opportunities for bio-based PCMs include further reducing the cost of products for building usage, especially in developing counties. The price of raw materials and manufacturing processes contributes to the cost of PCM products. The payback period for an attic when using PCM in the attic floor insulation could be less than five years in southern US climates, as the PCM price was around \$3.3/kg (\$1.5/lb) (Kosny et al. 2013). The cost reduction of PCMs is thus vital for massive usage in buildings. For instance, use of low-cost raw materials, such as waste cooking oils (WCOs) that are available everywhere in developing Asian countries, could further reduce the cost of bio-based PCM. This leads to the new research area on how to efficiently and effectively convert WCOs into useful PCMs.

# 6. CRYOGENIC ENERGY STORAGE

Cryogenic energy storage (CES) uses low temperature liquids (i.e., liquid air, nitrogen) as the storage medium in thermal-mechanical electricity storage systems. Liquid air is the most common working fluid for CES, also called liquid air energy storage (LAES). This technology is suitable for large-scale electricity storage and recovery. It can shift the excess electricity from off-peak to peak demand, thus improving the grid stability, promoting energy savings, and reducing greenhouse gas emissions. There are short-term and long-term energy storage technologies for various power plants applications. Short-term storage is used for daily electricity recovery. This technology can be used, for instance, to support a concentrated solar power plant in storing the excess electricity generated during the daytime for use after sunset. Long-term storage can also achieve seasonal electricity storage and shifting, allowing a wind plant, for instance, to store excess electricity during windy seasons for application in non-windy seasons.

LAES is a thermal-mechanical energy storage technology, which converts electricity to thermal and mechanical energy (charge), and then converts the thermal and mechanical energy back to electricity (discharge) when needed. Figure 8 shows a typical LAES process. Electricity is stored through compressed liquid air at a high pressure and low temperature (−195°C~15°C). The liquid air can be stored in a small volume container, which can be kept for a long time under atmospheric pressure and temperature. At times of high demand for electricity, the liquid air is pumped at high pressure into a heat exchanger that acts as a boiler. Hot air from the compression process, waste heat from the turbine or other industrial processes, renewable heat sources (such as geothermal energy), or even air from the atmosphere at ambient temperature can be used to heat the liquid air and turn it back into gas (Cetin et al. 2019; Highview Power 2022). The massive increase in the air’s volume and pressure (from liquid to gas) can drive the turbine for electricity generation (Highview Power 2022). Two TES systems (warm and cold) are integrated into the LAES system to shift the energy and increase its round-trip efficiency. The excess heat from air compression during charging can be stored in the warm thermal storage tank, and utilized for air heating during the discharging process. The cold energy from air evaporation during discharging can be stored in the cold thermal storage tank and used for air liquefaction in the chiller during the charging process. Because a turbine is involved in the LAES system, it can also be used to provide inertia to increase grid stability when large amounts of solar and wind power are connected.

**Figure 8: Process Flow Diagram of a Typical LAES Technology System**



LAES was first proposed by Smith in 1977 (Vecchi et al. 2021). Since then, several research groups have been studying various aspects of LAES and other CES technologies to improve their efficiency and promote usage for renewable energy storage, including working fluids, TES, and thermal energy utilization in other industrial applications.

***Working Fluids:*** Researchers have investigated various working fluids for CES systems, including not only air but also other gases (i.e., nitrogen, oxygen, argon, and methane). Methane (the major component in natural gas) was found to have the highest recovery and liquefaction efficiency as a working fluid and, therefore, the highest energy storage efficiency (Wojcieszak et al. 2017). Oxygen, having higher energy storage efficiency compared to air, could also be used as the working fluid for CES (Hu et al. 2017; Wojcieszak and Malecha 2018). Nevertheless, air is the most used working fluid for CES at present due to its availability everywhere with no cost.

***TES:*** A TES system is also vital for CES to store the produced heat and cold energy during charging (compression) and discharging (evaporation) periods for the usage in discharge (air heating) and charge (air liquefaction), respectively. A TES can help increase the efficiency of the CES system. A packed bed regenerator using quartzite rock particles or microencapsulated PCM have been considered as storage media for cold storage in CES systems (Wojcieszak and Malecha 2018; Morgan et al. 2020; Trivedi and Parameshwaran 2020).

***Excess Thermal Energy from CES for Other Industrial Applications:*** The cold energy generated from the evaporator can be used for industrial refrigerated warehouses, food chilling and freezing systems, cooling towers, and ice makers, among other applications (Fikiin et al. 2017; Murrant and Radcliffe 2018; Popov et al. 2021) The heat energy generated from air compression process can be stored in thermal oil (storage temperature up to 374°C), some of which can be applied as excess heat in the food industry (such as French fry producers) to accomplish washing, blanching, and frying processes, besides supporting the boiler for air heating in LAES (Popov et al. 2021). At low charging pressures, the LAES was found to be able to produce large amounts of excess heat. If effectively utilized, the LAES system can thus not only provide electricity, but also support cooling, heating, and hot water. Thus, the nominal round trip efficiency can reach 52%–76% if cooling, heating, hot water, and power supply are combined (She et al. 2020).

## 6.1 Current and Future Development of CES Systems

CES technology has drawing increasing attention recently. A 350-kW pilot-scale LAES power plant (with 2.5 MWh storage capacity) was designed and built in 2010 and successfully tested in 2013 by Highview Power and University of Birmingham (UK) (Damak et al. 2020; Vecchi et al. 2021; Highview Power 2022). Due to the small size of the plant, its round-trip efficiency was only around 8% (Damak et al. 2020). A 5 MW pre-commercial power plant (with 15 MWh storage capacity) was then built and operated in 2018 by Highview Power (Damak et al. 2020; Vecchi et al. 2021; Highview Power 2022). The plant is now in operation and providing power for around 200,000 homes per day (Damak et al. 2020). This pre-commercial power plant led to the recent deployment of two 50 MW commercial plants with LAES capacities up to 250–400 MWh in the United Kingdom and United States, which are expected to be operational in 2022 (Vecchi et al. 2021) as the first grid-connected LAES plants. With the development of commercial LAES plants, it is a 100 MW power plant with storage capacity from 600 MWh to in the order of GWh and a round-trip efficiency of >60% is expected in the future (Damak et al. 2020; Vecchi et al. 2021).

