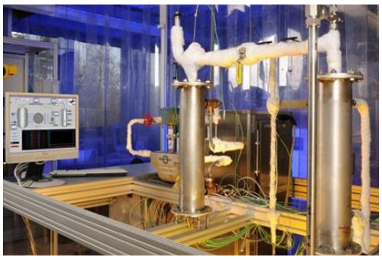
EERA Joint Program on Energy Storage
SP3 on Thermal Energy Storage
August 2018

Brochure on Thermal Energy Storage Technologies

1. Low-temperature sensible heat storage
2. High-temperature sensible heat storage
3. Low-temperature latent heat storage
4. High-temperature latent heat storage
5. Thermochemical reactions
6. Thermochemical storage with adsorption



What is the European Energy Research Alliance?

The European Strategic Energy Technology Plan (SET-Plan) is Europe's technology response to the pressing challenges of meeting its targets on greenhouse gas emissions, renewable energy and energy efficiency over the coming decades.

The European Energy Research Alliance (EERA) is an alliance of European public research centres and universities. It is one of the cornerstones of the European SET Plan. EERA brings together more than 150 research centres and universities. Actively working together on 17 joint research programmes, they build on national research initiatives. In a Joint Programme a research organisation join institutions in other European countries on shared priority setting and research projects.

What is the Joint Programme on Energy Storage?

As Europe moves towards a greater share of energy generated by renewable energy sources such as wind power and solar photovoltaic (PV), energy systems will require a greater degree of flexibility to adjust for the fluctuations in energy production. Energy storage – in combination with other technologies – is well-suited to respond to this challenge and ensure a continued security of energy supply at all times.

The EERA Joint Programme on Energy Storage is the first pan-European programme to bring together all major fields of energy storage research. JPES therefore represents a unique opportunity to align research and development activities in the field.

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BRNO UNIVERSITY OF TECHNOLOGY

DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

CIC energiGUNE
energy cooperative research centre

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1 - Low-temperature sensible heat storage

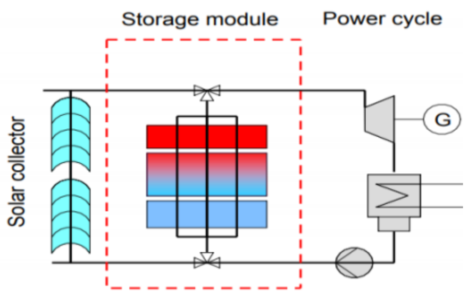
2 - High-temperature sensible heat storage

3 - Low-temperature latent heat storage

4 - High-temperature latent heat storage

5 - TCS – Chemical reactions

6 – TCS – Adsorption



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Low-Temperature Sensible Heat Storage

Storage Principle

In sensible heat storage, thermal energy is stored in a temperature change of the heat storage medium. The amount of stored heat is directly proportional to the change of the temperature.

Water is one of the most common mediums used in low-temperature thermal energy storage (TES). The range of low-temperature sensible heat storage can thus be generally defined as the temperature interval in which water exists in the liquid state at barometric pressure (0 °C – 100 °C). Most of the materials used for low-temperature sensible heat TES are inexpensive, non-toxic and recyclable.

Low-temperature sensible heat TES systems have generally very high Technology Readiness Levels (TRLs). Some of the technologies have been in use for decades. The most common methods of low-temperature sensible heat TES are heat storage tanks, water pit storage, aquifers and boreholes. The thermal mass of building structures can be utilized for heat and cold storage in built environments.

Power to heat has become another important application of low-temperature sensible heat TES given the rapid development of renewable power generation.

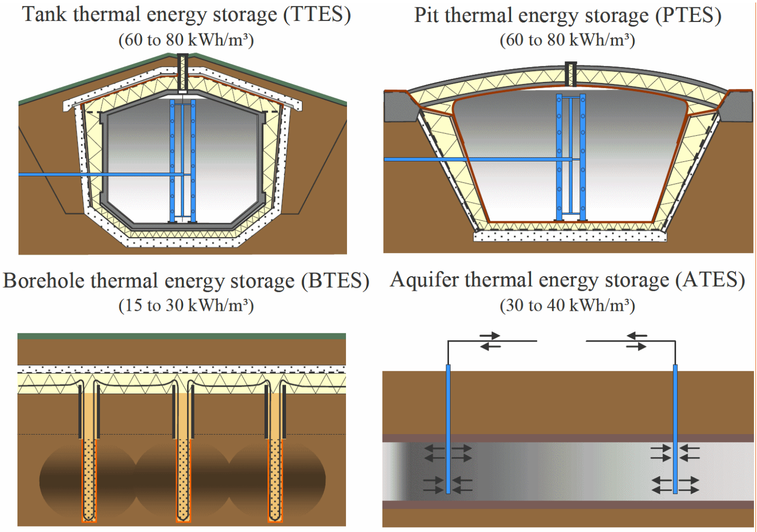

Figure 1. Methods of sensible heat thermal energy storage [1]

