ENERGY TECHNOLOGY SYSTEMS ANALYSIS PROGRAMME

IRENA
International Renewable Energy Agency

Thermal Energy Storage

Technology Brief

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As of December 2012, the membership of IRENA comprises some 160 States and the European Union (EU), out of which 104 States and the EU have ratified the Statute.

About IEA-ETSAP

The Energy Technology Systems Analysis Programme (ETSAP) is an Implementing Agreement of the International Energy Agency (IEA), first established in 1976. It functions as a consortium of member country teams and invited teams that actively cooperate to establish, maintain, and expand a consistent multi-country energy/economy/environment/engineering (4E) analytical capability.

Its backbone consists of individual national teams in nearly 70 countries, and a common, comparable and combinable methodology, mainly based on the MARKAL / TIMES family of models, permitting the compilation of long term energy scenarios and in-depth national, multi-country, and global energy and environmental analyses.

ETSAP promotes and supports the application of technical economic tools at the global, regional, national and local levels. It aims at preparing sustainable strategies for economic development, energy security, climate change mitigation and environment.

ETSAP holds open workshops twice a year, to discuss methodologies, disseminate results, and provide opportunities for new users to get acquainted with advanced energy-technologies, systems and modeling developments.

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Insights for Policy Makers

Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. TES systems are used particularly in buildings and industrial processes. In these applications, approximately half of the energy consumed is in the form of thermal energy, the demand for which may vary during any given day and from one day to next. Therefore, TES systems can help balance energy demand and supply on a daily, weekly and even seasonal basis. They can also reduce peak demand, energy consumption, CO_2 emissions and costs, while increasing overall efficiency of energy systems. Furthermore, the conversion and storage of variable renewable energy in the form of thermal energy can also help increase the share of renewables in the energy mix. TES is becoming particularly important for electricity storage in combination with concentrating solar power (CSP) plants where solar heat can be stored for electricity production when sunlight is not available.

There are three kinds of TES systems, namely: 1) *sensible heat storage* that is based on storing thermal energy by heating or cooling a liquid or solid storage medium (e.g. water, sand, molten salts, rocks), with water being the cheapest option; 2) *latent heat storage* using phase change materials or PCMs (e.g. from a solid state into a liquid state); and 3) *thermo-chemical storage* (TCS) using chemical reactions to store and release thermal energy.

Sensible heat storage is relatively inexpensive compared to PCM and TCS systems and is applicable to domestic systems, district heating and industrial needs. However, in general sensible heat storage requires large volumes because of its low energy density (i.e. three and five times lower than that of PCM and TCS systems, respectively). Furthermore, sensible heat storage systems require proper design to discharge thermal energy at constant temperatures. Several developers in Germany, Slovenia, Japan, Russia and the Netherlands are working on new materials and techniques for all TES systems, including their integration into building walls (e.g. by encapsulating phase change materials into plaster or air vents) and transportation of thermal energy from one place to another. These new applications are just now being commercialised, and their cost, performance and reliability need to be verified.

Thermal energy storage systems can be either centralised or distributed systems. Centralised applications can be used in district heating or cooling systems, large industrial plants, combined heat and power plants, or in renewable power plants (e.g. CSP plants). Distributed systems are mostly applied in domestic or commercial buildings to capture solar energy for water and space heating or cooling. In both cases, TES systems may reduce energy demand at peak times.

A TES system's economic performance depends substantially on its specific application and operational needs, including the number and frequency of storage cycles. In general, PCM and TCS systems are more expensive than sensible heat systems and are economically viable only for applications with a high number of cycles. In mature economies (e.g. OECD countries), a major constraint for TES deployment is the low construction rate of new buildings, while in emerging economies TES systems have a larger deployment potential.

Support for research and development (R&D) of new storage materials, as well as policy measures and investment incentives for TES integration in buildings, industrial applications and variable renewable power generation is essential to foster its deployment. R&D efforts are particularly important with regards to PCM and TCS systems.

