4.1 Energy storage
Energy storage - motivations

Several reasons motivate the storage of energy, either as heat, cold, or electricity:

- Supplies of energy are in many cases intermittent: *supply / demand mismatch*
- Increased *efficiency* of energy use must be part of the future’s energy distribution and use methods
- Improved *materials* based on nanotechnology (for example) allow for more advanced energy-related applications
- Linked to *renewable energy phase-in & fossil energy phase-out*
  - less emissions to the atmosphere and other environmental impact
  - but (!) not necessarily *water-use-efficient*.

---

Energy storage – options 1/2

- To be distinguished: storage of energy as physical exergy, and storage as chemical exergy (fuels, batteries)

- This gives the following main options:

  1. Storing energy as *chemical exergy* electricity in batteries (chemical potential) or using heat or power to produce fuel (e.g. H₂, ethanol) or reduced oxides (Si, Zn), including ”solar fuels”

Energy storage – options 2/2

- This gives the following main options:
  
  2. Storing energy as **physical exergy**:
    - Potential energy storage (e.g. pumped hydropower)
    - Compression/expansion of gas (e.g. compressed air storage)
    - Thermal storage as sensible heat: specific heat \( \times \Delta \) temperature
    - Thermal storage as latent heat: heat of vaporisation, condensation

- Important are, besides (of course) energy storage density (ESD), (J/kg or J/m\(^3\)):
  - Reversibility (i.e. repeatability), speed of charge/discharge, and stability (e.g. battery life, melt/solidify/melt/solidify ....... stability)
  - Size and weight
  - Complexity and of course costs (capex, opex)

ES supply or demand management

Energy storage is used for (a) supply management and (b) demand management.

Source: SS13
Mechanical energy storage: hydro

A pumped hydrostorage plant

![Diagram of a pumped hydrostorage plant]

Pictures: DR02

Mechanical energy storage: air

Compressed-air ES systems: (a) sliding pressure system, (b) compensated pressure system

![Diagram of compressed-air ES systems]

Pictures: DR02
Chemical energy: hydrogen, methane

methylene production from renewable electricity

Source: SS13

Energy density of selected compounds, based on reaction with O₂

Chemical energy: hydrogen storage

(a) Spherical storage tank of NASA [67] and (b) horizontal storage tank at the Linde Hydrogen Center, Unterschleissheim, Germany

Source: SS13

Investment costs gaseous storage
Chemical energy: ammonia

Source: SS13

Chemical energy: batteries

Source: SS13
# Secondary batteries: comparison

<table>
<thead>
<tr>
<th>Property</th>
<th>For electric vehicles</th>
<th>For stationary energy storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LIB</td>
<td>Li-S</td>
</tr>
<tr>
<td>Theoretical energy density (Wh kg⁻¹)</td>
<td>400-600</td>
<td>-2500</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>&gt; 90</td>
<td>80-90</td>
</tr>
<tr>
<td>Practical energy density (Wh kg⁻¹)</td>
<td>-300</td>
<td>-500</td>
</tr>
<tr>
<td>(electrode)</td>
<td>(electrode)</td>
<td>(electrode)</td>
</tr>
<tr>
<td>(cell)</td>
<td>-160 (cell)</td>
<td>-350 (cell)</td>
</tr>
<tr>
<td>Cycle life (year)</td>
<td>-5</td>
<td>-</td>
</tr>
<tr>
<td>Capital cost (US$ kWh⁻¹)</td>
<td>&gt; 1000</td>
<td>-</td>
</tr>
<tr>
<td>Prospective</td>
<td>High theoretical energy density</td>
<td>High theoretical energy density</td>
</tr>
<tr>
<td>Constraint</td>
<td>High cost</td>
<td>Limited driving distance</td>
</tr>
<tr>
<td>Source: SS13</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

---

**Na-S**

![Diagram: High-temperature sodium-sulfur battery (Wilbur, 1985)](image)

**T4.1 cell durability**

![Graph: Capacity and Efficiency over Charge and Discharge Cycles](image)