At present, no CES (e.g., LAES) power plant has been built in developing Asian countries. There is great potential to develop CES technology in Asian countries for large-scale electricity storage and continuous usage. This technology can be particularly integrated with renewable energy (e.g., concentrated solar, wind) power plants to increase capacity factors and therefore promote the growth of renewable energy power in the region.

# 7. COOLING LOAD RESPONSE AND APPLICATIONS

Similar to the various TES technologies mentioned above, DR can also shift chiller power. While TES helps users generate cold energy during off-peak hours and use the cold during peak hours, DR strategies focus more on the “voluntary and temporary” (Hirsch et al. 2011) mitigation of some cooling demand from peak hours to off-peak hours. Because users need the cooling service rather than the cold energy itself, DR works such that the cold energy generation can be mitigated without interfering with energy service provision with the help of thermal mass (Chase et al. 2017) or compromising service levels (Segu 2012). By reducing or postponing cooling power demand, DR offers benefits similar to TEST to the user and the utility grid. For users, DR reduces the operational costs and brings extra economic benefits related to cooling energy generation. For operators, DR contributes to renewable energy accessibility by avoiding curtailment of renewable sources by adding flexibility to the load (Swisher 2012), helping to stabilize the utility grid at fast time scales and to manage the network over longer time scales (Goldsworthy and Sethuvenkatraman 2020). For DR service providers, if adequate user capacity can be accumulated, they can be converted into a virtual power plant and participate in arbitrage in the power and carbon markets. Compared to battery storage systems, virtual power plants using TES and DR offer a more cost-effective solution than battery-based systems due to much lower costs (less than 0.1 USD/kWh) and much longer lifetimes (more than 20 to 30 years). Merchant battery banks already exist in liberalized power markets around the globe, and TES/DR could follow similar pricing structures and power purchase agreements. For global climate change actions, significant emissions due to cooling power generation can be reduced. A comparison of the TES and DR tactics for load shifting is presented in Table 5.

**Table 5: Comparison of TES and DR for Load Shifting**

| Performance and Impacts | Thermal Energy Storage | Demand Response |
|---|---|---|
| Impact on customer comfort or amenity | No impact | Limited, but declines with greater frequency and duration |
| Impact on end-use efficiency | Efficiency improves due to lower nighttime temperature. | Little efficiency gain, but some net energy savings from the unmet load |
| Round-trip storage efficiency | ~100% | Effectively 100% |
| Frequency | No limit (subject to cooling usage) | Usually maximum of 10–25 events per year |
| Availability and duration | Can be available at least 6 hours per day | Available 2–5 hours, may decline if called on consecutive days |
| Recovery | Storage recharge can be late at night, clearly off-peak | Recovery of thermal comfort increases energy use directly after the DR event |
| Usual annual hours of operation | 600–1,200 | 50–125 |
| Dispatchability | Can be dispatched daily, designed to run continuously 6+ hours | Can be dispatched quickly at any time, subject to frequency and duration limits |

Source: Adapted from Swisher 2012.

Depending on how, when, and by whom DR is managed, DR can be categorized into several types, as listed in Table 6. Some DR programs provide information to users so that they can decide when to turn their appliances off and on, while some DR services rely on programs and algorithms to make the decisions. In terms of timing, the DR programs can be static or dynamic, depending on whether the demand is changed at pre-set times or based on varying grid conditions. To attract customers to participate in DR programs, the usual stimuli are either price or incentive payments, while the information on environmental conditions or grid stability can also be considered (Chase et al. 2017).