Highlights

- **Process and Technology Status –** Thermal energy storage (TES) includes a number of different technologies. Thermal energy can be stored at temperatures from -40°C to more than 400°C as sensible heat, latent heat and chemical energy (i.e. thermo-chemical energy storage) using chemical reactions. Thermal energy storage in the form of sensible heat is based on the specific heat of a storage medium, which is usually kept in storage tanks with high thermal insulation. The most popular and commercial heat storage medium is water, which has a number of residential and industrial applications. Underground storage of sensible heat in both liquid and solid media is also used for typically large-scale applications. However, TES systems based on sensible heat storage offer a storage capacity that is limited by the specific heat of the storage medium. Phase change materials (PCMs) can offer a higher storage capacity that is associated with the latent heat of the phase change. PCMs also enable a target-oriented discharging temperature that is set by the constant temperature of the phase change. Thermo-chemical storage (TCS) can offer even higher storage capacities. Thermo-chemical reactions (e.g. *adsorption* or the adhesion of a substance to the surface of another solid or liquid) can be used to accumulate and discharge heat and cold on demand (also regulating humidity) in a variety of applications using different chemical reactants. At present, TES systems based on sensible heat are commercially available while TCS and PCM-based storage systems are mostly under development and demonstration.

- **Performance and Costs –** Thermal energy storage includes a number of different technologies, each one with its own specific performance, application and cost. TES systems based on sensible heat storage offer a storage capacity ranging from 10-50 kWh/t and storage efficiencies between 50-90%, depending on the specific heat of the storage medium and thermal insulation technologies. Phase change materials (PCMs) can offer higher storage capacity and storage efficiencies from 75-90%. In most cases, storage is based on a solid/liquid phase change with energy densities on the order of 100 kWh/m^3 (e.g. ice). Thermo-chemical storage (TCS) systems can reach storage capacities of up to 250 kWh/t with operation temperatures of more than 300°C and efficiencies from 75% to nearly 100%. The cost of a complete system for sensible heat storage ranges between €0.1-10/kWh, depending on the size, application and thermal insulation technology. The costs for PCM and TCS systems are in general higher. In these systems, major costs are associated with the heat (and mass) transfer technology, which has to be installed to achieve a sufficient charging/discharging power. Costs of latent heat storage systems based on PCMs range between €10-50/kWh while TCS costs are estimated to range from €8-100/kWh. The economic viability of a TES depends heavily on application and operation needs, including the number and frequency of the storage cycles.

- **Potential and Barriers –** The storage of thermal energy (typically from renewable energy sources, waste heat or surplus energy production) can replace heat and cold production from fossil fuels, reduce CO_2 emissions and lower the need for costly peak power and heat production capacity. In Europe, it has been estimated that around 1.4 million GWh per year could be saved—and 400 million tonnes of CO_2 emissions avoided—in the building and industrial sectors by more extensive use of heat and cold storage. However, TES technologies face some barriers to market entry. In most cases, cost is a major issue. Storage systems based on TCS and PCM also need improvements in the stability of storage performance, which is associated with material properties.

Process and Technology Status

Energy storage systems are designed to accumulate energy when production exceeds demand and to make it available at the user's request. They can help match energy supply and demand, exploit the variable production of renewable energy sources (e.g. solar and wind), increase the overall efficiency of the energy system and reduce CO_2 emissions. This brief deals primarily with heat storage systems or thermal energy storage (TES). An energy storage system can be described in terms of the following properties:

- **Capacity:** defines the energy stored in the system and depends on the storage process, the medium and the size of the system;
- **Power:** defines how fast the energy stored in the system can be discharged (and charged);
- **Efficiency:** is the ratio of the energy provided to the user to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle;
- **Storage period:** defines how long the energy is stored and lasts hours to months (i.e. hours, days, weeks and months for seasonal storage);
- **Charge and discharge time:** defines how much time is needed to charge/discharge the system; and
- **Cost:** refers to either capacity (€/kWh) or power (€/kW) of the storage system and depends on the capital and operation costs of the storage equipment and its lifetime (i.e. the number of cycles).

Capacity, power and discharge time are interdependent variables and in some storage systems, capacity and power can also depend on each other. For example, in TES systems, high power means enhanced heat transfer (e.g. additional fins in the heat exchanger), which, for a given volume, reduce the amount of active storage material and thereby the capacity.

Thermal energy (i.e. heat and cold) can be stored as sensible heat in heat storage media, as latent heat associated with phase change materials (PCMs) or as thermo-chemical energy associated with chemical reactions (i.e. thermo-chemical storage) at operation temperatures ranging from -40°C to above 400°C. Typical figures for TES systems are shown in Table 1 [1], including capacity, power, efficiency, storage period and costs.