**Source: SS13**
Li-air batteries

Aqueous (fast) – but water is consumed:

\[ 4 \text{Li} + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4\text{LiOH} \quad E^\circ = 3.45 \text{ V} \]

Non-aqueous (as in Figure):

\[ 2\text{Li} + \text{O}_2 \rightarrow \text{Li}_2\text{O}_2 \quad E^\circ = 3.10 \text{ V} \]

ES technologies and costs

<table>
<thead>
<tr>
<th>Storage technology</th>
<th>Storage mechanism</th>
<th>Power (MWh)</th>
<th>Capacity (MWh)</th>
<th>Storage period</th>
<th>Density (\text{kg m}^{-3})</th>
<th>Efficiency (%)</th>
<th>Lifetime (No. of cycles)</th>
<th>Cost ($ \text{kWh}^{-1}) delivered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium ion (Li ion)</td>
<td>Electrochemical</td>
<td>&lt; 1.7</td>
<td>&lt; 22</td>
<td>Day–month</td>
<td>84–160</td>
<td>0.89 – 0.88</td>
<td>1230–1377</td>
<td>620–2760</td>
</tr>
<tr>
<td>Sodium–sulfur (NaS) battery</td>
<td>Electrochemical</td>
<td>1–60</td>
<td>7–450</td>
<td>Day</td>
<td>99–150</td>
<td>0.75 – 0.86</td>
<td>1620–4500</td>
<td>210–920</td>
</tr>
<tr>
<td>Lead acid battery</td>
<td>Electrochemical</td>
<td>0.1–30</td>
<td>&lt; 30</td>
<td>Day–month</td>
<td>22–34</td>
<td>0.65 – 0.85</td>
<td>160–1060</td>
<td>350–850</td>
</tr>
<tr>
<td>Redox/flow battery</td>
<td>Electrochemical</td>
<td>&lt; 7</td>
<td>&lt; 10</td>
<td>Day–month</td>
<td>18–28</td>
<td>0.72 – 0.85</td>
<td>1510–2780</td>
<td>650–2730</td>
</tr>
<tr>
<td>Compressed air energy storage (CAES)</td>
<td>Mechanical</td>
<td>2–300</td>
<td>14–2050</td>
<td>Day</td>
<td>–</td>
<td>0.4 – 0.75</td>
<td>8620–17 100</td>
<td>15–2050</td>
</tr>
<tr>
<td>Pumped hydro energy storage (PHES)</td>
<td>Mechanical</td>
<td>450–2500</td>
<td>8000–190 000</td>
<td>Day–month 0.27 at 100 m</td>
<td>0.63 – 0.85</td>
<td>12 800–33 000</td>
<td>540–2790</td>
<td>40–160</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Chemical</td>
<td>Varies</td>
<td>Varies</td>
<td>Indefinite</td>
<td>34 000</td>
<td>2.7–160 at 1–700 bar</td>
<td>0.22–0.50</td>
<td>384–1408</td>
</tr>
<tr>
<td>Methane</td>
<td>Chemical</td>
<td>Varies</td>
<td>Varies</td>
<td>Indefinite</td>
<td>16 000</td>
<td>10 at 1 bar</td>
<td>0.24–0.42</td>
<td>–</td>
</tr>
<tr>
<td>Sensible storage – water</td>
<td>Thermal</td>
<td>&lt; 100</td>
<td>&lt; 100</td>
<td>Hour–year</td>
<td>10–50</td>
<td>0.5–0.9</td>
<td>5000</td>
<td>–</td>
</tr>
<tr>
<td>Phase change materials (PCMs)</td>
<td>Thermal</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>Hour–week</td>
<td>50–150</td>
<td>0.75–0.9</td>
<td>5000</td>
<td>–</td>
</tr>
<tr>
<td>Thermochemical storage (TCS)</td>
<td>Thermal</td>
<td>&lt; 10</td>
<td>&lt; 10</td>
<td>Hour–week</td>
<td>120–250</td>
<td>0.8–1</td>
<td>3500</td>
<td>–</td>
</tr>
</tbody>
</table>

