



Energy Storage Technology Roadmap

Technology Annex

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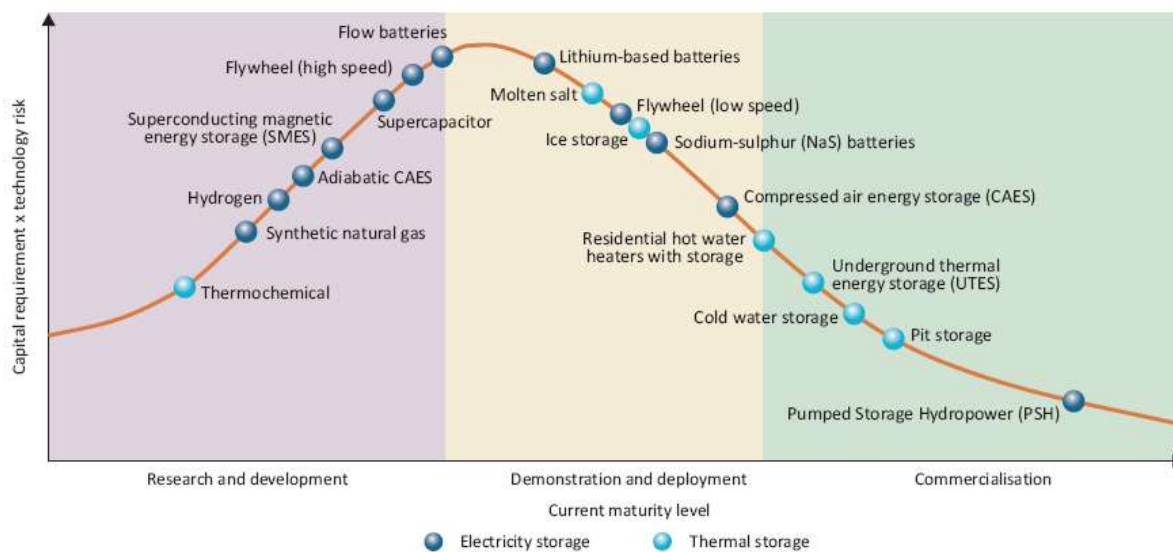
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Introduction

Energy storage technologies absorb energy and store it for a period of time before releasing it to supply energy or power services. In the *Technology Roadmap: Energy Storage*, technologies are categorised by output: **electricity** and **thermal** (heat or cold).¹ This Technology Annex aims to increase understanding among a range of stakeholders of the electricity and thermal energy storage technologies, in support of the *Technology Roadmap: Energy Storage*. The examples presented in this annex were chosen from a wide range of submissions from governments, industry, experts, and the IEA energy technology network including members of the Implementing Agreement for a Programme of Research and Development on Energy Conservation through Energy Storage (ECES IA). The IEA would like to thank these groups for their contributions.

The project examples presented here are not meant to represent best practices in energy storage deployment and use. Rather, they provide insight into how different organisations have applied energy storage to meet their goals and objectives across a technologically and geographically diverse set of cases. A list of all project examples submitted during this process is also included in this annex. These projects include different energy storage technologies, which vary widely with respect to their current level of maturity, as shown in Figure 1 and Table 1.

Figure 1: Maturity of energy storage technologies



Source: Decourt, B. and R. Debarre (2013), "Electricity storage", *Factbook*, Schlumberger Business Consulting Energy Institute, Paris, France and Paksoy, H. (2013), "Thermal Energy Storage Today" presented at the IEA Energy Storage Technology Roadmap Stakeholder Engagement Workshop, Paris, France, 14 February.

¹ Chemical (hydrogen) storage and fuel cell technologies are not included.

Table 1: Energy storage technologies: current status and typical locations in today's energy system²