- **Sensible Thermal Energy Storage –** The use of hot water tanks is a well-known technology for thermal energy storage [2]. Hot water tanks serve the purpose of energy saving in water heating systems based on solar energy and in co-generation (i.e. heat and power) energy supply systems. State-of-the-art projects [3] have shown that water tank storage is a cost-effective storage option and that its efficiency can be further improved by ensuring an optimal water stratification in the tank and highly effective thermal insulation. Today's R&D activities focus, for example, on evacuated super-insulation with a thermal loss rate of λ = 0,01 W/mK at 90°C and 0,1 mbar and on optimised system integration.

  Hot water storage systems used as a buffer storage for domestic hot water (DHW) supply are usually in the range of 500l to several m^3. This technology is also used in solar thermal installations for DHW combined with building heating systems (Solar-Combi-Systems). Large hot water tanks are used for seasonal storage of solar thermal heat in combination with small district heating systems. These systems can have a volume up to several thousand cubic meters (m^3). Charging temperatures are in the range of 80-90°C. The usable temperature difference can be enhanced by the use of heat pumps for discharging (down to temperatures around 10 °C).

  For example (Figure 1), the solar district heating "Am Ackermann-bogen" (Munich, Germany) supplies solar energy for space heating and domestic hot water for about 320 apartments in 12 multi-story dwellings with about 30,400 m^2 of living area. The system is designed to cover more than 50% of the annual heat demand (i.e. about 2,000 MWh/a) using solar energy collected by 2,761 m^2 of flat-plate collectors. The heat collected is used either directly or stored in a 6,000 m^3 underground seasonal hot water storage. Supplementary heating is provided by an absorption heat pump driven by the city district heating system using the seasonal storage as a low temperature heat reservoir. This allows for a wide operation temperature range of the storage (i.e. between 10-90°C). Direct connection of the district system and heating installations in the houses avoids typical temperature drops at heat exchangers and increases the temperature spread. The district system is operated at a supply temperature of 60°C with a return temperature of 30°C, which is properly monitored. The solar energy fraction in the second year of operation was 45% and could reach values above 50% after further optimisation [4].

- **Underground Thermal Energy Storage (UTES) –** UTES is also a widely used storage technology, which makes use of the underground as a storage medium for both heat and cold storage. UTES technologies include borehole

Table 1 – Typical Parameters of Thermal Energy Storage Systems [1]

TES System	Capacity (kWh/t)	Power MW)	Efficiency (%)	Storage period (h, d, m)	Cost (€/kWh)
Sensible (hot water)	10-50	0.001-10	50-90	d/m	0.1-10
PCM	50-150	0.001-1	75-90	h/m	10-50
Chemical reactions	120-250	0.01-1	75-100	h/d	8-100

Figure 1 – Large Hot Water Storage (construction and final state) combined with Solar Thermal District Heating "Am Ackermann-bogen" in Munich, Germany

storage, aquifer storage, cavern storage and pit storage. Which of these technologies is selected strongly depends on the local geological conditions.

Borehole storage is based on vertical heat exchangers installed underground, which ensure the transfer of thermal energy to and from the ground layers (e.g. clay, sand, rock). Many projects aim for seasonal storage of solar heat in summer to heat houses or offices in winter. Ground heat exchangers are also frequently used in combination with heat pumps where the ground heat exchanger extracts low-temperature heat from the soil.

Aquifer storage uses a natural underground water-permeable layer as a storage medium. The transfer of thermal energy is achieved by mass transfer (i.e. extracting/re-injecting water from/into the underground layer). Most applications deal with the storage of winter cold to be used for the cooling of large office buildings and industrial processes in the summer (Figure 2). A major prerequisite for this technology is the availability of suitable geological formations.

Cavern storage and pit storage are based on large underground water reservoirs created in the subsoil to serve as thermal energy storage systems. These storage options are technically feasible, but applications are limited because of the high investment costs.

For high-temperature (i.e. above 100 °C) sensible heat storage, the technology of choice is based on the use of liquids (e.g. oil or molten salts, the latter for temperatures up to 550°C. See ETSAP E10). For very high temperatures, solid materials (e.g. ceramics, concrete) are also taken into consideration. However, most of such high-temperature-sensible TES options are still under development or demonstration.