Figure 2. Thermal energy storage tank under construction [2]

Technical Characteristics

Power range (MW): 0 to > 20

Feasible size (MWh): small-scale (kWh-range) to over 10,000

Energy density (kWh/m^3): 15 – 80[1]

Response time (min.): < 1

Technical lifetime (y): > 20

Temperature range (°C): 0 - 100

Maturity

Worldwide use: widespread

Installation costs (€/kWh): as low as 0.5

Technology readiness level: 9

Challenges in development

- Reduction of heat losses
- More efficient heat exchangers
- Improvement of lifespan

Potential of technology

- High TRL
- Low capital costs per kWh
- Affordable and safe storage media
- Versatility and flexibility

Barriers

- Low energy density
- Suitable locations for large-scale TES

Common Applications

- Domestic hot water heating
- District heating and cooling
- Solar thermal heating plants
- Building heating and cooling systems
- Industrial process applications

Figure 3. Chilled water storage tank [3]

Example Applications

1. District heating and cooling

It is estimated that by 2050 more than 80 percent of Europe's population will live in urban areas [4]. Urban areas are particularly suitable for installation of district heating and cooling networks. Since the demand for heating and cooling changes during the day and throughout the year, thermal energy storage will have to be integrated with these systems for energy-efficient operation. Water heat storage tanks, water pit storage as well as aquifer and borehole storage are suitable for use in district heating and cooling systems.

Figure 4. District heating CHP plant with 5500 m^3 water heat storage.

2. Low-temperature solar thermal systems

Most solar thermal systems need TES to operate efficiently. Small residential solar thermal systems mostly employ water tank TES. Packed rock beds can be used in solar air heating systems. A variety of TES system exists for central solar plants. These include water tanks, pit storage, aquifers and boreholes. A new world's largest solar heating plant is commissioned almost every year and thus the demand for low-temperature sensible heat storage in solar thermal systems is increasing.

Figure 5. Solar heating plant and pit storage [5].

3. Buildings

Due to the number of TES system installations, the building sector represents the most common application of low-temperature sensible heat TES. Water tank storage systems are used in domestic hot water heating, hydronic space heating and chilled water air-conditioning systems. The thermal capacity of building structures can also be employed for TES. Boreholes under a building can be used for rejection of heat from air-conditioning systems in summer and as a heat source for heat pumps in winter.

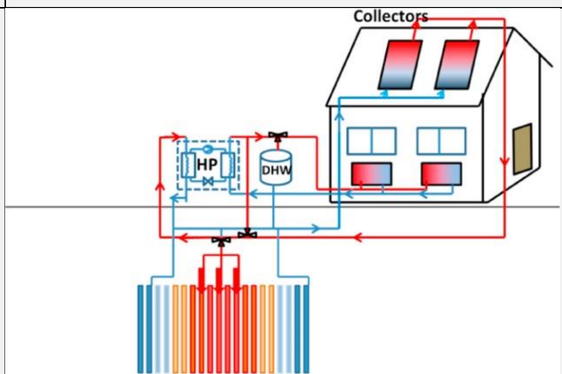

Figure 6. Borehole thermal energy storage [6].

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High-Temperature Sensible Heat Storage

Storage Principle

Sensible high temperature heat storage (SHTHS) raises or lowers the temperature of a liquid or solid storage medium (e.g. sand, pressurized water, molten salts, oil, ceramics, rocks) in order to store and release thermal energy for high-temperature applications (above 100°C). The amount of stored heat is proportional to the density, specific heat, volume, and temperature variation of the storage materials. Basically, specific heat, density and thermal conductivity are the main thermal properties of sensible heat storage materials. Fig. 1 shows the main thermal properties of sensible heat materials.

At higher temperatures the most common liquid storage material is molten salt (Fig. 2). The salt is pumped between a cold and a hot storage tank for (dis-)charging. In direct systems the salt is used as a storage medium and heat transfer fluid at the same time. Indirect systems employ a heat exchanger with an additional thermal oil cycle. Power and capacity of the storage are thus linked to separate units in the system, heat exchanger and storage tanks, respectively. Already highly commercialised, the grid-connected molten salt storage capacity for CSP grew larger than 30 GWh_{th} in 2015.

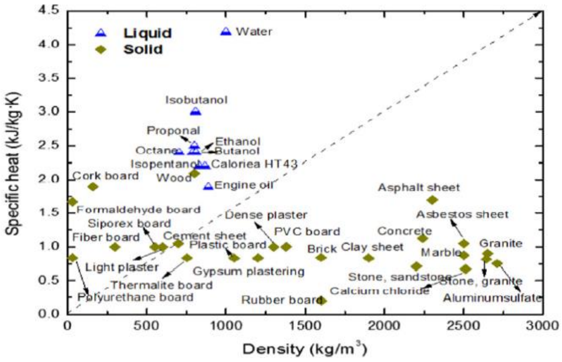

Fig. 1. Thermal properties of sensible heat materials [1].

