Heat, Cold, and Hydrogen Storage in a 100% WWS World

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2.8. WWS Heat, Cold, and Hydrogen Storage Technologies

In a 100 percent WWS world, low-temperature heat storage, cold storage, and hydrogen storage are needed along with electricity storage. Whereas most heat for air and water heating in buildings and most cold for air conditioning will be obtained directly from heat pumps, which run on electricity, some heat and cold will also come from hot and cold storage through domestic hot water heaters or district heating and cooling systems. The rest will come from solar or geothermal direct heat. In a 100 percent WWS world, excess electricity will be converted to heat, cold, and hydrogen, all of which will be stored or used immediately. Excess electricity occurs if current electricity demand has been met and electricity storage is already full.

This section discusses heat, cold, and hydrogen storage. It first examines short-term heat and cold storage in water tanks and their application to district heating. It then moves on to analyze seasonal heat and cold underground storage in boreholes, water pits, and aquifers. It subsequently summarizes heat and cold storage in building materials and cold storage in ice. Hydrogen storage is discussed last.

2.8.1. Heat and Cold Storage in Water Tanks

Tank thermal energy storage (**TTES**) is the most common type of heat and cold storage worldwide. It involves heating or chilling water as it sits in a storage tank. Water tanks are used primarily as part of small or large district heating and/or cooling systems. Domestic hot water tank heaters for individual homes or buildings are also a form of tank storage, but such tanks are much smaller than are those used for district heating.

District heating tanks are made of concrete, steel, or fiber-reinforced plastic. Concrete tanks usually contain an interior polymer or stainless steel liner to minimize water vapor and heat diffusion out of the tank. They are also insulated on the outside. Steel tanks are generally insulated as well.

Hot-water tanks are also called **boilers**. The stored hot water is used to heat building air or as potable hot tap water for showering, bathing, cooking, hand washing, and drinking. Cold-water tanks are also called **chillers**. The cold water stored in a chiller is used for air conditioning and, sometimes, refrigeration.

Although community-scale boilers and chillers can be large, they are generally used to store heat and cold for only days to weeks. Underground thermal energy storage (Section 2.8.3) is less costly per unit energy thus is now the main type of seasonal (between summer and winter) heat and cold storage. However, an advantage of above ground boilers and chillers is that they can be build almost anywhere, whereas borehole and aquifer underground storage can be built only where soil and/or groundwater conditions are sufficient.

Water stored in tanks can be heated directly with solar or geothermal heat or with heat from a heat pump powered by electricity. Similarly, water in a tank can be cooled with a heat pump. Ideally, electricity used to heat water is excess electricity that is not needed on the grid. Using excess electricity to produce heat is an ideal way of decreasing the cost of electricity because it reduces the **curtailment** (**shedding** or wasting) of excess renewable electricity.

Using heat pumps in conjunction with boilers and chillers also reduces winter energy demand by 68 to 81 percent because heat pumps have a much higher coefficient of performance (COP) than do gas heaters or electric resistance heaters (Section 2.3). Thus, boilers and chillers powered by heat pumps not only help to lower the cost of stabilizing the electric power grid by absorbing excess electricity instead of wasting it, but boilers powered by heat pumps also reduce energy requirements for heating.

Hot water stored in a water tank heats building air when the water passes through a radiator. **Radiators** are heat exchangers. **Heat exchangers** are devices that allow a heated liquid or gas to transfer its heat to another liquid or gas without the two fluids mixing together or otherwise coming into direct contact. The transfer occurs by conduction, where heat energy is passed from one molecule to the text in the metal or other material that separates the two fluids. In the case of a radiator, water flows through pipes, often with fins to increase the surface area exposed to the air. Heat from the water in a radiator conducts through the metal in the radiator to the air, where convection by heated air molecules carries the heat through the room. Radiators can be placed in or against a wall, under a floor (**radiant floor heating**), or in a ceiling. They may or may not be accompanied by a fan. After hot water passes through a radiator, it is piped to subsequent radiators until it returns back cold to the original source of the hot water for reheating.

Similarly, cold water piped to a building is used to cool air in the building when the water passes through a heat exchanger. The heat exchanger moves heat from the warm air in the building to the cool water in the pipe, which warms up. The warm water is then circulated back to the chiller, where it is cooled down again, ideally with a heat pump.

2.8.2. District Heating Systems

District Heating is the name given to a heating system whereby hot water in centralized boilers is distributed in a closed loop through insulated pipes to multiple residential or commercial buildings for either air heating (through radiators), potable water heating, or both. Once the heat is distributed, the cooler water is returned to the centralized boilers for reheating.