Source: SS13
Thermal energy storage: water

- ~2200 kJ/kg
- ~4.2×ΔT kJ/kg
- ~330 kJ/kg

Nanomaterials for TES

TES applications:
- Building heating / cooling
  e.g. PCM materials
- Electronics
- Automotive, IC engine
- Solar collectors

Organics
- Nanocomposites
- Inorganic Nanocomposites
- Ethylene
- Water Based
- Glycol
- Oil

Inorganics
- Nanomaterials
- Metals
- Metals Oxides
- Quantum Dots (QD)
- Nanotubes
- Nanocapsules
- Organics
- Organics Inorganics
- Inorganics
- Inorganic Nanoparticles

Source: DR02
4.2 Thermal energy storage: heat

General TES stages & types

<table>
<thead>
<tr>
<th></th>
<th>Small-scale/decentralized storage</th>
<th>Large-scale/centralized storage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New</td>
<td>Existing</td>
</tr>
<tr>
<td>Diurnal latent TES (e.g., salt hydrates)</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Diurnal sensible TES</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Seasonal latent TES</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Seasonal sensible TES (e.g., aquifers, rocks)</td>
<td>+++</td>
<td>-</td>
</tr>
</tbody>
</table>

+++ high probability; ++, medium probability; +, low probability.

Source: DR02
**Solar energy driven TES**

**Rock-bed/ solar TES**

**Solar storage tanks:**
(a) Direct link to collector;
(b) Sensible TES with heat exchanger;
(c) Thomason's technique with both water and stone as storage media

**Source: DR02**

---

**Thermal stratification TES**

**Types and configurations of storage tanks**

*HX = heat exchanger*

*HTF = heat transfer fluid*

---

**Source: DR02**
Aquifer TES (ATES)

Heat pump + ATES

Source: DR02

Solar ponds

A cross-section representation of a typical salinity-gradient solar pond

(see also course part 2b, and ÅA course New Energy Technologies)

Source: DR02
Evacuated solar collector TES

(a) Evacuated solar collector, (b) an integrated tank system

(see also course part 2b, and AA course New Energy Technologies)

Source: DR02

Phase change materials (PCMs)

Source: http://www.climatetechwiki.org/technology/jiqweb-pcm-0
Phase change materials (PCMs)

There are many different methods of using PCM storage systems for heating or cooling buildings, as demonstrated by the following concepts (Lane, 1988):

- A PCM melting at 5–15°C could be used for cool TES. The PCM is frozen by operating a chiller at night, when electricity demand and prices are low, and melted during the day to cool the building.
- A PCM melting near room temperature, for example, CaCl₂·6H₂O, which has a melting point (m.p.) of 27°C, could be incorporated into a building structure to temper diurnal swings in ambient temperature.
- A building could be heated and cooled using heat pumps that are connected to circulating water tempered by a PCM melting at 20–35°C, for example, CaCl₂·6H₂O (m.p. = 27°C).
- A solar hot-air heating system could use a PCM melting at 25–30°C, for example, CaCl₂·6H₂O, to provide night-time heating and as a preheat for daytime heating.
- A solar hot-air heating system could use a PCM melting at 40–60°C, for example, Mg(NO₃)₂·6H₂O–MgCl₂·6H₂O eutectic (m.p. = 58°C), for day and night heating.
- Domestic hot water could be preheated in a tank filled with an encapsulated PCM melting at 55–70°C, for example, Mg(NO₃)₂·6H₂O–MgCl₂·6H₂O eutectic.
- A solar hot-water baseboard system could employ a PCM melting at 60–95°C, for example, Mg(NO₃)₂·6H₂O (m.p. = 89°C).
- Off-peak electricity could be used to melt a PCM (with m.p. above 25°C) to heat a building during later periods.
- Concentrated solar energy could be used with a PCM melting at 100–175°C, for example, Mg(NO₃)₂·6H₂O (m.p. = 117°C), to drive an absorption air-conditioner.  