- **Phase Change Materials for TES –** Sensible heat storage is relatively inexpensive, but its drawbacks are its low energy density and its variable discharging temperature [2]. These issues can be overcome by phase change materials (PCM)-based TES, which enables higher storage capacities and target-oriented discharging temperatures. The change of phase could be either a solid/liquid or a solid/solid process. Melting processes involve energy densities on the order of 100 kWh/m^3 (e.g. ice) compared to a typical 25 kWh/m^3 for sensible heat storage options. Figure 3 compares the achievable storage capacity at a given temperature difference for a storage medium with and without phase change.

Phase change materials can be used for both short-term (daily) and long-term (seasonal) energy storage, using a variety of techniques and materials. Table 2 shows some of the most relevant PCMs in different temperature ranges with their melting temperature, enthalpy and density.

For example, the incorporation of micro-encapsulated PCM materials (e.g. paraffin wax) into gypsum walls or plaster can considerably increase the thermal mass and capacity of lightweight building walls. The micro-encapsulated PCMs cool and solidify by night and melt during the day, thus cooling the walls and reducing or avoiding the need for electric chillers ("passive cooling", see Figure 4). Other applications for active cooling systems involve the use of macro-encapsulated salts that melt at an appropriate temperature. The PCM can be stored in the building's air vent ducts and cold air can be delivered via large-area ceiling and floor ventilation systems. PCM slurries are a promising

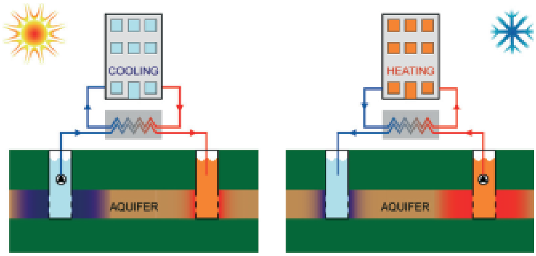

Figure 2 – Layout Scheme of an Aquifer Storage System

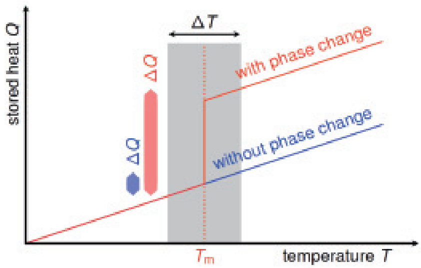

Figure 3 – Stored Heat vs. Temperature for Sensible (without phase change) and Latent TES [4]

Table 2 Thermal Storage PCM Properties

PCM	Melting Temp., °C	Melting Enthalpy, kJ/kg	Density, g/cm³
Ice	0	333	0.92
Na-acetate Trihydrate	58	250	1.3
Paraffin	-5 to 120	150-240	0.77
Erytritol	118	340	1.3

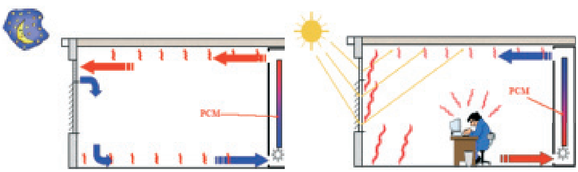

Figure 4 – Layout Scheme for "Passive Cooling"

technology. For example, ice-slurries or water-paraffin dispersions can be used for building or industrial cooling purposes. As slurries can be pumped, they can be used for either storing or distributing thermal energy.

A number of R&D activities, most of them aimed at industrial applications, currently focus on high-temperature PCM (above 150°C).

- **Thermal Energy Storage via Chemical Reactions –** High energy density (i.e. 300 kWh/m^3) TES systems can be achieved using chemical reactions (e.g. thermo-chemical storage, TCS) [2]. Thermo-chemical reactions, such as adsorption (i.e. adhesion of a substance to the surface of another solid or liquid), can be used to store heat and cold, as well as to control humidity. Typical applications involve adsorption of water vapour to silica-gel or zeolites (i.e. micro-porous crystalline alumino-silicates). Of special importance for use in hot/humid climates or confined spaces with high humidity are open *sorption* systems based on lithium-chloride to cool water and on zeolites to control humidity. Figure 5 shows an example of thermal energy storage by an adsorption process (e.g. water vapour on zeolite): during charging, water molecules are desorbed from the inner surface of the adsorbent. The TES remains in this state until water molecules can be adsorbed by the adsorbent and the TES is discharged again. Table 3 shows some of the sorption materials that are currently under investigation [6]. Interesting fields of application include waste heat utilisation. In this context, TCSs are able to store thermal energy with high efficiency and to convert heat into cold (i.e. desiccant cooling) at the same time, which makes these systems very attractive.