District heating originated in the United States. On March 3, 1882, the New York Steam Company began sending high-temperature (less than 200 $^{\circ}$C) steam through pipes to heat buildings in lower Manhattan, New York City. Burning coal to boil water created the steam. Heat losses from coal combustion and through poorly insulated and leaky pipes were significant but coal was plentiful. Steam district heating still exists today in Manhattan, with Consolidated Edison providing steam to over 1,700 buildings. From 1882 to 1930, steam-based district heating using coal combustion (**first-generation district heating**) was common in many cities in Europe and the United States.

From 1930 to 1970, **second-generation district heating** emerged. This system was based on burning coal and oil to heat water and sending the hot water through pressurized pipes to buildings. Water temperatures exceeded 100 $^{\circ}$C and system losses were less than with steam, partly due to the use of concrete ducts around pipes. These systems were installed worldwide but particularly in Eastern Europe after World War II.

Third-generation district heating evolved from 1970 to the present. It was developed and used first in Scandinavian countries. Today, 50 to 65 percent of building air and potable water heat in Denmark, Iceland, Sweden, Finland, Estonia, Latvia, Lithuania, Poland, Russia, and Northern China is from district heating. About 12.5 percent of all heat delivered in the European Union and about 8 percent delivered worldwide is district heating (Werner, 2017).

Third-generation district heating uses prefabricated, insulated water pipes buried underground to reduce heat loss. The insulation allows water temperatures to stay below 100 $^{\circ}$C, which in turn reduces the energy needed to heat the water. The heat for water in these systems was originally provided by a combination of coal, natural gas, and biomass combustion and by recycling the heat of combustion from electricity generated by these fuels. More recently, heat has also been recycled from data centers and created from excess electricity produced by wind, solar, and geothermal plants. In some district heating systems, the heat is stored underground (Section 2.8.3) instead of in aboveground boilers.

Fourth-generation district heating emerged in 2015 and is currently evolving. It combines district cooling with district heating. District cooling involves a centralized chiller that stores water that has been cooled. Like with district heating, the cold water is sent through an insulated piping network to buildings to cool air in the buildings. With fourth-generation, heat pumps are used for heating water in boilers and cooling water in chillers. The heat pumps, which run on electricity, extract heat or cold from the air, water, or the ground. If waste heat or cold from buildings datacenters, or manufacturing processes is the source of heat for each heat pump, the heat pump requires less electricity thus runs more efficiently. Ideally, in a fourth-generation system, all electricity for a heat pump is obtained from 100 percent WWS, and the heat pump uses hot and cold water circulated from buildings to help heat or chill water in the boiler or chiller, respectively.

An example of a fourth-generation district heating system is the Stanford Energy System Innovations (SESI) project (Stagner, 2016, Section 2.8.7). The round trip efficiency of the heating portion of this system (ratio of the energy returned as heating after storage to the energy in the electricity used to heat the water for storage) is around 83 percent. That of the cooling portion is around 84.7 percent (Stagner, 2017). Hot water temperatures in a fourth-generation system are below 70 $^{\circ}$C to minimize losses.

In a 100 percent WWS world, 4th generation district heating and cooling would be used as much as possible in densely populated areas, such as cities, where such systems are most advantageous. District heating can also be used on college campuses, military bases, and remote communities. Rural and many suburban homes and buildings are less ideal for district heating and cooling due to the length of trenches and pipes required and pipe losses. Homes and buildings that are not on district heating and cooling loops will have their own domestic hot water tanks and use heat pumps for all building and water heating and air conditioning.

2.8.3. Underground Thermal Energy Storage

Whereas boilers are useful forms of district or home heat storage for periods of days to weeks, the winter heat for boilers can be obtained from larger heat storage reservoirs filled primarily during summer. Such seasonal heat storage takes the form of **underground thermal energy storage** (**UTES**). Three main types of UTES have been developed: borehole, pit, and aquifer thermal energy storage. Table 2.3 summarizes some of the similarities and differences among these UTES systems and tank thermal energy storage (TTES) (Section 2.8.1). The different UTES options are discussed, next, in turn.

Table 2.3. Features of four different types of thermal energy storage systems.

Parameter	TTES	BTES	PTES	ATES
Storage Medium	Water	Soil/Rock	Water; gravel/water	Sand/water; Rock/water

| Heat capacity (kWh/m^3)	60-80	15-30	60-80; 30-50	30-40
Storage temperature (°C)	5-95	-5 to 95	5-95	Shallow: 2-20; Deep: 2-80
Depth (m)	5-15	30-100	5-15	20-100
Storage volume (m^3) for 1 m^3 water equivalent	1	3-5	1; 1.3-2	2-3

From IEA (2018a). TTES is tank thermal energy storage, BTES is borehole thermal energy storage; PTES is pit thermal energy storage; and ATES is aquifer thermal energy storage.