Source: DR02
### PCMs Physical Properties 1/2

<table>
<thead>
<tr>
<th>Compound</th>
<th>Melting temp. (°C)</th>
<th>Heat of fusion (kJ/kg)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inorganics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgCl₂ · 6H₂O</td>
<td>117</td>
<td>168.6</td>
<td>0.570 (liquid, 120 °C)</td>
<td>1450 (liquid, 120 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.694 (solid, 90 °C)</td>
<td>1569 (solid, 20 °C)</td>
</tr>
<tr>
<td>Mg(NO₃)₂·6H₂O</td>
<td>89</td>
<td>162.8</td>
<td>0.490 (liquid, 95 °C)</td>
<td>1550 (liquid, 94 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.611 (solid, 37 °C)</td>
<td>1636 (solid, 25 °C)</td>
</tr>
<tr>
<td>Ba(OH)₂·8H₂O</td>
<td>78</td>
<td>265.7</td>
<td>1.255 (solid, 23 °C)</td>
<td>2070 (solid, 24 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.653 (liquid, 85.7 °C)</td>
<td>1937 (liquid, 84 °C)</td>
</tr>
<tr>
<td>Zn(NO₃)₂·6H₂O</td>
<td>39</td>
<td>146.9</td>
<td>0.464 (liquid, 30.9 °C)</td>
<td>1937 (liquid, 84 °C)</td>
</tr>
<tr>
<td>CaBr₂·6H₂O</td>
<td>34</td>
<td>115.5</td>
<td>2.94 (solid, 24 °C)</td>
<td>1562 (solid, 32 °C)</td>
</tr>
<tr>
<td>CaCl₂·6H₂O</td>
<td>29</td>
<td>190.8</td>
<td>0.540 (liquid, 38.7 °C)</td>
<td>1802 (solid, 24 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.088 (solid, 23 °C)</td>
<td></td>
</tr>
<tr>
<td>Organics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paraffin wax</td>
<td>64</td>
<td>173.6</td>
<td>0.167 (liquid, 63.5 °C)</td>
<td>790 (liquid, 65 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.346 (solid, 33.6 °C)</td>
<td>916 (solid, 24 °C)</td>
</tr>
<tr>
<td>Polyglycol E400</td>
<td>8</td>
<td>99.6</td>
<td>0.187 (liquid, 38.6 °C)</td>
<td>1125 (liquid, 25 °C)</td>
</tr>
<tr>
<td>Polyglycol E600</td>
<td>22</td>
<td>127.2</td>
<td>0.187 (liquid, 38.6 °C)</td>
<td>1126 (liquid, 25 °C)</td>
</tr>
</tbody>
</table>

......continues on next page

**Source:** DR02

### PCMs Physical Properties 2/2

<table>
<thead>
<tr>
<th>Compound</th>
<th>Melting temp. (°C)</th>
<th>Heat of fusion (kJ/kg)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyglycol E6000</td>
<td>66</td>
<td>190.0</td>
<td>-</td>
<td>1085 (liquid, 70 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>1212 (solid, 25 °C)</td>
</tr>
<tr>
<td>Fatty acids</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stearic acid</td>
<td>69</td>
<td>202.5</td>
<td>-</td>
<td>848 (liquid, 70 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>965 (solid, 24 °C)</td>
</tr>
<tr>
<td>Palmitic acid</td>
<td>64</td>
<td>185.4</td>
<td>0.162 (liquid, 68.4 °C)</td>
<td>850 (liquid, 65 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>989 (solid, 24 °C)</td>
</tr>
<tr>
<td>Capric acid</td>
<td>32</td>
<td>152.7</td>
<td>0.153 (liquid, 38.5 °C)</td>
<td>878 (liquid, 45 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>1004 (solid, 24 °C)</td>
</tr>
<tr>
<td>Caprylic acid</td>
<td>18</td>
<td>148.5</td>
<td>0.149 (liquid, 38.6 °C)</td>
<td>901 (liquid, 30 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>981 (solid, 13 °C)</td>
</tr>
<tr>
<td>Aromatics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biphenyl</td>
<td>71</td>
<td>119.2</td>
<td>-</td>
<td>991 (liquid, 73 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-</td>
<td>991 (liquid, 73 °C)</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>80</td>
<td>147.7</td>
<td>0.132 (liquid, 83.8 °C)</td>
<td>976 (liquid, 84 °C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.341 (solid, 49.9 °C)</td>
<td>1145 (solid, 20 °C)</td>
</tr>
</tbody>
</table>