Fig. 2. Aerial view of Crescent Dunes storage [2].

Technical characteristics

Typical Power Range (MW): up to 300 MW [5]

Feasible size: up to 6 GWh liquid, 0.1 – 4 GWh solid media

Energy density (kWh/m^3):
ΔT=200°C → 138-176 [3]
ΔT=300°C → 207-264 [3]
ΔT=500°C → 345-440 [3]

Response time: Minutes, but depends on heat transfer area (solids) and heat exchanger (liquids) and the storage design and system integration.

Technical lifetime (y): 30 [6]
Temperature range (°C):100-1000°C

Maturity

Installed worldwide:	30 GWh_{th} of molten salt in 2015
Installation costs (€/kWh):	15-40 [2]
Technology readiness level:	4 (solids) - 9 (liquids) [2]

Challenges in development

- Reduce the size by increasing operation temperature window
- Develop single tank for liquids
- Develop packed bed storage
- Identify and qualify new fluids
- Develop salt-based nanofluids

Potential of technology

- Simple application with available materials.
- Long lifetime
- Cost-effective and long storage duration

Barriers

- Limitations arising from material properties
- Pressure losses and temperature decrease at the end of discharge mode (solids)
- Large size and temperature swing.

Common Applications

- Concentrated solar power (CSP)
- Flexible and hybrid conventional thermal power plants
- Industrial waste heat recovery
- Advanced adiabatic compressed air energy storage (AA-CAES)
- Industrial process flexibility and energy efficiency in glass, cement and steel industries, etc.
- Process steam supply from pressurized water storage, a.k.a. Ruths or steam accumulator
- Regenerator (Cowper) storage in the steelmaking and glass manufacturing

Example Applications

1. Solar thermal power plants

SHTES systems increase the percentage of solar energy produced by a power plant, improve operating behaviour, and lead to higher utilization of the power block. Depending on the design of the system, the heat transfer fluid (HTF) may serve as the heat source in an evaporator, creating steam which powers a stream turbine which drives a generator, or the HTF may directly vaporized as it passes through the solar field and then pass straight through the turbine without an intermediate heat exchanger. This excess solar thermal energy is currently stored in tanks filled with molten salt as high temperature sensible heat storage medium as shown in Fig. 3 [7].

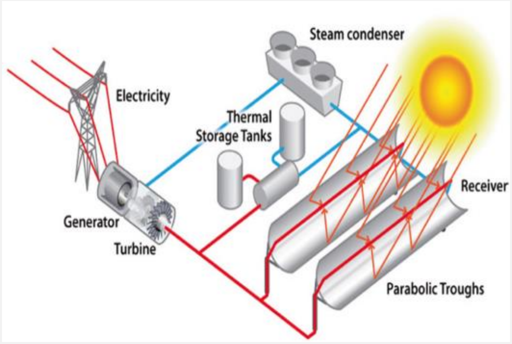

Fig. 3. A direct steam generation concentrating solar power plant with SHTES [7].

2. Waste heat valorisation in industrial processes

The implementation of a SHTES system to store discontinuous waste heat from the exhaust gas of an electric arc steel re-melting furnaces has been studied [4]. Two packed bed sensible heat TES systems were proposed in order to be used at a temperature range from 315 to 1500 °C in both the operational periods, so to time average the widely fluctuating temperature of the energy source, and in the peaking periods, so to hold energy until the demand arises (Fig. 4). The system proposed was expected to save 0.0227 MW per ton of produced steel.

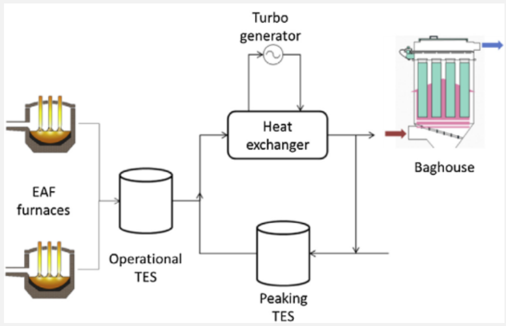

Fig.4. Steel electric arc furnace energy recovery and storage system [4].

4. Advanced adiabatic compressed air energy storage (AA-CAES).

The storage efficiency of an adiabatic CAES plants is reduced by cooling of the air before it enters the cavern, and by reheating the air prior to combustion. In the adiabatic cycle, thermal energy is extracted and stored separately before the compressed air enters the cavern. In such systems (Fig. 6), AA-CAES employs sensible storages to increase the efficiency in the storage of electricity.