2.8.3.1. Borehole Thermal Energy Storage

A **borehole thermal energy storage** (**BTES**) system is effectively a large, underground heat exchanger that stores solar heat collected in summer for later use during winter. It consists of an array of boreholes drilled into soil. A plastic pipe with a U-bend at the bottom is inserted down each borehole. The space around each pipe in each borehole is then filled with highly conducting grouting material to increase the molecule-to-molecule conduction of heat from hot water that passes through the pipe to the soil surrounding the grouting material. After water in the pipe transfers its heat to the soil, the water is cold and sent back to solar collectors or heat pumps to collect more heat, particularly during summer. When hot water is needed during winter or another time, cold water is sent down the pipe; heat stored in the surrounding soil conducts through the grouting material to the water through the pipe wall and the hot water is sent to a boiler for subsequent distribution to buildings.

A good example of a BTES storage system is the **Drake Landing Solar Community** (Figure 2.25) in Okotoks, Alberta, Canada, which is one hour driving south of Calgary. Starting in 2004, 52 homes were constructed. On the garage roof of each home, solar collectors were installed. The collectors contain a glycol solution (mix of water and non-toxic glycol) that absorbs solar heat, particularly during long summer days. The heated solution is transferred through underground, insulated pipes to a building (Figure 2.25), where the heat from the solution is transferred through a heat exchanger to water stored in a short-term hot water storage tank (boiler). The water temperature in the boiler is maintained at 40 to 50 °C. This tank is the connection source of all water and air heat for the 52 homes all year.

Figure 2.25. Diagram of Drake Landing Solar Community district heating system. Adapted from Drake Landing (2016).
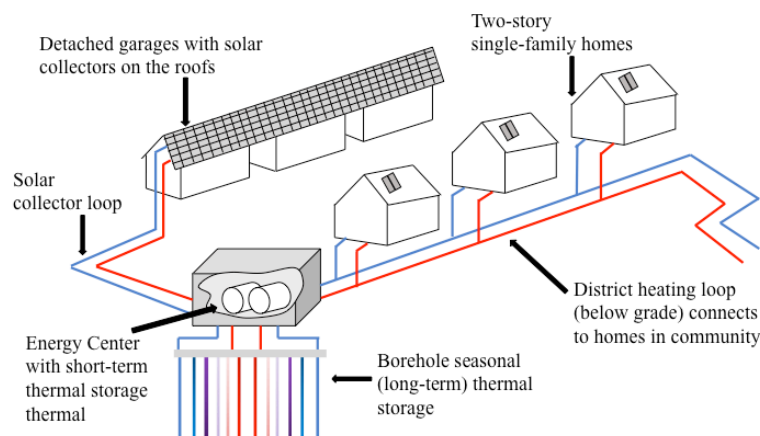
During summer and autumn, all home heating needs are met through water supplied to the boiler by the solar collectors without the need of heat stored in the nearby borehole field. In fact, the solar collectors produce a surplus of heat, and the excess heat is sent to the field to be stored until winter. The excess heat is piped by water to the borehole field, which is about 35 m in diameter. In this field, 144 holes were drilled to 35 m depth, and each was filled with a pipe with a U-bend at the bottom. Insulation was placed on top, and a grassy field, used as a community park, was grown on top of that (Figure 2.26).

Figure 2.26. Homes of the Drake Landing Solar Community during (left) summer (September 9, 2007) and (right) winter (January 12, 2010). © Drake Landing. (c) Bottom: Energy center housing the hot water tank and heat exchangers, and the borehole field covered with grass in 2015 (© Mark Z. Jacobson).

The hot water collected from the homes and sent to the boiler is then delivered through separate pipes to the borehole field. Each pipe containing hot water extends to the bottom of each borehole. The heat from the pipes is conducted to the surrounding soil, raising the soil temperature up to 80 $^{\circ}$C by the end of summer. Each pipe returns upward with cooler water and is sent back to the solar collectors of each home to collect more heat.

During winter or other times of the year, when the hot water tank alone cannot satisfy all building heat demand, cold water is piped through the boreholes to collect heat to bring back to the hot water tank. The hot water from the water tank is then distributed to the 52 homes for air and domestic water heating. With this system, up to 100 percent of winter heat is satisfied by summer heat collection.

The Drake Landing system has been operational since 2007. The efficiency of the UTES system, which is defined as the fraction of heated fluid entering underground storage that is ultimately returned during the year for air or water heat, is about 56 percent (Sibbitt et al., 2012).