**Table 6: Categories of DR Programs**

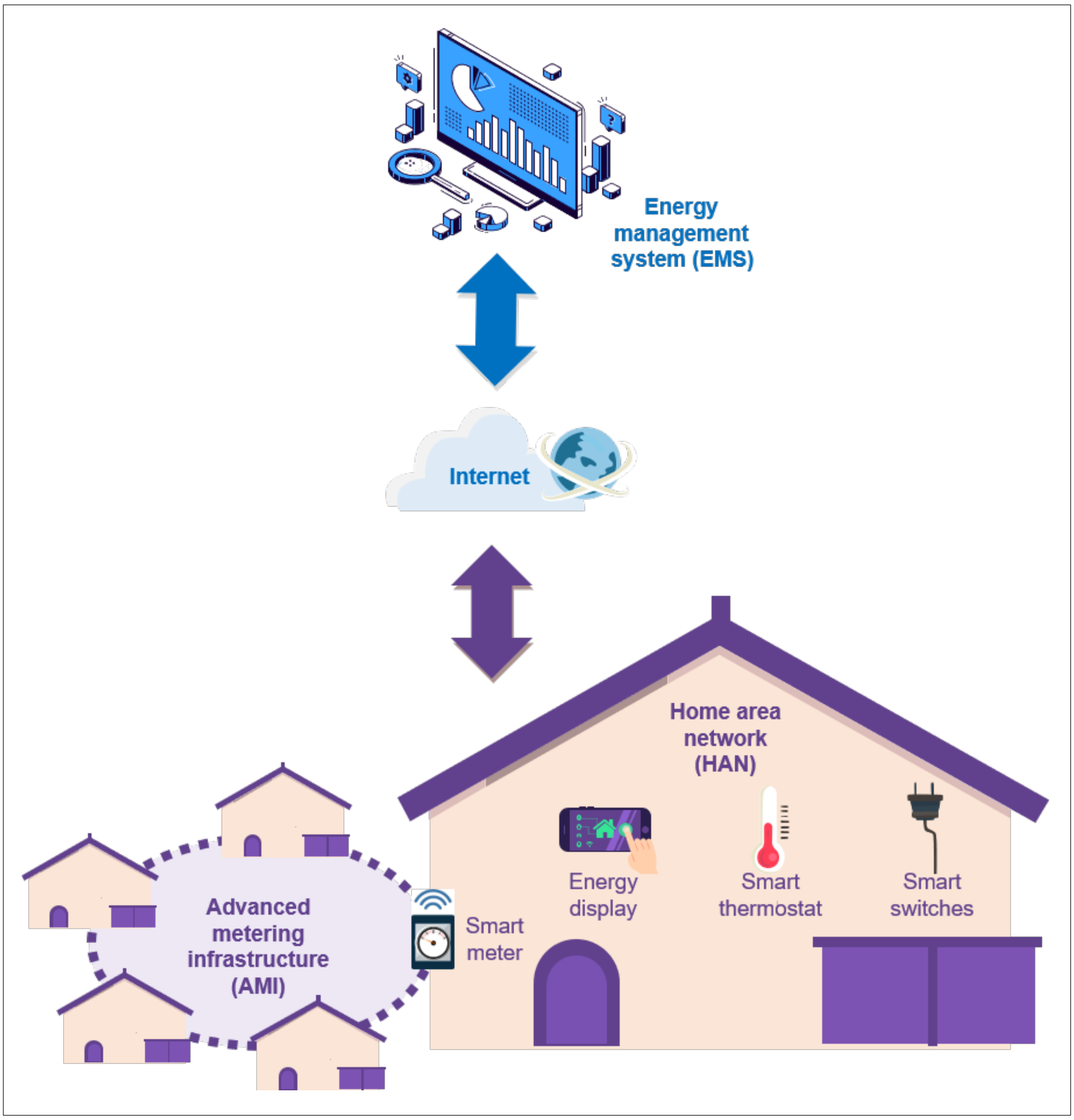
| Categories | | Description |
|---|---|---|
| Controlled by | Users | Manually turning on and off the appliances based on additional information through displays linked to meters on appliances, through mobile phone apps, or other web-based systems |
| | Programs and algorithms | Automation of appliances or through external control |
| Timing | Static | Changes demand at pre-set times of day |
| | Dynamic | Changes demand based on prevailing electricity system conditions as they vary at different times throughout the day or year |
| Stimuli | Price | Uses time-varying pricing to shift demand toward lower price periods |
| | Incentive payment | Uses incentives such as direct payments, bill credits, lower price appliances, or special tariff plans |
| | Other stimuli | Uses information about environmental conditions or grid stability |

Source: Adapted from DBEIS 2017; SMB 2018.

The combination of digitalization and energy technologies lies at the heart of DR deployment. The realization of DR relies on a series of information and communication technologies (ICTs). The key enabling technologies involved in a typical DR program are illustrated in Figure 9 and listed in Table 7.

On the user side, energy displays or smartphone applications and websites can be used to convey grid- and market-related information so they can make a decision about turning their appliances on and off. Smart controllers such as smart switches and thermostats allow for remote and automatic control if the user forgets to take action. Smart meters, which are the most critical user-side device in a DR program, measure user consumption, transmit that information to the load serving entity, and receive the grid signals from the load serving entity (Paterakis et al. 2017). The communication network contains three domains: the smart meter domain or the advanced metering infrastructure (AMI), which consists of millions of smart meters; the home area network (HAN) is the gateway between the AMI and the internet domain; and the energy management system (EMS) receives the signal from the AMI and implements actions through the HAN. In a DR program, the signals can be transferred through both wired or wireless systems. Wired systems include existing power transmission lines and external signal transmission wirings such as fiber-optics and ethernet, while wireless methods include ZigBee, Z-wave, Wi-Fi, Wi-MAX, cognitive radio, and cellular technologies such as GPRS, 4G, and future 5G systems.

Figure 9: Structure and Components of a Typical DR Program



DR has already been applied worldwide in households, commercial buildings, and industrial facilities. However, to limit the global temperature rise to 1.5°C, IEA (2021) estimates that 500 gigawatts of DR capacity should be built, enabling DR to shift 15% of average annual demand by 2050. Meanwhile, until 2016, only 1%, or 40 gigawatts, of the global electricity demand has been equipped with DR, mainly installed in North America (IEA 2018). The considerable gap between demand for DR and its current development stage poses massive opportunities in the next decades.

Table 7: Examples of Components Used in DR

| | Component | Description |
|---|---|---|
| User-side sensors and controllers | Energy display, mobile phone, website, etc. | Display grid and price related information, enables users to monitor utility signals and to take action to reduce load |
| | Smart switch | Remotely controlled switches for appliances |
| | Smart thermostat | Directly connected to the power market and weather forecast providers, eliminates the need for users to monitor utility signals and take action to reduce load |
| | Smart meter | Bi-directional communication between the load-serving entity and users about user consumption measurement and grid signals (e.g., price) |
| Communication network domains | Advanced metering infrastructure (AMI) | A network of millions of smart meters |
| | Internet (cloud) and intranet | Computing and information management platform |
| | Home area network (HAN) | The gateway between the AMI and Internet domain |
| Date collection and decision-making body | Energy management system (EMS) | Receives information from energy consumption and production and determines the optimal control strategy |

Source: Clean Energy Ministerial 2014; Paterakis et al. 2017; IEA 2018.