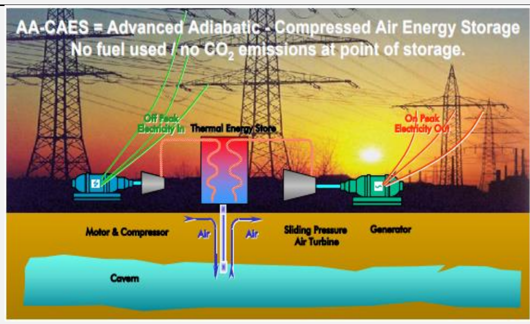

Fig. 6. Adiabatic CAES plant [9].

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Low-Temperature Latent Heat Storage

Storage Principle

Latent Heat Thermal Energy Storage (LHTES) systems with phase change materials (PCMs) store large amounts of heat at a nearly constant temperature. Most commonly applied materials are solid/liquid PCMs where the phase transition is defined by melting and solidification.

PCMs with phase change between -40 to 100 °C are especially attractive for low temperature applications, where volume plays a critical role. Otherwise, water instead of PCM is preferable because of its lower specific costs and ease of use. Most of low temperature PCMs have a low heat conductivity which then makes heat transfer enhancement techniques, i.e. fins or additives like graphite, necessary.

Figures 1 and 2 give an overview of latent heat and energy density versus phase change of PCMs reported in literature [1-5].

Most important parameters and their common values are given below:

Specific costs: 0.03 - 1 €/Wh
Heat conductivity: 0.15 – 0.7 W/mK
Energy density: 55 - 350 kJ/dm³

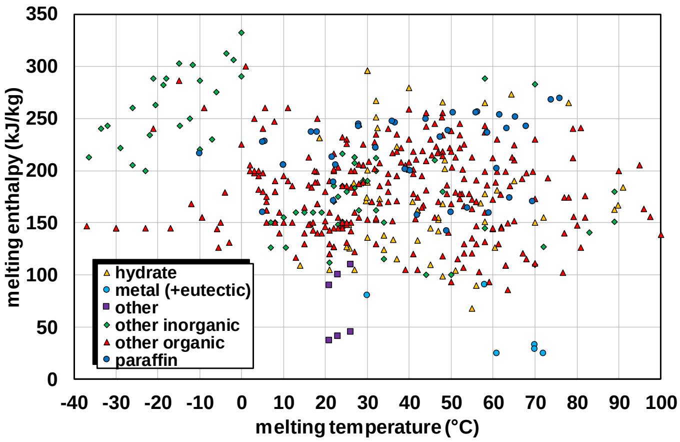

Fig. 1: Latent heat vs. phase change temperature of various low temperature PCMs (data [1-5]).

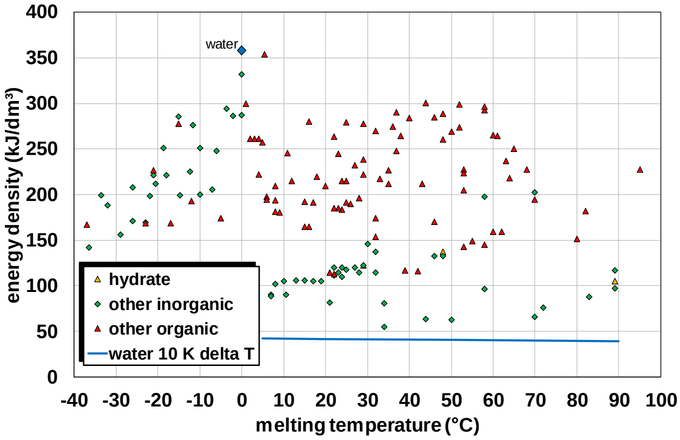

Fig. 2: Energy density vs. phase change temperature of various PCMs (data [1-5]).

Technical Characteristics

Typical Power (kW): -
Feasible size: application-dependent
Energy density (kWh/m³): 14 – 100
Response time: application-dependent
Technical lifetime (y): 10-50
Temperature range (°C): -40 - 100
Efficiency (%): -

Maturity

- Technology readiness level: 4 – 7

Challenges in development

- The research activities in the field are currently carried out at materials, components and system level.

Potential of technology

- Switchable and controllable store and release of thermal energy
- Environmental-friendly and widely available materials

Potential barriers

- High costs
- Low heat conductivity of PCM
- Toxicity, corrosivity, flammability

Common Applications

- Thermal load management and peak shaving in various applications, especially buildings
- High-performance electronics
- Automotive thermal management
- Textiles, fibers and fabrics
- Personal comfort

Example Applications

1. Thermal management for batteris

PCM was applied to a car battery module at AIT for optimal thermal management during quick charging of the batteries. Peak temperatures were reduced by 7.5 K. In that way charging times could be significantly accellerated. In figure 3, the temperature reference scenario is compared with various optimized scenarios employing PCMs. Further information can also be found in a work carried out at TU München [6].