In sum, Drake Landing is a district heating system with a community hot water tank but where much of the wintertime hot water is stored underground between summer and winter. The technology is repeatable for most any district heating system and requires little land. The borehole field is not visible and can be used simultaneously as grazing land, parkland, open space, or for the solar collectors used to provide heat to be stored in the field.

Transition highlight. Another borehole thermal energy storage facility serving a district heating system resides in Braedstrup, Denmark. The Braedstrup district heating system services 1,500 customers. The borehole field, installed in 2012, is honeycomb shaped and has 48 boreholes, each 45 m deep and 3 m apart. U-bend pipes are used, just as in Drake Landing. The storage field, which has a volume of 19,000 m^3 for heating and storage capacity of 400 MWh, is heated up to 55 to 60 °C during summer and cooled down to 12 to 15 °C during winter, when heat is drawn from the field. The round-trip efficiency is about 63 percent, slightly higher than that of Drake Landing, and the investment cost is 0.65 Euros/kWh ($0.74/kWh in 2019) (Sorensen and Schmidt, 2018). The boreholes, along with two additional steel water tanks totaling 7,700 m^3, are fed by 18,600 m^2 of solar collectors.

2.8.3.2. Pit Thermal Energy Storage

Pit thermal energy storage (**PTES**) consists of a lined pit dug into the ground and filled with a storage material, such as water or a mix of gravel and water, then covered with insulation and soil. The pit can be small or large. The material in the pit is supplied with heat primarily during the summer. The heat is extracted primarily during the winter and sent to a boiler, where it is distributed via district heating to homes for air and water heating.

As of 2018, the largest pit worldwide for PTES was in Vojens, Denmark, completed in 2015 (Figure 2.27). It is 13 m deep, 610 m in circumference, and filled with 200,000 m^3 of water. The pit is lined underneath and on the sides with welded plastic to ensure water does not leak through it. A few meters thick of soil outside the lining become warm, along with the water, insulating the storage pit. The surface of the water is also lined with a floating plastic cover topped with 60 cm of insulating expanding clay and a draining system to remove rainwater. The water temperature during summer can reach 95 °C but is maintained at a maximum of 80 °C to extend the life of the liner (Ramboll, 2016).

5,439 solar thermal panels (70,000 m^2) heat the water. The pit is connected to the district heating system of Vojens, which has 2,000 customers. The solar collectors plus PTES facility provide 45 to 50 percent, or 28 GWh/y, of the annual heat to the city. The peak heat discharge rate is 49 MW (Arcon/Sunmark, 2017).

Figure 2.27. Pit thermal energy storage system in Vojens, Denmark. The pit, empty in the figure, is on the left. When filled, it is then covered with floating plastic. The solar thermal collectors are to the right of the pit. © Ramboll.

Example 2.5. Energy storage in the Vojens water pit.
Estimate the maximum energy (GWh) that the Vojens water pit can store at a given time assuming the water temperature without storage is 15 °C and the water temperature with storage is a) 80 °C, b) 95 °C.

a) The specific heat of liquid water is 4,186 J/kg-K. Multiplying this by the density of liquid water, 1,000 kg/m³, the volume of water in the pit, 200,000 m³, the temperature difference with and without storage, 80-15=65 °C=65 K and by 1W-s/J, 10^{-9} GW/W, and 1 h/3600 s gives 15.1 GWh maximum energy storage;

b) The calculation is the same, except the temperature difference is 80 K, resulting in a maximum storage of 22.1 GWh.

The cost of wintertime heat from the solar heating combined with this PTES interseasonal heat storage in Vojens is competitive, even without subsidy, with the cost of heat from gas boilers due to economies of scale. In fact, heating bills declined by 10 to 15 percent with the seasonal heat storage system (Ramboll, 2016).

Transition highlight. A modified version of the Vojens PTES plant was built for the district heating system in Gram, Denmark, in 2015. Gram is a town with 2,500 residents, 99 percent of who are connected to the district heating system. The storage pit in this case is 15 m deep with 10 m below ground a 5 m above ground. A 5-m-tall sloped dam was built to raise the height of the pit. The water volume in the pit is 122,000 m³. The facility also has 44,800 m² of solar collectors, which directly and through PTES provide 61 percent, or 18.3 GWh/y, of the town's heating. The peak discharge rate of heat is 31 MW (Damkjaer, 2016).

Two other PTES storage systems coupled with solar collectors and district heating are in Marstal and Dronninglund, Denmark.

The Marstal systems, which serves 2,200 residents, consists of 33,365 m² of solar collectors, and 75,000 m³ of pit water storage with a thermal capacity of 6 GWh-th (completed in 2012). It also has 2,100 m³ of steel tank water storage, a pit maximum charge and discharge rate of 10 MW, a maximum measured temperature of 88 °C, a minimum measured temperature of 17 °C, an efficiency of 52 percent, and an investment cost of 0.44 Euros/kWh ($0.50/kWh in 2019) (Sorensen and Schmidt, 2018).