The high storage capacity of sorption processes also allows thermal energy transportation. Figure 6 shows a schematic view of such a system. For example, an ongoing demonstration project utilises waste heat from an incineration plant to be used at an industrial drying process. The sorption TES (using zeolite/water) is charged at 150°C, transported over seven kilometers and discharged at 180°C. Dry and hot air during discharging are directly integrated into the drying process. The higher discharging temperature is made possible because the enthalpy of the humid air from drying is converted into a temperature lift by the adsorption of water vapour. A pilot storage in a standard freight container containing 13 tonnes of zeolite, with a storage capacity of up to three MWh and a charging power of 500 kW, is currently on the road. The economic analysis shows that applications of mobile storage systems with more than 200 storage cycles per year allow the system to run with a final cost of delivered heat of about €55/MWh. Of course, the distance between energy source and demand site, investment costs and energy capacity have a strong influence on the energy price [9].

Table 4 lists some of the most interesting chemical reactions for thermal energy storage [7, 8]. While sorption storages can only work up to temperatures of about 350°C, chemical reactions can go much higher. Figure 7 shows the different TES technologies: sensible heat (i.e. water as an example); latent heat (i.e. different materials); and thermo-chemical (i.e. sorption and chemical reactions).

- **Applications –** Important fields of application for TES systems are in the building sector (e.g. domestic hot water, space heating, air-conditioning)

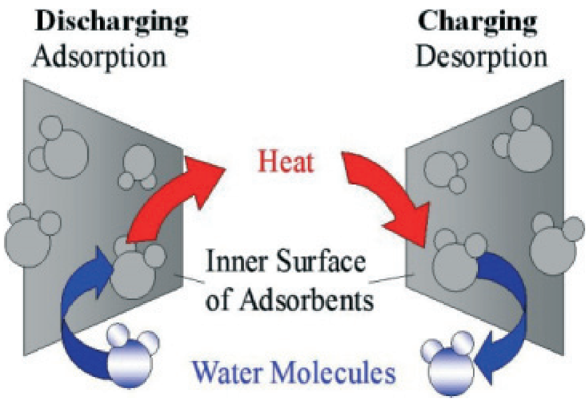

Figure 5 – TES De/Adsorption Process

Table 3 – Sorption Materials under Investigation [6]

Material		Example	Developer
Microporous materials	Bindeless zeolite	13XBF, 4ABF	Chemiewerke Germany
	Alumino-phosphate	APO-CHA	Nat. Institute of Chemistry Slovenia
	Functional adsorbents	FAM-Z01 FAM-Z02	Mitsubishi Japan
Composite materials	Selective water adsorbents	SWS-11 $CaCl_2$/silica	Boreskov Institute Russia
	Porous salt hydrates	$MgSO_4/MgCl_2$	ECN (NL) Weimar Univ. Germany