In recent years, interest in DR has been growing fast with advances in ICTs and more renewable energy sources, such as photovoltaic and wind, in the grid (IEA 2018). Many countries, such as Australia, Belgium, Chile, the People's Republic of China (PRC), Colombia, Singapore, and the United States, have taken concrete and encouraging actions to improve existing DR programs, promote the use of DR, or remove regulatory barriers that limit its development (IEA 2021). In Asia, Singapore, Japan, Republic of Korea, and the PRC are the leading countries in developing DR technologies. Project deployments in other countries are also catching up. For example, Bangladesh has started using advertisements to enhance DR program participation (Paterakis et al. 2017).

The major barriers to implementing DR include the lack of unified product protocols and standards, limitations in the regulatory framework and market entry criteria, high infrastructure and investment cost, difficulty in the engagement of customers, and low predictability and reliability of customer response (Clean Energy Ministerial 2014; Paterakis et al. 2017). Some of the barriers are technical, while most are economic, regulatory, or customer related. Despite continued advancements in DR technologies from hardware to software, more efforts should be made by the international community, the government of each country, and the DR industry. Future research could also focus more on regulatory frameworks, market entry criteria, and better-designed incentives that are more friendly to DR programs. These research directions will require cooperation from a wide range of disciplines, including but not limited to energy engineering, ICTs, political science, economy, marketing, and psychology. If these challenges can be properly addressed, more DR systems can be deployed in the next decades across the globe, especially in the developing countries of Asia with fast economic growth rates. With a joint effort from policymaking, academic research, and industrial practice, new market players, new appliance standards, new lower-cost smart products, and more flexible business models will arise (IEA 2021), helping fully release the enormous economic and environmental potential of DR.

# 8. CONCLUSIONS AND POLICY RECOMMENDATIONS

Both TES and DR technologies are crucial to reducing electricity consumption and carbon emissions to generate cooling energy by bridging the gap between cooling energy demand and production. There is not a single "most efficient" TES or DR technology. Each technology has its own advantages and limitations for different applications. TES shifts cooling energy production temporally or spatially. A comparison of TES technologies is summarized in Table 8. Chilled water and ice storage are the most commonly applied TES technologies for cooling applications. Due to the low cost and simplicity of manufacturing, both chilled water and ice storage can be used for building cooling (e.g., residential households, offices, shopping malls, and data centers), industrial process cooling, and waste cold recovery applications. Chilled water is more suitable for large-scale and long-term applications, while ice storage is more suitable for small-scale and re-deployable applications. Other PCMs offer a more flexible temperature range for building cooling, industrial process cooling, and the cold supply chain. Although various industries have used PCMs to mitigate cooling demand, more lower-cost PCMs and better system design should be explored. Making use of thermal lag, building thermal mass is an essential TES technology for buildings. Selecting the most appropriate building mass material will better protect the indoor thermal environment. More building thermal mass materials, especially composite materials that integrate PCMs, should be developed to have better performance and lower costs. CES is an essential part of thermal-mechanical energy storage systems, including LAES. Compared to electrochemical batteries, LAES offers a cost-effective and scalable solution to grid-level electricity storage. The development of CES is still at an early phase, but more commercial plants can be expected in the near future.

**Table 8: Comparison of Different TES Technologies**

| TES Technologies | Readiness Level | Storage Capacity per Volume | Cost | Potential Environmental Risks | Redeployability | Storage Temperature Range | Applications |
|---|---|---|---|---|---|---|---|
| Chilled water storage | Mature | Low | Low | No | No | Above 5°C | Building cooling (e.g., residential households, offices, shopping malls, data centers), industrial process cooling, waste cold recovery |
| Ice storage | Mature | High | Low | No | Yes | 0°C | Building cooling, industrial process cooling, waste cold recovery |
| Other PCMs | Early development (below −60°C) to mature (above −30°C) | Medium (below −60°C) to high (above −30°C) | Medium | Yes | Yes | All cooling temperatures | Building cooling, industrial process cooling, cold chain |
| Building thermal mass | Early development (integration with PCMs) to mature (traditional building materials) | Low (traditional building materials) to medium (integrated with PCMs) | Low (traditional building materials) to medium (integrated with PCMs) | No | No | All cooling temperatures | Building cooling |
| Cryogenic energy storage | Early development | Low | High (for electricity storage) | No | No | Below −180°C | Electricity storage |

DR, on the other hand, allows for users to manually adjust or willingly permit automated shifts in their demand profiles in return for lower energy costs or cash incentives. With the help of ICTs, DR has seen rapid development in recent years. However, more DR programs, including those combining TES technologies, should be deployed to achieve the goal of a 1.5°C limit to the global temperature rise. Users can choose the most cost-effective TES and DR strategies for their applications. A combination of TES and DR technologies can also offer joint benefits.

Despite developing TES and DR technologies by improving their performance and reducing costs, strong and effective policy interventions are essential for their deployment, as this would enable them to make a greater contribution to decarbonization and renewable energy development in Asia, especially for developing countries. In general, policymakers should remove the regulatory barriers and encourage the adoption of TES and DR technologies. Several key actions can be taken to accelerate their development and deployment:

- Remove fossil fuel subsidies and accelerate the development of carbon markets
- Remove policy barriers for TES and DR accessibility in the power market
- Provide special pricing schemes or mechanisms for TES and DR services in the power market, especially in the regulatory and ancillary markets
- Increase public awareness about the benefits of TES and DR technologies
- Provide special incentives, rebates, and low-interest loans for users to adopt TES and DR technologies
- Issue mandates to limit the cold energy consumption of residential, commercial, and industrial applications
- Encourage the construction of district cooling systems and thermal-mechanical electricity storage systems that can benefit from TES and DR adoption
- Encourage international cooperation by subsidizing TES and DR applications in developing countries
- Increase research funding support in developing more advanced and affordable TES and DR technologies from material development to system design, with special attention to the integration with broader energy processes, such as LNG and $LH_2$ cold energy utilization, industrial, commercial, and residential cold energy production, and enhancing renewables deployment in power grids.