The Dronninglund system, which serves 3,300 residents, consists of 37,573 m² of solar collectors, and 62,000 m³ of pit water storage. It began operating during March 2014. The storage has a capacity of 5.4 GWh-th, a maximum charge and discharge rate of 27 MW, a maximum measured temperature of 89 °C, a minimum measured temperature of 12 °C, an efficiency of 81 percent, and an investment cost of 0.43 Euros/kWh ($0.49/kWh in 2019) (Sorensen and Schmidt, 2018).

2.8.3.3. Aquifer Thermal Energy Storage

Aquifer thermal energy storage (**ATES**) is similar to PTES, except that the water used for storing heat is naturally occurring water in underground layers of groundwater, or aquifers. Aquifers can also be used to store cold water for cooling applications. Aquifers contain permeable sand, gravel, sandstone, or limestone layers with high hydraulic conductivity (IEA, 2018a). Aquifers can be used for UTES if they are encapsulated above and below them by impervious layers and if natural groundwater flow is slow.

Figure 2.28. Diagram of aquifer thermal energy storage system. During the summer, cold water is drawn up. Heat is transferred from building air to the water, warming the water and cooling the building air. The warm water is sent down to another part of the aquifer. During winter, heat is drawn from the warm part of the aquifer and released to heat the building air. The residual cold water is sent back down to the cold part of the aquifer and stored until summer. Adapted from Socaciu (2011).

Summer   Winter

aquifer   aquifer

warm cold   warm cold
well well   well well
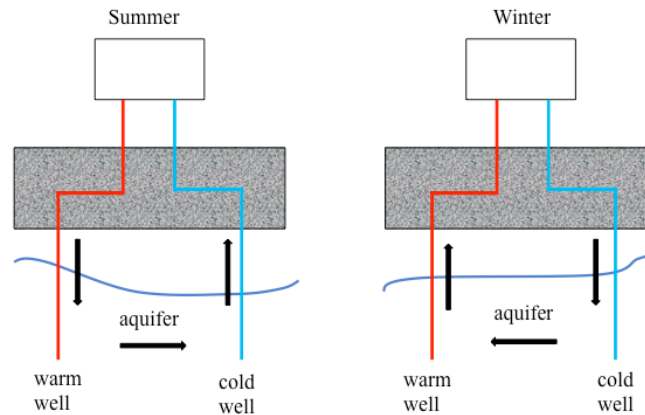
With ATES, two wells, or several pairs of wells, are drilled into an aquifer. During summer, cold water is extracted from one part of the well, heated with building heat (cooling the building), then returned to another part of the well, where it mixes with and heats that part of the well (Figure 2.28). During winter, warm water from the warm part of the aquifer is extracted, the heat is removed to heat the building, and the cold water is returned to the cold part of the aquifer (Figure 2.28).

Because aquifers cannot be insulated, heat storage at temperatures greater than 50 ^{o}C is efficient only for large, deep aquifers with volumes greater than 50,000 m^3 and a low surface-to-volume ratio (IEA, 2018a). As such, the maximum temperature in a shallow aquifer for heating is generally limited to 20 ^{o}C. For cooling, shallow aquifers are generally used.

Some ATES systems built to date include a 1.7 million cubic meter storage reservoir under Eindhoven University of Technology, The Netherlands, for 20 university buildings (2001); a one million cubic meter storage reservoir under Arlanda Airport in Stockholm for the Stockholm airport (2011); and a 180,000 cubic meter storage reservoir under the Riverlight Project in London for a new residential and mixed-use complex (2014).

The **Eindhoven ATES system** provides both direct cooling during summer and low-temperature heating during winter for heat pumps. 16 wells for cooling and 16 wells for heating are maintained. The aquifer lies between 28 and 80 m below the surface and has a natural temperature of 11.8 ^{o}C. The temperature in the aquifer varies from 6 to 16 ^{o}C during the year due to extraction or addition of heat. The maximum heating and cooling energy delivered is 15 to 30 GWh per year. The maximum charge and discharge rate of the reservoir for both heating and cooling is 17 MW (IEA, 2018a).

The **Stockholm airport ATES system** is also used for both heating and cooling. During winter, heat stored in the aquifer from the summer is used to preheat air used for ventilation in the terminal buildings and to melt snow at the gates. The extraction of heat cools the aquifer during winter. As such, by summer, the aquifer water is cold. The cold water is extracted during summer and used to provide air conditioning for the terminals. The aquifer well lies 15 to 30 m below the surface. The maximum heating and cooling energy delivered is 20 GWh per year. The maximum charge and discharge rates of the reservoir for both heating and cooling are both 10 MW (IEA, 2018a). The temperature in the aquifer varies from 2 to 25 ^{o}C during the year due to extraction or addition of heat.