**Source:** Lane (1980).

**See also:** Pielichosewka and Piliechowski, Progr. Mat. Sci. 65 (2014) 67-123

**Source:** DR02
MgCO₃ (from large-scale CO₂ mineralisation) and TES

\[ \text{MgCO}_3 + x\text{H}_2\text{O} \leftrightarrow \text{MgCO}_3\cdot x\text{H}_2\text{O} + \text{heat} \]

See also PCT/US97/15577:

**Magnesium Carbonate (MgCO₃):**

NOTE: The starting endothermic material is composed of Magnesium Carbonate (MgCO₃), Mg(OH)₂, and H₂O, i.e.: n MgCO₃ : n Mg(OH)₂ : n H₂O.

n MgCO₃ : n Mg(OH)₂ : n H₂O decomposes to →

n MgO + CO₂ and n H₂O at 300°C absorbing 285 cal/gm.

---

**4.3 Thermal energy storage for buildings & integration with heat pumps**

*(incl. R&D @ ÅA)*
Solar TES with a heat pump

Energy conservation for seasonal thermal energy storage with heat pump.


Water sorption on/with a salt

TE storage density with sorption

![Graph showing various storage materials and their energy storage density.]


---

TE seasonal storage: open / closed

![Diagram comparing open and closed systems with integrated reactor.]

Open (left) vs. closed (right) systems with integrated reactor.

*A. Solé et al. / Renewable and Sustainable Energy Reviews 47 (2015) 386–398*

---

TES: hydrated magnesium carbonates

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Hydration temp. (°C)</th>
<th>$\Delta G = 0$ (°C)</th>
<th>90% dehydr. (°C)</th>
<th>Dehydr. temp. (°C)</th>
<th>Specific Capacity (MJ/kg)</th>
<th>Specific capacity (GJ/m³)</th>
<th>Specific capacity (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{MgCO}_3 + 3\text{H}_2\text{O}(g) = \text{MgCO}_3 \cdot 3\text{H}_2\text{O}$</td>
<td>-20</td>
<td>45</td>
<td>61</td>
<td>60-65</td>
<td>1.0</td>
<td>1.83</td>
<td>490</td>
</tr>
<tr>
<td>$\text{MgCO}_3 + x\text{H}_2\text{O}(l) = \text{MgCO}_3 \cdot x\text{H}_2\text{O}$</td>
<td>Irrev.</td>
<td>Irrev.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{MgCO}_3 + 5\text{H}_2\text{O}(g) = \text{MgCO}_3 \cdot 5\text{H}_2\text{O}$</td>
<td>5-10</td>
<td>55</td>
<td>66</td>
<td>65-70</td>
<td>1.41</td>
<td>2.54</td>
<td>705</td>
</tr>
<tr>
<td>$\text{MgSO}_4 + x\text{H}_2\text{O}(g) = \text{MgSO}_4 \cdot x\text{H}_2\text{O}$</td>
<td>-20</td>
<td>145</td>
<td>153</td>
<td>122(1)</td>
<td>1.7</td>
<td>2.9</td>
<td>806</td>
</tr>
<tr>
<td>$2\text{H}_2\text{O}(20 ^\circ \text{C}) = 2\text{H}_2\text{O}(60 ^\circ \text{C})$</td>
<td>20(2)</td>
<td>-</td>
<td>65(3)</td>
<td>100</td>
<td>0.17</td>
<td>0.17</td>
<td>93</td>
</tr>
<tr>
<td>$\text{Silica Gel}$</td>
<td>-20</td>
<td>-</td>
<td>65(3)</td>
<td>100</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Silica Gel dehydrated at 65 °C)</td>
<td>-20</td>
<td>-</td>
<td>-</td>
<td>65</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Zeolite HY [4]}$</td>
<td>-20</td>
<td>-</td>
<td>-110</td>
<td>110</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{Zeolite Na-Y (dehydrated)} = \text{Zeolite Na-Y (hydrated)} [4]$</td>
<td>-20</td>
<td>-</td>
<td>-140</td>
<td>140</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\text{MgCl}_2 \cdot 6\text{H}_2\text{O} = \text{MgCl}_2 \cdot 2\text{H}_2\text{O} + 4\text{H}_2\text{O}$ [6]</td>
<td>60</td>
<td>100</td>
<td>-</td>
<td>150</td>
<td>-0.5(6)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) Partly dehydrates at 122 °C [3]. 2) The required operating temperatures for using water as latent heat storage with a $\Delta T$ of 40 °C. 3) 85% dehydrated, matched to NO hydration temperature. 4) Figure from laboratory testing [6].