Technology	Location ³	Output	Efficiency (%)	Initial investment cost (USD/kW)	Primary application	Example projects
PSH	Supply	electricity	50-85	500 - 4 600	long-term storage	Goldisthal Project (Germany), Okinawa Yanbaru Seawater PSH Facility (Japan), Pedreira PSH Station (Brazil)
UTES	Supply	thermal	50-90	3 400 - 4 500	long-term storage	Drake Landing Solar Community (Canada), Akershus University Hospital and Nydalen Industrial Park (Norway)
CAES	Supply	electricity	27 - 70	500 - 1 500	long-term storage, arbitrage	McIntosh (Alabama, USA), Huntorf (Germany)
Pit storage	Supply	thermal	50-90	100 - 300	medium temperature applications	Marstal district heating system (Denmark)
Molten salts	Supply	thermal	40-93	400-700	high-temperature applications	Gemasolar CSP Plant (Spain)
Batteries	Supply, demand	electricity	75-95	300 - 3 500	distributed/ off-grid storage, short-term storage	NaS batteries (Presidio, Texas, USA and Rokkasho Futamata Project, Japan), Vanadium redox flow (Sumimoto's Densetsu Office, Japan), Lead-acid (Notrees Wind Storage Demonstration Project, USA), Li-ion (AES Laurel Mountain, USA and Toronto, Ontario, Canada), Lithium Polymer (Autolib, France)
Thermochemical	Supply, demand	thermal	80~99	1 000 - 3 000	low, medium, and high-temperature applications	TCS for Concentrated Solar Power Plants (R&D)
Chemical – hydrogen storage	Supply, demand	electrical	22-50	500-750	long-term storage	Utsira Hydrogen Project (Norway), Energy Complementary Systems H2Herten (Germany)
Flywheels	T&D	electricity	90-95	130 - 500	short-term storage	PJM Project (USA)
Supercapacitors	T&D	electricity	90-95	130 - 515	short-term storage	Hybrid electric vehicles (R&D phase)
Superconducting magnetic energy storage (SMES)	T&D	electricity	90-95	130 - 515	short-term storage	D-SMES (US)
Solid media storage	Demand	thermal	50-90	500 - 3000	medium temperature applications	
Ice storage	Demand	thermal	75-90	6 000 - 15 000	low-temperature applications	Denki University (Tokyo, Japan), China Pavilion project (China)
Hot water storage (residential)	Demand	thermal	50-90	****	medium temperature applications	Peak demand reduction (France), TCES Building (US)
Cold-water storage	Demand	thermal	50-90	300-600	low-temperature applications	Shanghai Pudong International Airport (China)

* Typical locations in today's energy system. These locations may change as the energy system evolves.

** Energy storage capabilities present in hot water storage tanks can be utilised for negligible additional cost.

² Sources: (IEA, 2014a), (IEA, 2011), (Black & Veatch, 2012), (EPRI, 2010), (Eyer, J. and G. Corey, 2010), (IEA- ETSAP and IRENA, 2013), (IEA-ETSAP and IRENA, 2012), (Sandia National Laboratories, 2011)

³ Typical locations in today's energy system. These locations may change as the energy system evolves.

Electricity Storage – Mechanical

Mechanical energy storage refers to technologies that convert electricity to mechanical or potential energy and then store it for later use as electricity. Today, pumped storage hydropower (PSH) and compressed air energy storage (CAES) are generally considered the most mature method for electricity storage, with PSH representing 99% of currently installed electricity storage capacity. Flywheels are another example of mechanical energy storage and are potentially well suited for frequency regulation, as has already been seen in some markets.

Pumped storage hydropower (PSH) systems utilise elevation changes to store off-peak electricity for later use. Water is pumped from a lower reservoir to a reservoir at a higher elevation during off-peak periods. Subsequently, water is allowed to flow back down to the lower reservoir, generating electricity in a fashion similar to a conventional hydropower plant. Historically, these facilities were built with 1-2 GW of capacity in order to meet peak load demands.

Project examples: Goldisthal Project (Germany), Okinawa Yanbaru Seawater PSH Facility (Japan), Pedreira PSH Station (Brazil)

Compressed air energy storage (CAES) systems use off-peak electricity to compress air, storing it in underground caverns or storage tanks. In today's CAES systems, this air is later released to a combustor in a gas turbine to generate electricity during peak periods. Two diabatic CAES facilities are currently in operation today – one each in Germany and the United States. These facilities use salt formations over a depth of 500m to 1300m for storing the compressed air at an operating pressure of 50-100 bar. Germany currently plans to open a new adiabatic CAES facility that will store the heat generated during compression and later recuperates it during the expansion phase, significantly increasing system efficiency.

Project examples: McIntosh (Alabama, USA), Huntorf (Germany)

Flywheels are mechanical devices that spin at high speeds, storing electricity as rotational energy. This energy is later released by slowing down the flywheel's rotor, releasing quick bursts of energy (i.e. releases of high power and short duration).