Transition highlight. The **Riverlight Project ATES system** is along the River Thames in London. It serves 806 residential apartments in addition to several commercial businesses. The ATES system is coupled with

heat pumps and provides cooling during the summer and heating during the winter. The system consists of 4 warm wells and 4 cold wells drilled into the London chalk aquifer. The well depths are about 100 m each. The thickness of the aquifer in this layer is about 25 m. The maximum heating and cooling energy delivered is 1.4 GWh per year. The maximum charge and discharge rate is 3.7 MW for cooling and 1.6 MW for heating (IEA, 2018a). The temperature in the aquifer varies from 8 to 24 ^{o}C during the year due to the extraction or addition of heat.

2.8.4. Passive Heating and Cooling in Buildings

The energy required to heat and cool buildings can be reduced significantly with **passive heating and cooling techniques**. These techniques include installing thermal mass, ventilated facades, window blinds, glazing on windows, and night ventilation (de Gracia and Cabeza, 2015). Each is discussed, in turn.

2.8.4.1. Thermal Mass

Thermal mass is a building material used to absorb, store and release heat in a building in such a way as to keep building temperature relatively constant during day and night. At least three types of thermal mass materials store energy. These include sensible heat storage materials, latent heat storage materials, and thermochemical storage materials.

Sensible heat storage materials are materials that do not change temperature much during day or night thus help to keep buildings near a constant temperature. Good sensible heat storage materials are materials with a combination of a high volumetric heat capacity and a moderate thermal conductivity. **Volumetric heat capacity** is the product of specific heat capacity (or just specific heat) and density. **Specific heat** is the energy (J) required to increase the temperature of 1 kg of a substance 1 K (or 1 ^{o}C). Substances with a high volumetric heat capacity absorb solar radiation during the day without their temperature increasing much and release thermal-infrared (heat) radiation at night without their temperature decreasing much. On the other hand, substances with low a volumetric heat capacity warm rapidly during the day upon absorbing sunlight and cool rapidly at night upon releasing heat radiation.

The volumetric heat capacity of liquid water is 3.5 times that of loose sand (Table 2.4). As such, the same amount of sunlight heats up a given volume of loose sand 3.5 times as much as it does water. This is why ocean beach water is relatively cool during the day whereas sand feels hot. Conversely, the loss of the same amount of heat radiation at night decreases the temperature of sand 3.5 times the temperature decrease of water.

Conduction is the transfer of energy from molecule to molecule. The **thermal conductivity** of a substance is a measure of its ability to conduct heat in the presence of a temperature gradient. Units of thermal conductivity are W/m-K, which is the same as J/m-K-s. A thermal conductivity of 1 W/m-K means that a 1-m-long material will transfer 1 J per second from one end of the material to the other if the temperature difference between one end and the other is 1 K. Steel has a thermal conductivity of 45 W/m-K, thus it is extremely conductive. Pinewood, on the other hand, has a conductivity of 0.15 W/m-K, which is hardly conductive.

A good thermal mass material should have a moderate thermal conductivity. If the conductivity is too high, such as with steel, the material will transfer its heat (or cold) too fast to the air or other materials, even if the material has a high volumetric heat capacity. If the conductivity is too low, such as with wood, the material won't conduct its heat (or cold) to the air when the heat or cold is needed. Table 2.4 identifies materials that are **effective thermal mass materials**, namely those with high volumetric heat capacities and moderate thermal conductivities.

Table 2.4. Specific heats, densities, volumetric heat capacities, and thermal conductivities of several substances. The last column indicates the effectiveness of the substance as a thermal mass.

Substance	Specific heat (J/kg-K)	Density (kg/m^3)	Volumetric heat capacity (kJ/m^3-K)	Thermal Conductivity (W/m-K)	Effectiveness thermal mass materials
Water	4,186	1,000	4,186	0.6	High
Steel	7,800	480	3,744	45	Low
Dense concrete	1,100	2,400	2,640	1.63	High
Marble	880	2,700	2,376	1.8	High
Granite	790	2,750	2,173	1.7	High
Brick	800	1,700	1,360	0.73	High
PVC	1,000	1,380	1,380	0.19	Low
Oak	2,390	545	1,303	0.16	Low
Loose sand	830	1,442	1,197	0.2	Low
Pine	2,300	400	920	0.15	Low

Table 2.4 indicates that the use of water concrete, marble, granite, or brick in building walls or floors modulates the temperature of the building in comparison with using wood or steel. Another way to think of it is that these materials store heat during the day without raising the temperature of the building and slowly release this heat to the building air at night, keeping the building warm at night. Water can be used as a thermal mass material when it is placed in tubes in a wall or under a floor. A disadvantage of sensible heat storage in comparison with, for example, phase change material storage, is that sensible heat storage requires a larger volume of storage mass to have the same impact on building temperature as does phase change material storage.