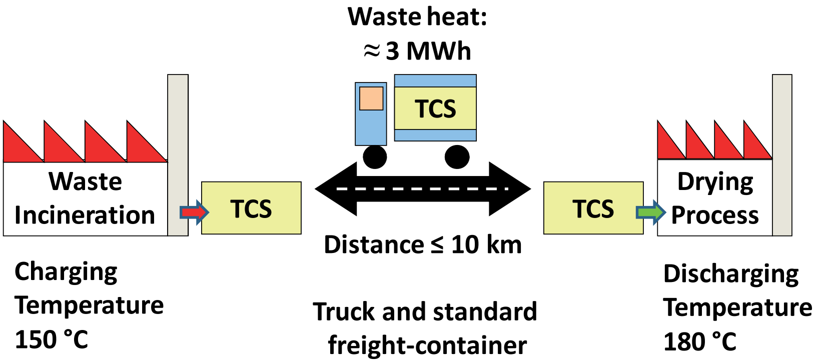

Figure 6 – Mobile Sorption Storage System for Industrial Waste Heat Utilisation

and in the industrial sector (e.g. process heat and cold). TES systems can be installed as either centralised plants or distributed devices. Centralised plants are designed to store waste heat from large industrial processes, conventional power plants, combined heat and power plants and from renewable power plants, such as concentrated solar power (CSP). Their power capacity ranges typically from hundreds of kW to several MW (i.e. thermal power). Distributed devices are usually buffer storage systems to accumulate solar heat to be used for domestic and commercial buildings (e.g. hot water, heating, appliances). Distributed systems are mostly in the range of a few to tens of kW.

TES systems – either centralised or distributed - improve the energy efficiency of industrial processes, residential energy uses and power plants by storing waste or by-product heat or renewable heat when it is available and supplying it upon demand. Thermo-chemical storage systems can also convert waste heat into higher temperature heat or into cold. A number of energy-intensive industrial sectors and processes (e.g. cement, iron and steel, glass) benefit from TES systems. Manufacturing industry (e.g. automobile industry) can also benefit significantly from TES. Most importantly, TES can help integrate variable solar heat into the energy system. This applies either to short-term storage based on daily heat buffers for domestic hot-water production or to long-term heat storage for residential and industrial heating purposes, based on large central storage systems and district heating networks.

TES systems can also help integrate renewable electricity from PV and wind. For example, the efficiency of a (mechanical) compressed air energy storage (CAES) can be improved from about 50% to more than 70% by storing heat during compression and discharging it to support expansion (see ETSAP E18). Charging a cold storage system using renewable electricity during high solar irradiation periods or wind peaks and delivering cold to consumers on demand is a further potential TES application.

Table 5 lists applications for centralised and distributed TES technologies, along with their contribution to energy efficiency or to the integration of renewable energy.

Costs of TES Systems

Cost estimates of TES systems include storage materials, technical equipment for charging and discharging, and operation costs.

TES systems for sensible heat are rather inexpensive as they consist basically of a simple tank for the storage medium and the equipment to charge/discharge. Storage media (e.g. water, soil, rocks, concrete or molten salts) are usually relatively cheap. However, the container of the storage material requires effective thermal insulation, which may be an important element of the TES cost. A number of seasonal TES have been installed in Germany [11]. Most systems consist of a 5,000-10,000 m^3 water container with energy content between 70-90 kWh/m^3 and investment costs between €50-200/m^3 of water equivalent, thus translating into a specific investment cost from €0.5-3.0 per kWh. [11]

In the case of UTES systems, boreholes and heat exchangers to activate the underground storage are the most important cost elements. Specific costs range from €0.1-10 per kWh [12] and depend heavily on local conditions.

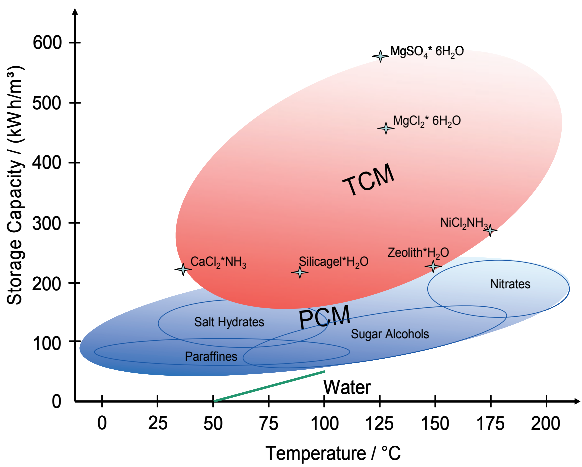

Figure 7 – Storage Capacity vs. Temperature for Sensible, Latent and Thermo-chemical TES [10]

Table 4 – Most Interesting Chemical Reactions for Thermal Energy Storage [7, 8]

Reaction		Temp. °C	En. density, kJ/kg
Methane steam reforming	$CH_4+H_2O=CO+3H_2$	480-1195	6053
Ammonia dissociation	$2NH_3=N_2+3H_2$	400-500	3940
Thermal dehydrogenation of metal hydrides	$MgH_2=Mg+H_2$	250-500	3079 heat stor. 9000 H_2 stor.
Dehydration of metal hydroxides	$CA(OH)_2=CAO+H_2O$	402-572	1415
Catalytic dissociation	$SO_3=SO_2+ ½O_2$	520-960	1235