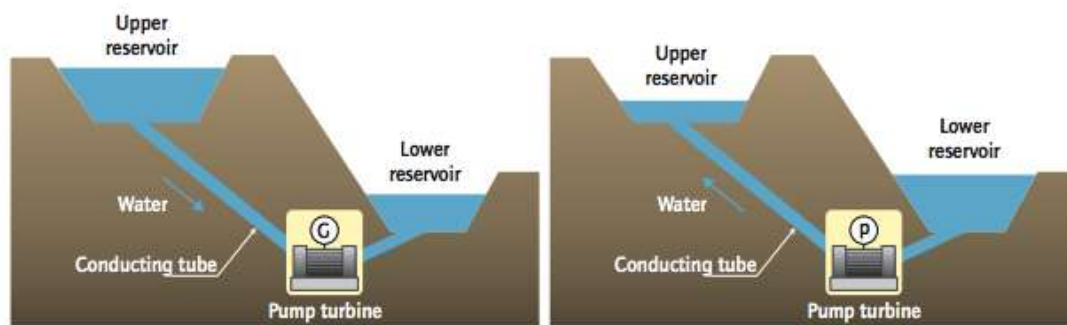
Project example: PJM Project (USA)

Pumped Storage Hydropower (PSH)

Project Example – Goldisthal Pumped Storage Hydropower (Germany)

In Germany, the 1 060 MW Goldisthal Pumped Storage Hydropower (PSH) project uses elevation changes to store electricity during off-peak demand periods for up to eight hours. Commissioned in 2004 as the first variable speed pumped storage unit in Europe, this project includes two constant (synchronous) and two variable (asynchronous) speed pump-turbines. This design results in improved efficiency compared to other PSH designs at partial load conditions. At the same time, these generators allow for highly dynamic control of power delivery for grid stabilization purposes. Using an elevation change of 301 meters and a twelve (12) million cubic meter upper reservoir capacity, the project cost approximately USD 860 million to construct over a period of seven years.

Figure 2: Pumped storage hydropower plant (IEA 2012)



Source: Inage, 2009.

Project Example – Yanbaru Seawater Pumped Storage Hydropower (Japan)⁴

In Okinawa, water resources limitations discourage the use of conventional pumped storage power plant designs that use freshwater as well as traditional thermal power plants for demand response. However, the mountainous coastline presented an opportunity for energy storage, resulting in the use of seawater as a storage medium for a new pumped storage facility. As a result, the 30 MW Okinawa Yanbaru Seawater Pumped Storage facility in Japan began operation in 1999.



The hydropower plant has a total head – the vertical distance, or drop, between the intake of the plant and the turbine – of 136 meters. The upper reservoir is located 600 meters from the coast and

⁴ [“Seawater intake/outlet of the Okinawa Yanbaru Seawater Pumped Storage Power Station”](#) by gpzagogo and exists in the public domain via Wikimedia Commons.

the system uses the ocean as its lower reservoir. Over its more than 14 years of operation, this facility has faced many challenges – in particular, corrosion - due to the system’s reliance on salt water and its unique interaction with the ocean, which has resulted in increased operation and maintenance costs.

Project Example - Pedreira Pumped Hydro Power Station (Brazil)

Originally placed into commercial operation in 1937, the Pedreira PSH facility in Brazil was the world’s first reversible pump-turbine, designed to provide arbitrage services to the São Paulo region. Today, the now 20 MW open-loop PSH facility is owned and operated by the federally owned utility, Empresa Metropolitana de Águas e Energia.

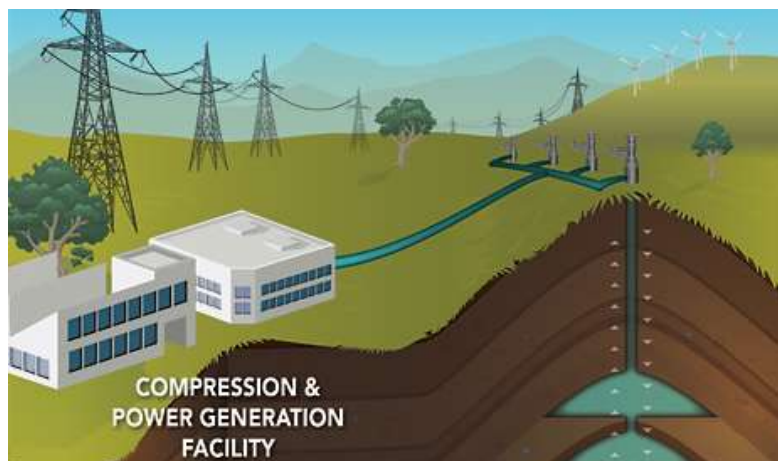
Reversible pump-turbines have the capability to use the same system to move water from lower to higher elevations (in pumping mode) or to generate electricity by allowing water to flow back down to the lower elevation (in turbine mode). The former is done by using energy from the power grid, effectively storing this electricity as water at a higher elevation. This energy is then recovered in turbine mode. This system allowed the Pedreira pumped hydro power station to change from storing to generating mode more rapidly than previous designs.