# REFERENCES

Abolghasemi, M., Keshavarz, A., and Ali Mehrabian, M. (2012). Heat transfer enhancement of a thermal storage unit consisting of a phase change material and nano-particles. *Journal of Renewable and Sustainable Energy*, *4*(4). https://doi.org/10.1063/1.4747824.

Al-Abidi, A. A., Bin Mat, S., Sopian, K., Sulaiman, M. Y., Lim, C. H., and Th, A. (2012). Review of thermal energy storage for air conditioning systems. *Renewable and Sustainable Energy Reviews*, *16*(8), 5802–5819. https://doi.org/10.1016/j.rser.2012.05.030.

Australia. Department of the Environment and Energy. (2016). *Your Home: Australia's Guide to Environmentally Sustainable Homes*. Australian Government – Department of Industry and Science. https://books.google.com.sg/books?id=1eGEjwEACAAJ.

Bragança, L., Russo Ermolli, S., and Koukkari, H. (2011). Phase Changing Materials in Buildings. *International Journal of Sustainable Building Technology and Urban Development*, *2*(1), 43–51. https://doi.org/10.5390/susb.2011.2.1.043.

California ISO. (2021). *Root Cause Analysis: Mid-August 2020 Extreme Heat Wave*. http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf.

Castell, A., Martorell, I., Medrano, M., Pérez, G., and Cabeza, L. F. (2010). Experimental study of using PCM in brick constructive solutions for passive cooling. *Energy and Buildings*, *42*(4), 534–540. https://doi.org/10.1016/j.enbuild.2009.10.022.

Cetin, T. H., Kanoglu, M., and Yanikomer, N. (2019). Cryogenic energy storage powered by geothermal energy. *Geothermics*, *77*, 34–40. https://doi.org/10.1016/j.geothermics.2018.08.005.

Chase, A., Gross, R., Heptonstall, P., Jansen, M., Kenefick, M., Parrish, B., and Robson, P. (2017). *Realising the potential of demand-side response to 2025: Summary report* (Issue November 2017). www.nationalarchives.gov.uk/doc/open-government-.

Chiu, J. N. (2009). A Review of Thermal Energy Storage Systems with Salt Hydrate Phase Change Materials for Comfort Cooling. *Inorganic Materials*, *15*(1), 24–46.

Clean Energy Ministerial. (2014). *Energy Efficient Cooling and Demand Response*.

Damak, C., Leducq, D., Hoang, H. M., Negro, D., and Delahaye, A. (2020). Liquid Air Energy Storage ({LAES}) as a large-scale storage technology for renewable energy integration {\textendash} A review of investigation studies and near perspectives of {LAES}. *International Journal of Refrigeration*, *110*, 208–218. https://doi.org/10.1016/j.ijrefrig.2019.11.009.

Delgado, M., Lázaro, A., Mazo, J., and Zalba, B. (2012). Review on phase change material emulsions and microencapsulated phase change material slurries: Materials, heat transfer studies and applications. *Renewable and Sustainable Energy Reviews*, *16*(1), 253–273. https://doi.org/10.1016/j.rser.2011.07.152.

DOE. (2016). Thermal Energy Storage. *Combined Heat and Power Technology Fact Sheets Series*, *December*, 1–5. https://www.energy.gov/sites/default/files/2016/09/f33/CHP-Recip Engines.pdf.

Farid, M. M., Khudhair, A. M., Razack, S. A. K., and Al-Hallaj, S. (2004). A review on phase change energy storage: Materials and applications. *Energy Conversion and Management*, *45*(9–10), 1597–1615. https://doi.org/10.1016/j.enconman.2003.09.015.

Fikiin, K., Stankov, B., Evans, J., Maidment, G., Foster, A., Brown, T., Radcliffe, J., Youbi-Idrissi, M., Alford, A., Varga, L., Alvarez, G., Ivanov, I. E., Bond, C., Colombo, I., Garcia-Naveda, G., Ivanov, I., Hattori, K., Umeki, D., Bojkov, T., and Kaloyanov, N. (2017). Refrigerated warehouses as intelligent hubs to integrate renewable energy in industrial food refrigeration and to enhance power grid sustainability. *Trends in Food Science {\&} Technology*, *60*, 96–103. https://doi.org/10.1016/j.tifs.2016.11.011.

Gao, D., and Deng, T. (2013). Energy storage : Preparations and physicochemical properties of solid- liquid Phase change materials for thermal energy storage. *Materials and Processes for Energy*, 32–44.

Giovannini, L., Goia, F., Verso, V. R. M. Lo, and Serra, V. (2017). Phase Change Materials in Glazing: Implications on Light Distribution and Visual Comfort. Preliminary Results. *Energy Procedia*, *111*, 357–366. https://doi.org/10.1016/j.egypro.2017.03.197.

Goldsworthy, M., and Sethuvenkatraman, S. (2020). Air-conditioning demand response resource assessment for Australia. *Science and Technology for the Built Environment*, *26*(8), 1048–1064. https://doi.org/10.1080/23744731.2020.1785813.

Hasan, A., Al-Sallal, K., Alnoman, H., Rashid, Y., and Abdelbaqi, S. (2016). Effect of Phase Change Materials (PCMs) Integrated into a Concrete Block on Heat Gain Prevention in a Hot Climate. *Sustainability*, *8*(10), 1009. https://doi.org/10.3390/su8101009.