Latent heat storage materials are materials that modulate building temperature by changing phase near room temperature. As such, they are also called **phase change materials** (PCMs). PCMs used in buildings include paraffin wax, fatty acids, and salt hydrates. Paraffin wax consists of hydrocarbon molecules with the chemical formula C_nH_{2n+2}, where n is the number of carbon atoms, typically numbering 20 to 40.

Much less mass of a phase change material than of a high volumetric heat capacity material is needed to modulate building temperature. When a PCM absorbs heat, its temperature quickly reaches its melting point at which point the material absorbs more heat in order to melt without raising its temperature.

For example, if paraffin wax is distributed within south-facing walls of a Northern-Hemisphere building, the wax absorbs heat, increasing its temperature until the melting point (37 to 65 ^{o}C, depending on which wax is used) is reached. During melting, the wax absorbs more heat, but that heat is used to melt the wax, so the wax temperature doesn't rise further until all the wax is melted. By absorbing heat without increasing in temperature, the wax keeps the building cool. After the sun goes down, the wax loses heat due to thermal-infrared radiation cooling. Once it cools to its freezing point (similar to its melting point), the melted wax freezes (solidifies), releasing latent heat to the air, keeping the air warm without the wax dropping its temperature further. Thus, PCMs keep the temperature of a wall relatively constant during the day and night. A PCM can be encapsulated within a wallboard, mixed in concrete, or mixed with insulation material.

With **thermochemical heat storage**, a chemical absorbs heat (from sunlight) and decomposes into two chemical products, which store the heat. The two products are separated until the heat is needed again (e.g., at night), at which time the products are brought together to chemically react to reproduce the original chemical and release the heat back to the air. Thus, the reaction is reversible. Thermochemical heat storage has not been used much in buildings to date.

2.8.4.2. Ventilated Façades

A **ventilated façade** is a weather-protective wall, separated by air from the wall of a building. The air between the façade and the wall can flow, providing ventilation and exchange of the warm or cold cavity air with ambient air. The cavity provides acoustic as well as thermal benefits to the building. The façade can also be made of a thermal mass material to modulate temperatures received by the building wall.

2.8.4.3. Window Blinds

Window blinds are used to control sunlight into buildings. Lowering window blinds reduces direct and diffuse ultraviolet, visible, and solar-infrared radiation into a building during hot, sunny days. Raising the blinds increases direct and diffuse sunlight penetrating into the building during cloudy days.

2.8.4.4. Window Glazing

Similarly, putting a transparent or translucent **window glazing** on a window reduces the penetration of UV, visible, and solar-infrared light into a building by increasing the window's solar reflectivity. Window glazing also reduces the outgoing thermal-infrared heat radiation from the building. An advantage of window glazing is that it can significantly reduce the penetration of UV radiation into a building, reducing damage to furniture and people's skin and eyes. During the winter, though, the reduction in solar radiation penetrating into a room may be greater than the reduced heat loss from the room, resulting in a cooler room than desired. However, in the annual average, glazing is usually beneficial in terms of heat and always beneficial in terms of reducing UV radiation.

2.8.4.5. Night Ventilation

Night ventilation is the use of natural ventilation to remove heat from a building during the night. During the day, thermal mass in a building heats up due to absorption of solar and thermal-infrared radiation. During the night, thermal mass releases its heat to the building, keeping the building warm. However, in hot climates, building heat can accumulate during the day and night over periods of days to weeks, even with a thermal mass. To shed some of this heat, night ventilation is useful. Night ventilation takes advantage of either nighttime wind or thermally generated pressure to push heat added to the air inside the building out of a stack to the outside air. In all cases, cool outside air flushes the warm inside air. Since the inside air is now cooler, the thermal mass in the building cools down further as well. The next day, the thermal mass does not heat so much as it would with no nighttime ventilation.