Phase change material (PCM) storage and thermo-chemical storage (TCS) systems are significantly more complex and expensive than the storage systems for sensible heat. In most cases (e.g. thermo-chemical reactors), they use enhanced heat and mass transfer technologies to achieve the required performance in terms of storage capacity and power, and the cost of the equipment is much higher than the cost for the storage material. In general, the cost of a PCM system ranges between €10-50 per kWh [12]. The cost of systems using expensive micro-encapsulated PCMs, which avoid the use of heat exchange surfaces, can be even higher. For example, the cost of complete plaster board (€17/kg) with micro-encapsulated paraffin to be used as a passive cooling device within building structures (e.g. gypsum boards) includes the price of paraffin (about €5/kg) and the micro-encapsulated material (€13/kg) [13].

The difference between the pure PCM and the complete TES system is even higher for active PCM installations. As an example, the costs of a calcium-chloride storage for the heat rejected from a thermally-driven absorption chiller includes [14] the cost of calcium-chloride, which is rather inexpensive (€0.3/kg) and the cost of a container, heat exchanger and other components that is around €65/kWh. Materials for thermo-chemical storage (TCS) are also expensive as they have to be prepared (e.g. pelletised or layered over supporting structures).

Also expensive are the containers and the auxiliary TCS equipment for both heat and mass transfer during energy charging and discharging. TCS systems can be operated as either open systems (i.e. basically packed beds of pellets at ambient

Table 5 – TES-relevant Applications

Application	Technology	Central/ Distrib.	Energy Effic./ Ren. Energy
Cold storage. (buildings)	PCM (ice, passive cooling)	D	EE + RE
Cold storage. (industry, appliances),	PCM (slurries) Absorption stor. (heat to cold)	D	EE+RE
Domestic hot water (buffer storage)	Sensible storage (hot water)	D	RE
Heating (buildings, seasonal stor.)	Sensible stor. (UTES, large water tanks, district heating)	C	RE
Process heat (industrial heating/drying, appliances)	Thermo-chem. storage. (sorption storage)	D	EE+RE
Waste heat (cement, steel & glass industry)	Sensible stor. (solids), PCM, chem. reactions	C+D	EE
High temp. storage (>400°C) for CSP & CAES	Sensible stor. (liquids, molten salt) PCM, chem. reactions	C	RE

Table 6 – Economic Viability of TES Systems as a Function of the Number of Storage Cycles per Year [15]

	Cycles per year	5-yr energy savings, kWh	5-yr economic savings, €	Invest. cost €/kWh
Seasonal storage	1	500	25	0.25
Daily storage	300	150,000	7500	75
Short-term storage (3 c/day)	900	450,000	22,500	225
Buffer storage (10 c/day)	3,000	1,500,000	75,000	750

pressure) or closed systems. Open systems are often the cheapest option while closed systems need sophisticated heat exchangers. The TCS cost ranges from €8-100 per kWh [12].

Table 7 – State of Development, Barriers and Main R&D Topics for Different TES Technologies

Technology	Status (%) Market/R&D	Barriers	Main R&D topics
Sensible TES			
Hot water tanks (buffers)	95/5		Super insulation
Large water tanks (seasonal)	25/75	System integration	Material tank, stratification
UTES	25/75	Regulation, high cost, low capacity	System integration
High temp. solids	10/90	Cost, low capacity	High temp materials
High temp. liquids	50/50	Cost, temp<400C	Materials
PCM			
Cold storage (ice)	90/10	Low temp.	Ice production
Cold storage (other)	75/25	High cost	Materials (slurries)
Passive cooling (buildings)	75/25	High cost, performance	Materials (encapulation)
High temp. PCM (waste heat)	0/100	High cost, Mat.stability	Materials (PCM containers)
TCS			
Adsorption TES	5/95	High cost, complexity	Materials, and reactor design
Aborption TES	5/95	High cost, complexity	Materials and reactor design
Other chemical reactions	5/95	High cost, complexity	Materials and reactor design