He, T., Chong, Z. R., Zheng, J., Ju, Y., and Linga, P. (2019). LNG cold energy utilization: Prospects and challenges. *Energy*, *170*, 557–568. https://doi.org/10.1016/j.energy.2018.12.170.

Highview Power. (2022). *Reshaping Renewables for an Always on World*. https://highviewpower.com/.

Hirakawa, S., and Kosugi, K. (1981). Utilization of LNG cold. *International Journal of Refrigeration*, *4*(1), 17–21. https://doi.org/10.1016/0140-7007(81)90076-1.

Hirsch, A., Clark, J., Deru, M., Trenbath, K., Doebber, I., and Studer, D. (2011). *Pilot Testing of Commercial Refrigeration-Based Demand Response* (Issue October). http://www.openadr.org/assets/docs/understanding_openadr_20_webinar_11_10_11_sm.pdf.

Houl, Y. (2019). *Increasing Effective Thermal Resistance of Building Envelope's Insulation Using Polyurethane Foam Incorporated With Phase Change Material*. University of North Texas.

Hu, Y., Tewari, A., Varga, L., Li, H., and Yan, J. (2017). System dynamics of oxyfuel power plants with liquid oxygen energy storage. *Energy Procedia*, *142*, 3727–3733. https://doi.org/10.1016/j.egypro.2017.12.268.

Incropera, F. P., DeWitt, D. P., Bergman, T. L., and Lavine, A. S. (2007). Fundamentals of Heat and Mass Transfer. In F. P. Incropera and F. P. F. O. H. A. M. T. Incropera (Eds.), *Water* (Vol. 6th). John Wiley & Sons. https://doi.org/10.1016/j.applthermaleng.2011.03.022.

International Energy Agency (IEA). (2018). *The Future of Cooling*. https://www.iea.org/reports/the-future-of-cooling.

———. (2019). *World Energy Outlook 2019*. https://www.iea.org/reports/world-energy-outlook-2019.

———. (2021). *Demand Response*. https://www.iea.org/reports/demand-response.

International Renewable Energy Agency (IRENA). (2020). *Innovation Outlook: Thermal Energy Storage*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Innovation_Outlook_TES_2020.pdf?rev=6950b7b9792344b5ab28d58e18209926.

IRENA, IEA, and REN21. (2020). Renewable Energy Policies in a Time of Transition: Heating and Cooling. In *IRENA, OECD/IEA and REN21*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_IEA_REN21_Policies_Heating_Cooling_2020.pdf?rev=9c0d3621b4124e00b2f0c8ff89a329ac.

Ismail, K. A. R., and Henríquez, J. R. (2001). Thermally effective windows with moving phase change material curtains. *Applied Thermal Engineering*, *21*(18), 1909–1923. https://doi.org/10.1016/s1359-4311(01)00058-8.

Ismail, K. A. R., and Henríquez, J. R. (2002). Parametric study on composite and PCM glass systems. *Energy Conversion and Management*, *43*(7), 973–993. https://doi.org/10.1016/S0196-8904(01)00083-8.

Kanbur, B. B., Xiang, L., Dubey, S., Choo, F. H., and Duan, F. (2017). Cold utilization systems of LNG: A review. *Renewable and Sustainable Energy Reviews*, *79*(August 2016), 1171–1188. https://doi.org/10.1016/j.rser.2017.05.161.

Karaipekli, A., and Sari, A. (2008). Capric-myristic acid/expanded perlite composite as form-stable phase change material for latent heat thermal energy storage. *Renewable Energy*, *33*(12), 2599–2605. https://doi.org/10.1016/j.renene.2008.02.024.

Khudhair, A. M., and Farid, M. M. (2004). A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. *Energy Conversion and Management*, *45*(2), 263–275. https://doi.org/10.1016/s0196-8904(03)00131-6.

Kośny, J. (2015). Short History of PCM Applications in Building Envelopes. In *Engineering Materials and Processes* (pp. 21–59). Springer International Publishing. https://doi.org/10.1007/978-3-319-14286-9_2.

Kosny, J., Shukla, N., and Fallahi, A. (2013). *Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes in Southern U.S. Climates*. Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/1067934.

Kuznik, F., David, D., Johannes, K., and Roux, J.-J. (2011). A review on phase change materials integrated in building walls. *Renewable and Sustainable Energy Reviews*, *15*(1), 379–391. https://doi.org/10.1016/j.rser.2010.08.019.

Li, S., Zhong, K., Zhou, Y., and Zhang, X. (2014). Comparative study on the dynamic heat transfer characteristics of PCM-filled glass window and hollow glass window. *Energy and Buildings*, *85*, 483–492. https://doi.org/10.1016/j.enbuild.2014.09.054.

Li, S., Zhou, Y., Zhong, K., Zhang, X., and Jin, X. (2013). Thermal analysis of PCM-filled glass windows in hot summer and cold winter area. *International Journal of Low-Carbon Technologies*, *11*(2), 275–282. https://doi.org/10.1093/ijlct/ctt073.

Li, X., Zhou, Y., Nian, H., Ren, X., Dong, O., Hai, C., Shen, Y., and Zeng, J. (2016). Phase change behavior of latent heat storage media based on calcium chloride hexahydrate composites containing strontium chloride hexahydrate and oxidation expandable graphite. *Applied Thermal Engineering*, *102*, 38–44. https://doi.org/10.1016/j.applthermaleng.2016.03.098.

Lindsay, B. B., Andrepont, J. S., Dorgan, C., Maccracken, M., Markel, L., Reindl, D., Turnbull, P., Williams, V., and Bares, G. (2019). Evolution of thermal energy storage for cooling applications. *ASHRAE Journal*, *61*(10), 42–59.