2.8.5. Cold Storage in Ice

A type of thermal energy storage that is effectively a type of electricity storage is cold storage in ice. **Ice storage** has been used for decades in universities, hospitals, stadiums, and other large facilities. It involves freezing liquid water to produce ice when excess electricity is available or when electricity prices are low, then running water through coils in the ice when cooling is needed (Figure 2.29). Water passing through coils embedded in ice is chilled by conduction, and the cold water is piped to a building. In the building, the cold water is run through a radiator to air condition the building. In this way, ice storage avoids the need for daytime electricity use for air conditioning. Since summer electricity demand peaks during the late afternoon in many places, ice storage is a method of reducing peak electricity demand in these places. The main advantage of ice storage over battery storage is the lower cost of ice storage. Ice storage costs \$35 to \$40/kWh-thermal storage. The round trip efficiency (cooling energy output to electricity input) of ice storage is around 82.5 percent (IRENA, 2013).

Figure 2.29. Example of ice storage. Ice is formed when excess electricity is available or when the electricity price is low. When cooling is needed, such as during a hot afternoon, liquid water flows through the coils in the ice. The cold water is then piped to a building to cool the building, thereby reducing air conditioning electricity demand. As such, ice storage shifts the time of electricity use, just as a battery does. © Ice Energy (Ice Bear 40 energy storage copper ice coils).

2.8.6. Hydrogen Storage

In a 100 percent WWS world, hydrogen will be used primarily in fuel cells to provide electricity to run an electric motor in transportation vehicles (Section 2.2.2). The modes of transport that will benefit most from hydrogen use will be long-distance, heavy transport, namely long-distance ships, aircraft, trucks, and trains. Electrolysis will produce the hydrogen for fuel cells. Electrolysis couples electricity with water in an electrolyzer to split the water into hydrogen plus oxygen (Section 2.2.2.1). In a WWS world, all electricity will be produced with WWS sources.

Hydrogen for fuel cell vehicles will either be used immediately or stored in a storage tank. An advantage of using hydrogen in a 100 percent WWS economy is that WWS electric power generators can produce hydrogen when excess WWS electricity is available on the grid. Currently, excess WWS electricity is curtailed or shed, resulting in wasted electricity and a higher cost of WWS generators than necessary. If excess WWS electricity is used to produce hydrogen, and if the hydrogen is stored, the cost of WWS generation will be lower than if the WWS electricity is shed. In a similar manner, excess WWS electricity can power heat pumps to produce heat or cold for storage and later use. As such, electricity, heat, cold, and hydrogen can work together to help power a 100 percent WWS economy at low cost.

At 1 bar of pressure and 0 $^{\circ}$C, hydrogen gas' density is 0.08988 kg/m^3. For comparison, gasoline's density at 1 bar is 750 kg/m^3. Since hydrogen gas has a low density, it requires a large storage volume. Alternatively, hydrogen can be compressed into a small volume or its temperature can be dropped until it liquefies.

Compressed hydrogen is usually used in hydrogen fuel cell ground vehicles or stored in tanks for later use. Liquefied (**cryogenic**) hydrogen is usually used in aircraft, rockets, and Space Shuttles to minimize storage volumes. However, cryogenic hydrogen can be used in ground vehicles as well.

For ground transport, hydrogen is usually compressed to 350 bars or 700 bars. At 350 bars and 15 ^{o}C, hydrogen density is about 26 kg/m^3. At 700 bars and 15 ^{o}C, hydrogen density is about 40 kg/m^3. Hydrogen storage containers for use in vehicles at these pressures are made of either low-alloy steel or a composite material or both. Long-term exposure to hydrogen can make the steel brittle, which is why composites are useful. Stationary compressed hydrogen storage containers are often made of these materials, but in some cases, they are made of both stainless steel and carbon steel encapsulated within pre-stressed concrete (e.g., Feng, 2018).

Liquefied hydrogen is obtained by reducing hydrogen's temperature below its boiling point, which is -252.882 ^{o}C (20.268 K) at an ambient pressure of 1 bar. At 1 bar of pressure, liquefied hydrogen's density is 70.9 kg/m^3, thus higher than compressed hydrogen's density. Cryogenic hydrogen is stored in cryogenic tanks below the boiling point temperature of hydrogen. If the tank is closed, even a small increase in temperature will evaporate hydrogen, building up the pressure from 1 bar to 10^4 bars. As such, cryogenic hydrogen tanks require additional insulation to prevent hydrogen from evaporating (boiling).

About 12.8 percent of the energy stored in cryogenic hydrogen (15.3 MJ/kg out of 119.96 MJ/kg) is needed to cool the hydrogen enough to liquefy it. Cryogenic hydrogen has one-fourth the energy density as jet fuel. But, because the overall energy conversion efficiency of jet fuel is 0.25 to 0.4, whereas that of a fuel cell system is 0.34 to 0.56, the volume ratio of hydrogen fuel to jet fuel in an aircraft is only 1.8 to 4.8 (Example 2.2). As such, a cryogenic hydrogen storage tank needs to be more voluminous than does a jet fuel storage tank.

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