Source: EZ17a,b

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TES: hydrated magnesium carbonates

**Discharging heat**

- High COP: $\Delta T = 15-25 ^\circ \text{C}$
- 35-45°C → 20°C

**Storing heat**

- 10-15°C → 30°C
- Cooling Heat Pump

**Heat source:** Solar panels, secondary district heat

**Scheme of the process coupled with a heating system. In case district heating**

Source: EZ17b

"The process" = $\text{MgCO}_3 + x\text{H}_2\text{O} = \text{MgCO}_3 \cdot x\text{H}_2\text{O} + \text{heat}
4.4 Thermal energy storage: cold

(see also ÅA course 424519.0 Refrigeration / Kylteknik #8)

Cold thermal energy storage (CTES)

- Night-time off-peak (cheaper) energy can be stored (batteries) for day-time peak use for air conditioning
- Cooling capacity can be stored as cold or frozen water, or other materials such as glycol and eutectic salt + water systems
- Also special phase transition materials (PCMs) were developed
- Note also that with lower outside (night-time) temperatures, cooling and freezing processes are more efficient!

PCMs: see http://www.teappcm.com/ (Accessed April 2017)

Picture: http://www.enesystem.co.kr/english2/images/our_img04.gif
Chilled water vs. ice banks

Chilled water storage tanks

Chilled water storage tanks are usually used as buffers in the chilled water system (e.g. 6/12 °C) in order to store refrigeration energy for short periods (minutes or a few hours). This allows refrigeration equipment operation to be optimized, or they are used to improve control stability, especially if the fill volume (= storage mass) of the chilled water system is small in proportion to the installed compressor power.

Similar or identical considerations apply to chilled water storage tanks as to hot water storage tanks with regard to hydraulic circuits, control, etc. – but the other way round, of course. Therefore, this type of refrigeration energy storage will not be covered in any greater detail.

Ice banks

Due to the phase transition from ice to water (and vice versa), ice has an 80 times greater thermal storage capacity than water. Therefore, ice banks are also referred to as PCM (phase change material) devices.

Ice banks offer a much greater storage density (kWh/m³ or kWh/m² of required floor space) than chilled water storage tanks.

The temperature level of the ice bank is around 0 °C due to the phase transition, which has additional advantageous effects.

The use of ice banks offers many advantages but requires appropriate basic control knowledge and correct hydraulic integration into the overall refrigeration system. These topics will be covered in the following.

Source: S?

Ice bank with plastic-filled balls

- ↑ An ice CTES system has 18x more capacity per kg than a water CTES system
- Example of an ice TES system → atmosperic ice ball (single tank) system

Pictures: DR02
Partial storage vs. full storage

Sources

- ESA: Energy storage association http://energystorage.org/
- EZ17b: Erlund, R., Zevenhoven, R. “Hydration of magnesium carbonate in a thermal energy storage process and its heating application design” ECOS’2017, July 2-6, 2017, San Diego (CA) USA - paper 182
- S??: Refrigeration technology, Siemens Building technologies (year?) section 7 https://www.downloads.siemens.com/download-center/Download.aspx?pos=download&fct=getasset&id1=8359