Compressed Air Energy Storage (CAES)

Project Example - McIntosh Compressed Air Energy Storage Facility (United States)⁵

The McIntosh Power Plant in Alabama, United States includes a 110 MW CAES facility and four natural gas combustion turbines. In operation since 1991, the facility is primarily used to supply peak power demand by storing energy from nuclear power plants at night in a salt dome. It is also capable of producing up to 110 MW of power within 14 minutes, allowing facility operators to supply reserve requirements in the energy system.

The 220-ft diameter salt cavern used for storing compressed air at the McIntosh facility has a total volume of 10 million cubic feet. It is operated between 650 and 1 100 pounds per square inch (psi), with a discharge period of up to 26 hours at 54% efficiency. When the compressed air is released, it flows at a rate of 340 pounds per second into the natural-gas



turbine. In order to reduce natural gas use at the facility, these turbines also use an air-to-air heat exchanger to capture excess heat and use it to preheat the air from the cavern. This preheating process reduced fuel usage by approximately 25%.

⁵ Photo by PNNL (Pacific Northwest National Laboratory) (2013), “Compressed Air Energy Storage,” caes.pnnl.gov/

Project Example - Huntorf Compressed Air Energy Storage Facility (Germany)

The 321 MW Huntorf power plant facility stores off-peak electricity as compressed air in two underground cylindrical salt caverns with a total storage volume of 300,000 cubic meters. In operation since 1978, the CAES facility was upgraded from 290 MW to 321 MW in 2006 and operates at an overall power plant efficiency of 42%. The facility is currently used for arbitrage, spinning reserve, and blackstart applications and is able to reach full output within 6 minutes in absence of external energy sources.

During off-peak periods, this facility uses low-cost electricity to compress and store air in the salt caverns located 600 meters below the surface. Subsequently, during periods of peak demand, the compressed air is released and used to burn natural gas in the combustion turbine. This combustion gas is then passed through a gas turbine to spin a generator and produce electricity. The storage system can release energy for up to two hours at full capacity.

Project Example - Adiabatic Compressed Air Energy Storage (Germany)

Adiabatic CAES facilities capture the heat produced during the air compression process and store it for later use in producing electricity. As a result, overall storage efficiency can be increased. In Germany, this design is being applied through the combined efforts of RWE Power, General Electric, Züblin and DLR in the ADELE Project.

This project will be able to store 360 MWh of electricity with a rated maximum power output of 360 MW. This adiabatic CAES facility will include thermal storage to capture the heat produced during compression. When the compressed air is subsequently discharged, this heat will be released back into the compressed air, reducing the amount of natural gas needed to heat this air. The ADELE CAES facility is predicted to achieve efficiency levels of up to 70% by using this waste heat recovery process. Its primary application is expected to lie in managing system peak load.

Flywheels

Project Example - 20-MW Flywheel in the PJM Interconnection (United States)

In the United States, a 20 MW flywheel in the PJM interconnection provides frequency regulation services to the electricity grid. This flywheel system consists of 200 flywheels connected in parallel, designed to provide 100 kW of output and to store 25 kWh of energy with a less than 4 second response time. The system has zero direct emissions.

The flywheel system can respond nearly instantaneously to a system operator's control signal at a rate 100 times faster than traditional generation resources, making them an appealing addition to the energy system. In terms of design, a flywheel system's rotor consists of a flywheel, superconducting magnetic radial, thrust bearing and superconducting coil, and generator motor within a vacuum-sealed housing to minimize friction.

Electricity Storage – Electrochemical

Electrochemical batteries use chemical reactions with two or more electrochemical cells to enable the flow of electrons. Examples include lithium-based batteries (e.g. lithium-ion, lithium polymer), sodium-sulphur and lead-acid batteries.

Lithium-based batteries use lithium metal or lithium-based compounds. Examples include lithium-ion and lithium-polymer batteries, which are frequently used in mobile applications.

Project examples: Lithium polymer batteries in an electric vehicle sharing program (France), Lithium-ion batteries at AES Laurel Mountain (United States), Lithium-ion batteries for community energy storage (Canada)

Sodium-sulphur batteries use liquid sodium and sulphur and are typically used in stationary applications.

Project examples: Rokkasho Futamata Project (Japan), Presidio, Texas (United States)

Lead-acid batteries use two lead-based plates and an electrolyte to produce an electric current. They are frequently used for stationary applications as backup power sources.