Ling, Z., Zhang, Z., Shi, G., Fang, X., Wang, L., Gao, X., Fang, Y., Xu, T., Wang, S., and Liu, X. (2014). Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules. *Renewable and Sustainable Energy Reviews*, *31*, 427–438. https://doi.org/10.1016/j.rser.2013.12.017.

Medina, M., King, J., and Zhang, M. (2008). On the heat transfer rate reduction of structural insulated panels (SIPs) outfitted with phase change materials (PCMs). *Energy*, *33*(4), 667–678. https://doi.org/10.1016/j.energy.2007.11.003.

Medrano, M., Yilmaz, M. O., Nogués, M., Martorell, I., Roca, J., and Cabeza, L. F. (2009). Experimental evaluation of commercial heat exchangers for use as PCM thermal storage systems. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2009.01.014.

Memon, S. A. (2014). Phase change materials integrated in building walls: A state of the art review. *Renewable and Sustainable Energy Reviews*, *31*, 870–906. https://doi.org/10.1016/j.rser.2013.12.042.

Mondal, S. (2008). Phase change materials for smart textiles – An overview. *Applied Thermal Engineering*. https://doi.org/10.1016/j.applthermaleng.2007.08.009.

Morgan, R., Rota, C., Pike-Wilson, E., Gardhouse, T., and Quinn, C. (2020). The Modelling and Experimental Validation of a Cryogenic Packed Bed Regenerator for Liquid Air Energy Storage Applications. *Energies*, *13*(19), 5155. https://doi.org/10.3390/en13195155.

Murrant, D., and Radcliffe, J. (2018). Analysis of when and where the integration of {LAES} with refrigerated warehouses could provide the greatest value to Europe. *Energy Procedia*, *151*, 144–149. https://doi.org/10.1016/j.egypro.2018.09.039.

Pacific Gas and Electric Company. (1997). Thermal Energy Storage Strategies for Commercial HVAC Systems. In *PG&E Energy Efficiency Information© "Thermal Energy Storage."* https://www.pge.com/includes/docs/pdfs/about/edusafety/training/pec/inforesource/thrmstor.pdf.

Paterakis, N. G., Erdinç, O., and Catalão, J. P. S. (2017). An overview of Demand Response: Key-elements and international experience. *Renewable and Sustainable Energy Reviews*, *69*(September 2015), 871–891. https://doi.org/10.1016/j.rser.2016.11.167.

Popov, D., Akterian, S., Fikiin, K., and Stankov, B. (2021). Multipurpose System for Cryogenic Energy Storage and Tri-Generation in a Food Factory: A Case Study of Producing Frozen French Fries. *Applied Sciences*, *11*(17), 7882. https://doi.org/10.3390/app11177882.

Raj, V. A. A., and Velraj, R. (2010). Review on free cooling of buildings using phase change materials. *Renewable and Sustainable Energy Reviews*, *14*(9), 2819–2829. https://doi.org/10.1016/j.rser.2010.07.004.

Renewable Energy Consumer Code (RECC). (2018). *A RECC consumer guide to Demand-Side Response*. https://www.recc.org.uk/pdf/demand-side-response-guide.pdf.

Royal Dutch Shell. (2021). *Shell LNG Outlook 2021*. https://doi.org/10.1007/978-3-322-82686-2_17.

Sayyar, M., Weerasiri, R. R., Soroushian, P., and Lu, J. (2014). Experimental and numerical study of shape-stable phase-change nanocomposite toward energy-efficient building constructions. *Energy and Buildings*, *75*, 249–255. https://doi.org/10.1016/j.enbuild.2014.02.018.

Schossig, P., Henning, H., Gschwander, S., and Haussmann, T. (2005). Micro-encapsulated phase-change materials integrated into construction materials. *Solar Energy Materials and Solar Cells*, *89*(2–3), 297–306. https://doi.org/10.1016/j.solmat.2005.01.017.

Segu, R. (2012). Demand-Response Management of a District Cooling Plant of a Mixed Use City Development. *Fuel*, *80*(12), 1757–1763. http://www.diva-portal.org/smash/record.jsf?pid=diva2:531199.

Shafigh, P., Asadi, I., and Mahyuddin, N. B. (2018). Concrete as a thermal mass material for building applications – A review. *Journal of Building Engineering*, *19*, 14–25. https://doi.org/10.1016/j.jobe.2018.04.021.

Sharma, A., Tyagi, V. V., Chen, C. R., and Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews*, *13*(2), 318–345. https://doi.org/10.1016/j.rser.2007.10.005.

She, X., Zhang, T., Peng, X., Wang, L., Tong, L., Luo, Y., Zhang, X., and Ding, Y. (2020). Liquid Air Energy Storage for Decentralized Micro Energy Networks with Combined Cooling, Heating, Hot Water and Power Supply. *Journal of Thermal Science*, *30*(1), 1–17. https://doi.org/10.1007/s11630-020-1396-x.

Shi, J., and Li, M. (2021). Lightweight mortar with paraffin/expanded vermiculite-diatomite composite phase change materials: Development, characterization and year-round thermoregulation performance. *Solar Energy*, *220*, 331–342. https://doi.org/10.1016/j.solener.2021.03.053.

Silva, T., Vicente, R., Amaral, C., and Figueiredo, A. (2016). Thermal performance of a window shutter containing PCM: Numerical validation and experimental analysis. *Applied Energy*, *179*, 64–84. https://doi.org/10.1016/j.apenergy.2016.06.126.

Soares, N., Costa, J. J., Samagaio, A., and Vicente, R. (2013). Numerical evaluation of a phase change material–shutter using solar energy for winter nighttime indoor heating. *Journal of Building Physics*, *37*(4), 367–394. https://doi.org/10.1177/1744259113496388.