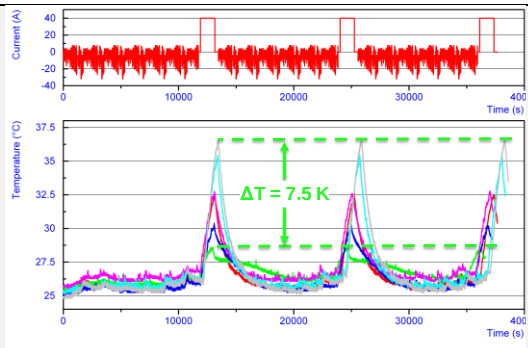

Figure 3: Peak shaving with low temperature PCMs during quick charging of batteries (source: AIT)

2. PCM in evaporators of heat pumps and air conditioning systems

The evaporator has an aditional PCM section filled with paraffin. In stop and go traffic the AC can still provide cool air with the compressor switched off. The PCM is recharged when the vehicle is moving again.[1]

This technique is also being investigated for domestic heat pumps.[2]

Figure 4: AC-Evaporator with PCM (source: Delphi Automotive PLC)

3. PCMs for personal comfort

PCMs are used in many fabrics, most of them for sports. As an example the Canadian wheelchair rugby team[3] uses PCM cooling vests. There is a whole lot of different products, including hats, caps and vests including products for pets.[4]

Figure 5: Cooling dog pad[4]

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[1] Phase Change Material evaporator
[2] www.akg-group.com
[3] Wheelchair Rugby team
[4] www.techniche-intl.com

High-Temperature Latent Heat Storage

Storage Principle

Latent heat thermal energy storage (LHTES) systems exploit melting and solidification phenomena of a phase change material (PCM) to absorb or release heat at a nearly constant temperature, as shown in Fig. 1. PCMs are particularly attractive due to high-energy storage density and small temperature variation in the storage and retrieval processes.

LHTES can be broadly classified into two categories of low temperature (up to 100°C) and high temperature (HT-LHTES, above 100°C), with the latter being described here. Depending on working temperature range and type of application, the materials for HT-LHTES can be sugar alcohols, metals and their alloys, or salts [1].

Different device designs and system configurations can be adopted for using the PCMs depending on the chemical and physical compatibility of the storage materials with heat transfer medium and containment, and thermal conductivity and volume change during phase transition of the storage materials. Fig. 2 shows some examples of device designs.

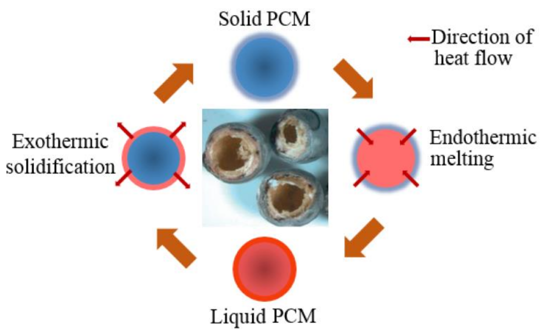
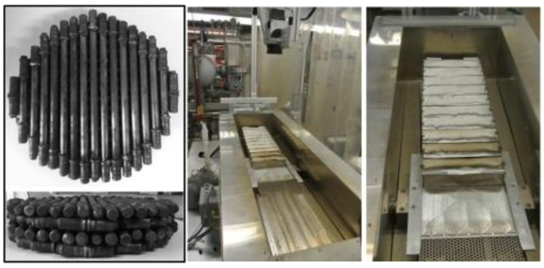


Figure 2. PCM working concept (LHTES) with 5 mm high-temperature PCM capsule with voids shown in the centre [1].



(a) (b)

Figure 2. HT-LHTES (a) encapsulated PCM [2] and (b) lab-scale testing device [2].

Technical Characteristics

Power of a single typical device (MW_{th}): 0.7- 6 [3,4]
Typical size of a single device (MWh): 0.01-10 [3]
Energy density (kWh/m³): 90-100 [3]
Typical operation mode: charge 4-10 hours; discharge 12-24 hours [7][8]
Response time (min.): 2-8 [4]
Technical lifetime (y): 10000 cycles [4]
Temperature range (°C): 100-1000[3]
Cost (€/kWh)[5]: 20-80 [3]
Efficiency (%): 90-98 [4]

Maturity

Installation costs (€/kWh)[1]: 20- 80 [4][8]
Technology readiness level: 5-8 [3]

Challenges in development

- Thermal and chemical stability at high temperatures [6]
- Mechanical stability at high temperatures
- Chemical compatibility between PCM and other components
- Cost-effective PCMs with melting temperature between 300 and 600°C

Potential of technology

- Balancing heat demand and supply for domestic, industrial and commercial applications
- Power-to-Heat applications for grid stabilisation
- Renewable heat and electrification of heat
- Waste heat utilisation

Barriers

- High component costs
- Low TRL for most HT-LHTES storage systems
- HT-PCM material availability with different melting ranges
- High cost of PCMs for some temperature ranges

[5] Projected costs for mature HT-LHTES technology.