Project examples: Notrees Wind Storage Demonstration Project (United States)

Lithium-based batteries

*Project Example – Lithium polymer batteries in an electric vehicle sharing program (France)*⁶

In France, the Autolib electric car-sharing programme began in December 2011. The public-private partnership programme currently includes 1 740 Bolloré Bluecars, which use a 30-kWh lithium polymer battery and have a 250 km (160 mile) range. These vehicles park at one of 700 car-charging stations in the city of Paris. Each charging station has space for at least three vehicles. The programme currently has plans to expand to 3 000 cars and 1 050 stations, with more than 2 000 cars on a particular day.



The four-seater Autolib' cars are unpainted to reduce their weight and their cost. Each car runs on a lithium metal polymer battery that weighs 300 kilograms and can power the car for 250 kilometres of city driving and 150 kilometres on highways at up to 130 kilometres per hour. A trip all the way across Paris uses only about 15 percent of the total battery charge. The 220-volt, 16-ampere battery needs 10 hours for full charging on average. At any given moment, most of the cars have at least a 70 percent charge.

The average Autolib trip lasts 42 minutes, with the longest rentals running about three hours. The busiest time for the vehicles is the end of workdays. In its first year of operation, more than 42 000 people signed up for Autolib membership and completed over 646 000 trips. Those same trips with a comparable fossil-fuelled car would have emitted more than 730 metric tonnes of CO₂.

Project Example – Lithium-ion batteries at AES Laurel Mountain (United States)

The AES Laurel Mountain facility in the United States consists of a 98 MW wind power generation plant with 61 individual wind turbines plus a 32 MW lithium-ion battery storage system. The latter can store up to 8 MWh of electricity, providing short-term reserve capacity to the Pennsylvania-New Jersey-Maryland (PJM) Interconnection. This project is designed for power regulation partly because utilities in the United States are required to maintain reserve power resources to use in response to grid fluctuations.

This storage project can provide a near-instantaneous response to power requests from grid operators, helping to match generation and demand. This battery as an operating reserve capacity plays a critical role in maintaining overall grid reliability with greater than 95% availability. The storage system also allows the wind facility to control the ramp rate of its generators, smoothing out fluctuations in their minute-to-minute output.

⁶ [Photo of autolib electric vehicles](#) in Paris by mariordo59 and used and exists in the public domain via a [Creative Commons Attribution-ShareAlike 2.0 Generic license](#).

Project Example – Lithium-ion batteries for Community Energy Storage (Canada)⁷

In Toronto, Canada a lithium-ion battery system is currently used to support the rapidly changing local distribution network in order to maintain electricity system reliability. The system came online in 2012 with one 250 kWh battery unit and is expected to add two additional units at the end of 2014. Operated by Toronto Hydro Electric System, the system has proven its ability to perform load shifting and price arbitrage services. In 2014 and 2015, the system will also be used for power quality support applications as a part of a 40-step testing program.

This storage system cost a total of USD 16.3 million, funded in part by Sustainable Development Technology Canada (USD 5.4 million), Toronto Hydro (USD 4.2 million), eCAMION (USD 5.7 million), and the University of Toronto (USD 1.1 million). It is expected to have a lifespan of 5 000 full cycles, or approximately 10 years of operation with a storage efficiency of 92%. The batteries cost approximately USD 2 100 per kW.

In addition to serving as a support mechanism for the distribution grid, this battery storage system is meant to help in developing standards and certifications that currently apply or should apply to these types of systems. Today, utility-owned infrastructure is exempt from the Ontario Electrical Safety Code (OESC). Instead, the code allows utilities to establish their own internal standards practices. Due to the current lack of familiarity with energy storage equipment, utility engineers are using this project to develop best practices for assessing system safety and impact.



⁷ Photograph of Toronto Li-ion Community Storage project by eCAMION and used with permission.

Sodium-Sulphur (NaS) batteries

Project Example –Rokkasho Futamata Project (Japan)

Sodium sulphur (NaS) batteries are the most advanced type of high temperature battery to have been commercially deployed to date. Operating at a temperature between 300-350°C, NaS batteries have been used for fast power reserve services and to defer new transmission and distribution investments.