Soares, N., Samagaio, A., Vicente, R., and Costa, J. (2011). Numerical Simulation of a PCM Shutter for Buildings Space Heating During the Winter. In *Linköping Electronic Conference Proceedings*. Linköping University Electronic Press. https://doi.org/10.3384/ecp110571797.

Socaciu, L., Pleşa, A., Ungureşan, P., and Giurgiu, O. (2014). Review on phase change materials for building applications. *Leonardo Electronic Journal of Practices and Technologies*, *13*(25), 179–194.

Somarriba, M. J. (2012). Chilled Water Thermal Energy Storage Tank Overview. In *DN Tanks*. https://www.dntanks.com/.

Swisher, J. N. (2012). The Role of Demand-Side Resources in Integration of Renewable Power Growth of Renewable Generation Variation of Renewable Power Production Flexibility in the Power Supply System. *ACEEE Summer Study on Energy Efficiency in Buildings*, 399–413.

Trane. (2020). *How Thermal Energy Storage Works*. http://www.calmac.com/how-energy-storage-works.

Trivedi, G. V. N., and Parameshwaran, R. (2020). Cryogenic conditioning of microencapsulated phase change material for thermal energy storage. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-75494-8.

Tyagi, V. V., and Buddhi, D. (2008). Thermal cycle testing of calcium chloride hexahydrate as a possible PCM for latent heat storage. *Solar Energy Materials and Solar Cells*. https://doi.org/10.1016/j.solmat.2008.02.021.

Tyagi, V. V., Buddhi, D., Kothari, R., and Tyagi, S. K. (2012). Phase change material (PCM) based thermal management system for cool energy storage application in building: An experimental study. *Energy and Buildings*, *51*, 248–254. https://doi.org/10.1016/j.enbuild.2012.05.023.

U.S. Department of Energy. (n.d.). *Liquefied Natural Gas (LNG)*. Retrieved 21 May 2020, from https://www.energy.gov/fe/science-innovation/oil-gas/liquefied-natural-gas.

Valenta, P. (2021). *Ice Storage or Chilled Water Storage ? Which Is Right for the Job ?* Trane. https://coolingbestpractices.com/system-assessments/chillers/ice-storage-or-chilled-water-storage-which-right-job.

Vecchi, A., Li, Y., Ding, Y., Mancarella, P., and Sciacovelli, A. (2021). Liquid air energy storage (LAES): A review on technology state-of-the-art, integration pathways and future perspectives. *Advances in Applied Energy*, *3*(June), 100047. https://doi.org/10.1016/j.adapen.2021.100047.

Viking Cold Solutions. (2016). *Case Study: Butterfield and Vallis uses PCM thermal storage to cut refrigeration costs 40%*. https://www.vikingcold.com/case-study-butterfield-and-vallis-uses-pcm-thermal-storage-to-cut-refrigeration-costs-40/.

Wojcieszak, and Malecha, Z. (2018). Cryogenic energy storage system coupled with packed-bed cold storage. *E3S Web of Conferences*, *44*, 190. https://doi.org/10.1051/e3sconf/20184400190.

Wojcieszak, P., Poliński, J., and Chorowski, M. (2017). Investigation of a working fluid for cryogenic energy storage systems. *{IOP} Conference Series: Materials Science and Engineering*, *278*, 12069. https://doi.org/10.1088/1757-899x/278/1/012069.

Xiao, F., Yang, L., He, L., Gil, A., Rajoo, S., Zhao, Z., Romagnoli, A., and Cabeza, L. F. (2022). Performance enhancement of horizontal extension and thermal energy storage to an abandoned exploitation well and satellite LNG station integrated ORC system. *Applied Thermal Engineering*, *214*(118736), 118736. https://doi.org/10.1016/j.applthermaleng.2022.118736.

Yang, H., Wang, Y., Yu, Q., Cao, G., Yang, R., Ke, J., Di, X., Liu, F., Zhang, W., and Wang, C. (2018). Composite phase change materials with good reversible thermochromic ability in delignified wood substrate for thermal energy storage. *Applied Energy*, *212*, 455–464. https://doi.org/10.1016/j.apenergy.2017.12.006.

Yang, L., Villalobos, U., Akhmetov, B., Gil, A., Khor, J. O., Palacios, A., Li, Y., Ding, Y., Cabeza, L. F., Tan, W. L., and Romagnoli, A. (2021a). A comprehensive review on sub-zero temperature cold thermal energy storage materials, technologies, and applications: State of the art and recent developments. *Applied Energy*, *288*, 116555. https://doi.org/10.1016/j.apenergy.2021.116555.

Yang, L., Villalobos, U., Akhmetov, B., Gil, A., Khor, J. O., Palacios, A., Li, Y., Ding, Y., Cabeza, L. F., Tan, W. L., and Romagnoli, A. (2021b). A comprehensive review on sub-zero temperature cold thermal energy storage materials, technologies, and applications: State of the art and recent developments. *Applied Energy*, *288*, 116555. https://doi.org/https://doi.org/10.1016/j.apenergy.2021.116555.

Yang, L., Villalobos, U., Akhmetov, B., Onn, K. J., Gil, A., Tan, W. L., and Romagnoli, A. B. T.-R. M. in E. S. and E. S. (2022). Active TES With PCM for Refrigeration Applications. In *Encyclopedia of Energy Storage*. Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-819723-3.00029-9.

Yang, L., Xu, H., Cola, F., Akhmetov, B., Gil, A., Cabeza, L. F., and Romagnoli, A. (2021). Shell-and-tube latent heat thermal energy storage design methodology with material selection, storage performance evaluation, and cost minimization. *Applied Sciences*, *11*(4180). https://doi.org/10.3390/app11094180.

Zhou, D., Zhao, C. Y., and Tian, Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied Energy*, *92*, 593–605. https://doi.org/10.1016/j.apenergy.2011.08.025.