Common Applications

- Industrial waste heat recovery for an increased efficiency and a reduced energy consumption.
- Decoupling of power and heat in cogeneration plants.
- Thermal management of thermally driven processes.
- Storage of renewable heat to facilitate a temporal separation from energy production. (Fig. 3).
- Utilization of Power-to-Heat concepts for flexible supply and/or grid stabilisation.
- LHS integration in subcritical steam cycles.

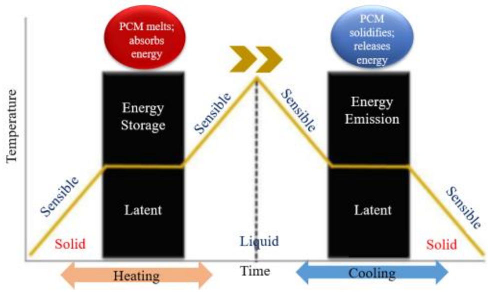


Figure 3. PCM heating-cooling cycles used in applications.

Example Applications

1. Co-generation plants

In co-generation plants, power and heat are simultaneously generated from the same fuel. In such plants, a steam generator is used to produce superheated steam for power generation, whereas heat is stored in HT-LHTES for back-up and peak shaving (Fig. 4).

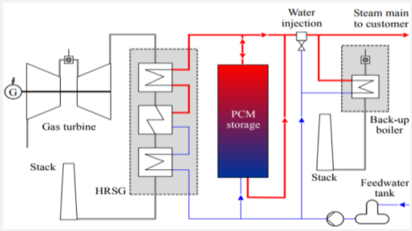


Figure 4. LTES integration in a Co-gen plant [4].

2. Concentrating Solar Power (CSP) plants

Integration of HT-LHTES with CSP offers dispatchable power, increases the share of solar electricity and reduces levelized cost of energy (Fig. 5) [7].

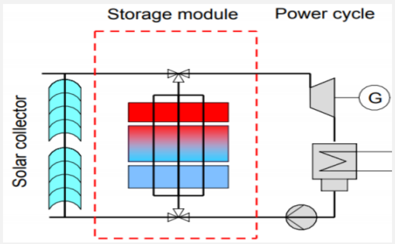


Figure 5. LHTES storage integrated with CSP [7].

3. Direct steam generation processes

Integration of HT-LHTES with direct steam generation processes ensures heat input at nearly constant temperature. Figure 6 shows a 100kWth module with inorganic PCM coupled with a solar-driven direct steam generation process

Figure 6. 100 kW, 220°C storage module [4].

4. Power-to-Heat

A system with a heating power of 6 MW and a total heat storage capacity of 36 MWh was designed and built in 2016 to provide space heating for 57,000 m^2 (Fig. 7). The system takes curtailed wind power (10kV), turning the power to heat and store the heat in high temperature composite PCM at ~700 °C. The overall thermal efficiency is >~95 % [8].

Figure 7. World's first composite PCM (700°C) plant: capacity 6 MW/35 MWh [8].

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Thermochemical Energy Storage – Chemical Reactions

Storage Principles

Thermochemical energy storage (TCS) with chemical reactions is one of the most promising storage technologies of the future. The principle of TCS is a reversible gas-solid reaction consisting of two reactants. There are two basic driving forces for the reaction: a) a supply or release of thermal energy and b) an increase or decrease in the availability of the reactants.

While some reactions offer extremely high storage densities, the main characteristics of TCS systems are that the storage period is free of losses and the heat release is controllable with respect to time, temperature and power level. Furthermore, as the reaction temperature of equilibrium reactions is a function of the gas pressure, the reaction temperature is adjustable. This has major implications that allow not only thermal energy storages to be realized, but also heat pumps, heat transformers and combinations of both [1].

$$AB(s) + \Delta H \underset{\text{exothermic}}{\overset{\text{endothermic}}{\rightleftarrows}} A(s) + B(g)$$

Figure 3. Generalized reversible gas-solid reaction mechanism.

Figure 4. 100 kWh pilot plant for TCS with quicklime (DLR).

Technical Characteristics

Typical Power (MW): application-specific

Feasible size (MWh):

Energy density (kWh/m³): 100 – 400 [2]

Response time (min.): <1 [3]

Temperature range (°C): application dependent.

Efficiency (%): very high, reversible reactions can proceed almost loss-free

Maturity

Installed worldwide (GW): N/A

Installation costs (€/kWh): N/A

Technology readiness level: 2 – 3

Challenges in development

- Need for focus on application-oriented rather than just material aspects
- Integration of gaseous reactants
- Scaling from prototypes to application-relevant sizes
- Development of new materials with tunable reaction temperatures

Potential of technology

- Switchable and controllable release of thermal energy
- Adjustable reaction temperature
- Low-cost and widely available materials
- Long-term, loss-free storage that can be used seasonally

Barriers

- Low technology readiness level for all types of technology
- Available reaction temperatures are limited
- Complex reactor design

Common Applications

- Solar thermal power plants
- Industrial process heat (heat transformation)
- Building engineering
- Automotive thermal management
- Seasonal storage and peak-shifting
- Industrial waste heat
- Buffer storage in district heating
- Domestic heating, cooling and hot water