In Japan, the Rokkasho Futamata Project uses 34 MW of NGK Insulators' NaS Batteries for load levelling and enabling sale of low cost off-peak wind power during peak times. In total, 17 sets of 2MW NaS battery units are monitored and integrated with the 51 MW Rokkasho Windfarm via a centralized control centre. The batteries are stored indoors to protect them from the corrosive salty air of the region. Each Battery unit consists of 40, 50kW modules. The batteries are charged at night, when the demand for power is lower, and the stored electricity can be supplied to the grid along with electricity generated by the wind turbines during peak demand times. (O'Malley, 2008)

Project Example – Presidio, Texas (United States)

The city of Presidio, Texas, USA is located in the deserts of West Texas on the banks of the Rio Grande River. Prior to 2010, the city suffered from a large number of power outages because the only transmission line bringing power from neighbouring Marfa to the city was a 60-mile, 69-kV line constructed in 1948. This aging transmission line crosses harsh terrain and its deteriorating condition and frequent lightning strikes have resulted in unreliable power for the residents of Presidio.

Electric Transmission Texas proposed the construction of a sodium-sulphur (NaS) battery system, a second 138/69-kV autotransformer at Marfa's Alamito Creek Substation and a new 69-kV transmission line connecting the Alamito Creek Substation to Presidio. Both the Public Utility Commission of Texas (PUCT) and the Electric Reliability Council of Texas (ERCOT) approved the proposal. The NaS battery was energized in late March 2010 and dedicated on April 8, 2010. (Reske 2010)

The energy storage system is a 4 MW, 32 MWh NaS battery consisting of 80 modules, each weighing 3600 kg. The Japanese firm NGK-Locke manufactured the battery. The total cost of the battery system was USD 25 million and included USD 10 million for construction of the building to house the batteries (done by Burns & McDonnell) and the new substation at Alamito Creek. The proposed additional transmission line had an approximate cost of USD 45 million, yielding a total project cost of USD 70 million. (Reske 2010)

The Presidio battery system and additional transmission line were financed through ERCOT as a necessary transmission upgrade for the residents of Presidio. As such, the cost was shared among all transmission and distribution providers and passed on to all rate-paying customers through a common ERCOT-wide "postage-stamp transmission rate" fee. It has been and continues to be ERCOT's policy to use the postage stamp rate to pay for all transmission upgrades necessary to ensure reliable service to all customers. Even though the cost to supply Presidio with reliable power was high compared to the number of people served and amount of power sent to Presidio, ERCOT

financed this project as a necessary transmission project because the customers in the city of Presidio should receive the benefit of at least the minimum level of service.

The primary purpose of the Presidio NaS battery is to provide backup power for an aging transmission line and to reduce voltage fluctuations and momentary outages for the city and residents of Presidio. The battery system can respond quickly to rapid disturbances as well as supply uninterrupted power for up to 8 hours in the case of a transmission outage. Between 2001 and 2006 there were 247 power outages including nine long-term outages with an average duration of 6.8 hours. Additionally, between July 8 and September 8, 2007 there were 81 poor voltage quality events. (ERCOT 2008) The NaS battery was designed to minimize these power disturbances and fluctuations starting from its inception in 2010 until the new 69-kV line could be completed in 2012. After completion of the new transmission line, the battery system remains a vital source of voltage support and backup power in case fierce storms (that are common among the West Texas region) disrupt Presidio's main electric supply line.

The battery system is controlled by an energy management system that includes an automatic controller and power converter than facilitates the battery charging and discharging process in response to real time conditions of the grid. (S&C Electric 2013)

Lead-acid batteries

Project Example – Notrees Wind Storage Demonstration Project (United States)⁸

The aim of the Notrees Wind Storage Demonstration Project is to analyse and discern how energy storage can compensate for the inherent intermittency of wind power generation resources. This project includes fast-response capabilities provided by advanced lead-acid batteries. The storage system is configured to provide 36 MW of peak power output and has a total storage capacity of 24 MWh. (US DOE, 2013)

The energy storage system was designed and constructed using fast response, advanced lead-acid batteries configured to provide 36 MW output peak power with the Notrees wind farm (152.6MW), owned and operated by Duke Energy Renewables. Fully operational in 2013, the system is meant to demonstrate how energy storage and an integrated power management system can moderate the intermittent nature of wind by storing excess energy when the wind is blowing and making it available later to the electric grid to meet customer demand.



⁸ Photo of Notrees Wind Storage Demonstration Project by U.S. Department of Energy.
<http://energy.gov/articles/smoothing-renewable-wind-energy-texas>

Other batteries

Project Example – Vanadium Redox Flow Batteries in Sumitomo's Densetsu Office (Japan)

Installed in 2000, the Vanadium redox flow battery energy storage system at Sumitomo's Densetsu Office is used primarily for peak reduction. This system is comprised of sixty 50 kW Sumitomo battery modules, which store energy from a 200 kW concentrated photovoltaic (CPV) system. Connected to external commercial power networks, the system can also store electricity provided by power companies during the night. This system employs an energy management system (EMS), which monitors the amount of solar electricity that is generated, battery storage and power consumption, and stores the measurement data in the central server.