The overall economic evaluation of a TES system depends significantly on the specific application and operation needs, including the number and frequency of storage cycles. This dependency is shown in Table 6 [15] where a simplified calculation is based on a TES system with a 100-kWh storage capacity, a price of thermal energy of €0.05/kWh and an investment return time of five years. The calculation focuses on the price of thermal energy and determines the cost range for TES to be economically competitive based on today's energy prices. Table 6 shows that, for seasonal storage, with one cycle per year, the energy saving over five years amounts to just €25, which leads to a maximum (affordable) specific investment cost of €0.25/kWh. This cost can only be viable using a cheap sensible heat TES system (i.e. basically a large water tank). PCM and TCS systems, which are in general much more expensive, are economically viable only for applications with a higher number of cycles. For applications with more than 1,000 cycles per year, the viable investment cost is higher than €250/kWh.

Potential and Barriers

TES technologies face some barriers to market entry and cost is a key issue. Other barriers relate to material properties and stability, in particular for TCS. Each storage application needs a specific TES design to fit specific boundary conditions and requirements. R&D activities focus on all TES technologies. Most of such R&D efforts deal with materials (i.e. storage media for different temperature ranges), containers and thermal insulation development. More complex systems (i.e. PCM, TCS) require R&D efforts to improve reacting materials, as well as a better understanding of system integration and process parameters (Table 7).

TES market development and penetration varies considerably, depending on the application fields and regions. Penetration in the building sector is comparably slow in Europe where the construction of new buildings is around 1.3% per year and the renovation rate is around 1.5%; of course, the integration of TES systems is easier during construction. The estimate of the European potential is based on a 5% implementation rate of TES systems in buildings [16]. Penetration could be much higher in emerging economies with their high rates of new building construction.

TES potential for co-generation and district heating in Europe is also associated with the building stock. The implementation rate of co-generation is 10.2% [17], while the implementation of TES in these systems is assumed to be 15%. As far as TES for power applications is concerned, a driving sector is the concentrating solar power (CSP) where almost all new power plants in operation or under construction are equipped with TES systems, mostly based on molten salt. This is perhaps the most important development filed for large, centralised TES installations [18]. In the industrial sector, about 5% of the final energy consumption is assumed to be used by TES installations. In particular, the use of industrial waste heat is expected to grow since the price of fossil fuels will rise and energy efficiency will be the key to competitiveness. Based on the University of Lleida study [16], the expansion of TES technologies is expected to be significant in Europe and Asia (particularly Japan) and somewhat lower (50%) in the United States. The global potential is estimated at approximately three times the European potential.

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Table 8 – Summary Table: Key Data and Figures for Thermal Storage Technologies

Technical performance	**Typical current international values and ranges**		
Energy Input/Output	Solar heat, waste heat, variable renewable energy sources (PV, wind), electricity/heat		
Technology Variants	Sensible Thermal Energy Storage, **STES**	Storage in Phase Change Materials, **PCM**	Thermo-chemical Energy Storage, **TCS**
Storage Capacity (kWh/t)	10 - 50	50 - 150	120 - 250
Thermal Power (MW)	0.001 - 10	0.001 - 1	0.01 - 1
Efficiency, %	50 - 90	75 - 90	75 -100
Storage Period (h,d,w,m)	d - y	h - w	h - d
Cost (€/kWh)	0.1 - 10	ott-50	8 - 100
Technical lifetime, yr	10-30+ (depending on storage cycles, temperature and operating conditions)		
Load (capacity) factor, %	80	80	55
Max. (plant) availability, %	95	95	95
Typical (capacity) size, MW_e	25	0.5	100
Installed capacity, GW_e (GW_{th})	9–10 (all types)	<<1	18 (estimate)
Environmental Impact	Negligible, with GHG emissions reduction, depending on the amount of primary fossil energy saved by using energy storage		
Costs (USD 2008)	**Typical current international values and ranges**		
Investment cost, $/kW	3400 – 4500	6000 – 15,000	1000 – 3000
O&M cost (fixed & variable), $/kW/a	120	250	20 – 60
Fuel cost, $/MWh	N/A	N/A	N/A
Economic lifetime, yr	20		
Total production cost, $/MWh	80 – 110	120 – 300	25 – 75
Market share, %	0.25	Negligible	N/A

Disclaimer

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