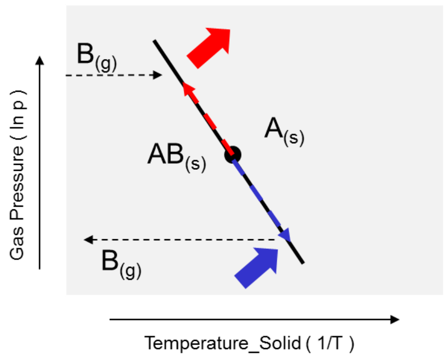

Figure 3. Reversible gas-solid reactions allow the temperature to be a function of the gas pressure.

Example Applications

1. Concentrating solar power

Thermochemical energy storages integrated in solar thermal power plants provide an improved plant capacity factor, reduced levelized cost of electricity, dispatchable power and improved energy efficiency. Quicklime a.k.a calcium hydroxide, a low-cost material widely available, can use solar heat to undergo reversible hydration reactions (with water vapour) that store the thermal energy [4].

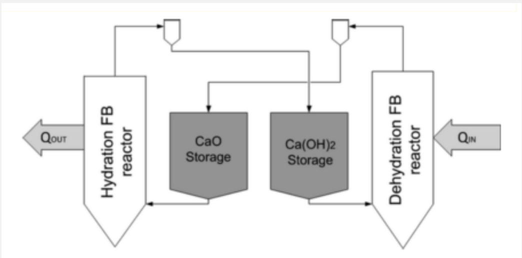

Figure 4. Basic storage system scheme [5].

2. Heat transformation in industrial processes

Heat transformation permits the storing of normally un-used waste heat at low temperatures and release at higher temperatures, with possible output temperature of over 140°C. Although similar in principle to a heat pump, a heat transformer does not require a high-grade energy source (i.e. electricity) – it is driven by low-temperature waste heat [6].

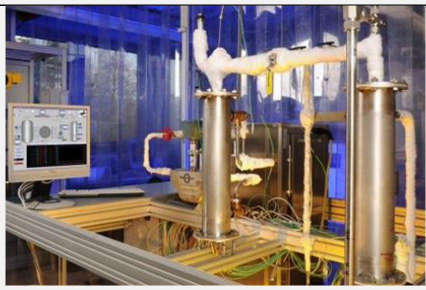

Figure 5. Test stand for thermal upgrade of waste heat at T>140 °C (DLR).

3. Thermal management in automobiles

When used with hydrogen, metal hydrides (MeH) have high power densities and fast reaction times that indicate potential for applications in automobiles. In winter, MeH devices can be used to preheat vehicle components to decrease pollutants in ICEs or improve the lifespan of fuel cells [7]. In summer, MeH devices provide cold for air conditioning that improves vehicle range [8].

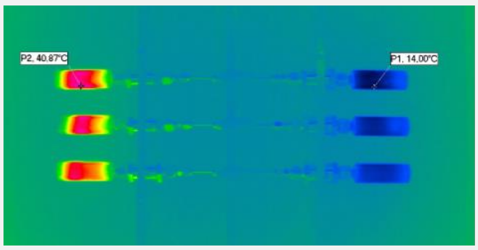

Figure 6. Experimental system with MeH.

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Thermochemical Energy Storage - Adsorption

Storage Principles

Adsorption heat storage belongs to the wider class of thermochemical heat storage. The principle on which this technology is based is the interaction between a liquid sorbate, usually water, and a solid sorbent (e.g. zeolites, silica gels, activated carbons). This interaction occurs between the sorbate molecules and the available surface of the solid, as represented in Figure 1.

Moreover, adsorption heat storages can be considered an indirect TES process. Indeed, in this case, heat is employed to drive a desorption process, which means that energy is stored in the form of adsorption potential energy. Actually, heat is stored without any loss until the refrigerant fluid (adsorbate) is kept separated from the adsorbent.

Generally, there are two system configurations for adsorption TES: closed and open cycle. Figure 2 and Figure 3 illustrate the working principles of the two configurations.

Adsorption TES is considered quite a promising technology both for seasonal and daily storage applications, nevertheless, its commercial diffusion is still not completely developed, mainly for its cost as well as lack of technical knowledge at system level. This means that there is still need for development and research, in order to make the technology commercially competitive. The research activities in the field is currently carried out at materials, components and system level.

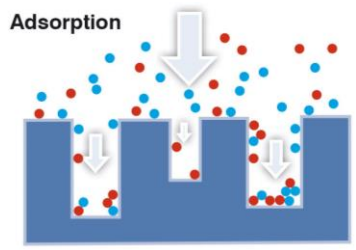

Fig. 1. Adsorption of refrigerant over the external surface of an adsorbent solid material (Klingenburg GmbH).