Vanadium redox flow batteries use electrodes and an electrolyte that are not subject to deterioration even after repeated charge/discharge operations while operating at ambient temperatures. In a redox flow battery, the system is charged/discharged through the oxidation-reduction reaction of vanadium or other ions. An electrolyte is stored in tanks and then pumped through a central reaction unit where a current is applied or delivered. The size of the tank determines the energy capacity of the battery and the reaction unit (cell stack) determines the power of the battery.

Electricity Storage – Electrical

Electrical energy storage technologies use static electric or magnetic fields to directly store electricity. Examples include super-capacitors and superconductive magnetic energy storage (SMES). These technologies generally have high cycle lives and power densities, but much lower energy densities. This makes them best suited for supplying short bursts of electricity into the energy system. Today's technologies struggle with high costs and significant research is underway with a primary focus on decreasing cost through improved energy density.

Supercapacitors store energy in large electrostatic fields between two conductive plates, which are separated by a small distance. Electricity can be quickly stored and released using this technology in order to produce short bursts of power.

Superconducting magnetic energy storage (SMES) systems store energy in a magnetic field. This field is created by the flow of direct current (DC) electricity into a super-cooled coil. In low- temperature superconducting materials, electric currents encounter almost no resistance, so they can cycle through the coil of superconducting wire for a long time without losing energy.

Project examples: D-SMES System (United States)

Project Example – Distributed SMES and Power Quality Industrial Voltage Regulator (United States)

Commercial small-scale SMES systems have been built in the US, including the D-SMES (Distributed SMES) and PQ-IVR (Power Quality Industrial Voltage Regulator) systems that were deployed in facilities operated by Wisconsin Public Service Co. (WPS). The D-SMES system included a maximum power output of 800 kW and was used to support the electricity grid.

The PQ-IVR system was applied to the demand portion of the energy system, to reduce power quality concerns for industrial users. This system was designed to protect these customers from sudden voltage changes.

In the D-SMES system, six individual SMES units were installed at five substations within the WPS 115 kV Rhinelander Transmission Loop, an approximately 200-mile network near Wausau and Eagle River. The systems were brought online in 2000 and used successfully for 3.5 years to provide voltage stabilization services while the WPS built a new high-voltage transmission line to the area. (Electric Light & Power, 2000)

Electricity Storage – Chemical

Chemical energy storage uses the chemical energy carriers to store electricity, for example through electrolysis. Electricity is converted, stored, and then re-converted into the desired end-use form (e.g. electricity, heat, or liquid fuel).⁹

Project examples: Utsira Hydrogen Project (Norway), Energy Complementary Systems (ECS) H2Herten (Germany)

Project example - Utsira hydrogen project (Norway)

In 2004, the Utsira hydrogen project in Norway began storing excess power from two 600 kW wind turbines and converting it into hydrogen using a 48 kW electrolyzer. This energy was then converted back into electricity via a fuel cell when wind turbine output drops. Constructed on an island 20 km off the coast from Haugesund in Norway, the system also included a 48 kW water electrolyzer, hydrogen gas storage (2400 normal cubic meters at 200 bar), 55 kW hydrogen engine, 5.5 kW compressor, and a 10 kW proton exchange membrane (PEM) fuel cell.

The remote system gave 2–3 days of full energy autonomy for 10 households on the island, allowing them to receive 100% of their electricity from wind power. This demonstration project was run continuously for four years, until 2008. During operation, the system identified the need to improve the efficiency of the hydrogen-electricity conversion process, technical challenges with the fuel cell including coolant leaks, and operating system errors (including frequent false grid failure alarms). Furthermore, the fuel cell rapidly degraded during the demonstration project's operation. (IPHE, 2011)

Project Example – Energy Complementary Systems (ECS) H2Herten (Germany)

Commissioned in 2013, the ECS H2Herten system in Germany uses both hydrogen storage and lithium ion batteries to supply energy to the H2Herten application centre. Electricity is supplied by wind turbines and then stored in the lithium-ion batteries (50 kW and 30 kW systems) and hydrogen storage pressure vessel (2400 normal cubic meters at 50 bar). Funded by the European Union, the primary goals of this project are reducing greenhouse gas emissions, increasing energy efficiency, and reducing peak energy demand. System construction took three years to complete.