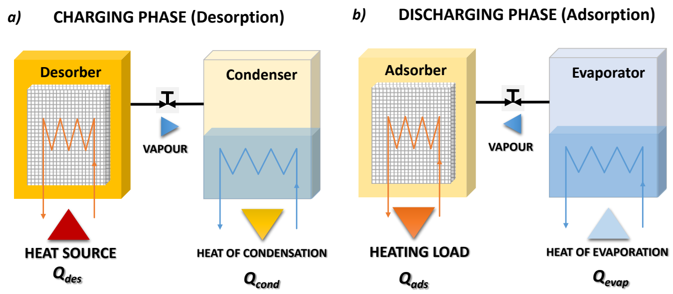

Fig. 2. Closed adsorption heat storage cycle: a) charging phase; b) discharging phase.

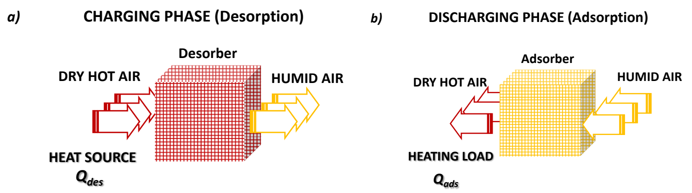

Fig. 3. Open adsorption heat storage cycle: a) charging phase; b) discharging phase.

Technical Characteristics

Typical Power (kW): 1-1000

Feasible size (MWh): depends on the application

Energy density (kWh/m³): 100 – 200

Response time (min.): < 1

Technical lifetime (y): 10-50

Temperature range (°C): 60 - 150

Maturity

- Technology readiness level: 1 - 3

Challenges in development

- The research activities in the field are currently carried out at materials, components and system level.
- Scaling from prototypes to real.

Potential of technology

- Switchable and controllable store and release of thermal energy
- Environmental-friendly

Potential barriers

- Low technology readiness level for all types of technology
- System complexity
- System Engineering

Common Applications

- Solar thermal power plants
- Industrial process heat (heat transformation)
- Solar Cooling
- Automotive thermal management
- Seasonal storage and peak-shifting
- Industrial waste heat recovery
- Buffer storage in district heating
- Domestic heating, cooling and hot water (Figure 4)

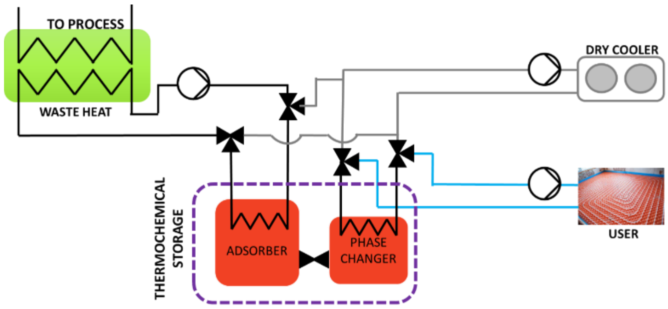

Fig. 4. Example of process diagram for the thermochemical storage

Example Applications

1. Mobile TES for Industrial application

An example of adsorption TES, is a large scale system for industrial heat recovery, storage and transportation, based on an open adsorption cycle. Figure 5 summarizes the concept, developed at ZAE Bayern laboratories [1]. It consists in recovering heat from an industrial site, by flowing hot air through a zeolite 13X bed. Once the adsorbent material is regenerated, the reactor full of dried zeolite (charged TES) is transported to the site where it is discharged, by flowing humid air through the zeolite bed, thus releasing heat to drive another industrial process.

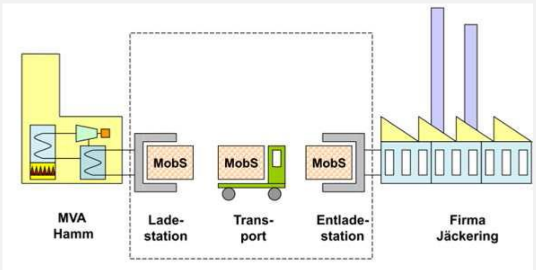

Fig. 5. Mobile adsorption TES for industrial applications.

2. Waste heat sorption storage for space cooling (Prototype)

The thermochemical storage prototype developed at ITAE is intended for cold storage starting from waste heat recovery in industrial processes at low temperature (T<100°C). Equipment cooling or space cooling are two examples of the possible applications of the storage. However, the storage is still at lab-scale and therefore there is not a specific application already set [2].

The prototype, shown in Fig. 6, consists of two vacuum chambers, representing the adsorber and the phase changer (working alternatively as condenser and evaporator). Both chambers are realised in AISI316, to avoid corrosion problems; the chamber of the adsorber has a removable cover, in order to change the heat exchangers to be tested, whereas the chamber of the phase changer is entirely welded. Inside the phase changer, 4 commercial fin-and-tube heat exchangers with copper fins and stainless steel tube have been placed.

Fig.6. Thermochemical storage installed in the lab

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