⁹ These technologies will be discussed in detail in the forthcoming IEA Hydrogen Technology Roadmap

Thermal Energy Storage – Sensible Heat

Sensible heat storage refers to the use of a medium to store energy as heating or cooling capacity without the use of a phase change or chemical reaction. The sole effect of energy stored on the system is a change in temperature. Sensible storage can be broadly considered the most mature form of thermal energy storage, with many technologies having already achieved high levels of deployment. (IEA-ETSAP, 2013) Perhaps the most common example of sensible heat storage is found in the hot and cold-water storage tanks found in residential, commercial, and industrial facilities worldwide. Underground Thermal Energy Storage (UTES) has been successfully deployed on a commercial scale in the Netherlands, Sweden, Germany, and Canada to provide heating and cooling capacity. Other examples include pit storage, molten salts, solid media storage, and hot- and cold-water storage.

Underground thermal energy storage (UTES)¹⁰ systems pump heated or cooled water underground for later use as a heating or cooling resource. These systems include aquifer and borehole thermal energy storage systems, where this water is pumped into (and out of) either an existing aquifers or man-made boreholes.

Project examples: Drake Landing Solar Community (Canada), Akershus University Hospital (Norway) and Nydalen Industrial Park (Norway)

Pit storage systems use shallow pits, which are dug and filled with a storage medium (frequently gravel and water) and covered with a layer of insulating materials. Water is pumped into and out of these pits to provide a heating or cooling resource.

Project examples: Marstal district heating system (Denmark)

Molten salts are solid at room temperature and atmospheric pressure, but undergo a phase change when heated. This liquid salt is frequently used to store heat in CSP facilities for subsequent use in generating electricity.

Project examples: Gujarat Solar One (India), Gemasolar Plant (Spain)

Solid media storage systems store thermal energy in a solid material for later use in heating or cooling. In many countries, electric heaters include solid media storage (e.g. bricks or concrete) to assist in regulating heat demand.

Project examples: Electric Thermal Storage Heaters in Kentucky (United States)

Hot- and cold-water storage in tanks can be used to meet heating or cooling demand. A common example of hot water storage can be found in domestic hot water heaters, which frequently include storage in the form of insulated water tanks.

Project examples: Shanghai Pudong International Airport's Terminal 2 (China), Residential Water Heaters (France), Tahoe Center for Environmental Sciences Building (United States)

¹⁰ Common types of UTES include aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES)

Underground Thermal Energy storage (UTES)

Project Example – Drake Landing Solar Community in Canada

In operation since 2007, Canada's Drake Landing Solar Community (DLSC) supplies 90% of the community's heat demand (52 single-detached homes) using a seasonal underground thermal energy storage system. In the summer, heat is collected and stored underground in a borehole thermal energy storage (BTES) design and then returned to the homes as heat during the winter.

There are five main components in this DLSC project: solar collection, short-term energy storage, seasonal borehole thermal energy storage (BTES), and a district heating system. The homes are certified R-2000 standard homes and meet the Built Green Alberta Gold standard. The homes sold for an estimated average \$380,000 and range in size from 138-151 square meters.

Solar collection is completed using 800 panels mounted on garages throughout the community. These panels generate 1.5 MW thermal power on a typical summer day. This heat is used to increase the temperature of a reservoir of glycol, which flows along the roof overhand, down the end of the garage, and then underground into a shallow buried trench system until it arrives at a heat exchanger within the community's 2,500 square foot Energy Centre building. A heat exchanger transfers heat to water in one of two short-term storage tanks. These tanks are 12 feet in diameter and 36 feet long.

A borehole thermal energy storage (BTES) system was built as an in ground heat sink with 144 holes that stretch 37 meters below the ground and cover an area 35 meters in diameter. By the end of the summer, the heat transferred into the ground increases the ground temperature to 80 degrees C. The BTES area is covered with sand, high-density R-40 insulation, a waterproof membrane, clay, and other landscaping materials in order to trap the heat in the ground until winter.

In the winter, heated water is circulated to homes through the district heating loop. In each home, the water passes through a heat exchanger within a low-temperature air-handling unit in the home's basement. A fan in the unit blows air across the warmed fan coil, moving heat into the home's ductwork. An automatic valve in the basement shuts off the heat input from the district heating loop when the home's desired temperature is achieved. If the system cannot meet the demand for heat, a back-up natural gas boiler is used to meet residual demand.

Project Example –Borehole Thermal Energy Storage Systems in Norway

Due to the favourable geology in Norway, approximately 90 borehole energy systems have been installed around the country. (Midttømme, Hauge and Grini, 2009)

Akershus University Hospital

Norway's Akershus University Hospital in Lørenskog is a large capacity borehole thermal energy storage (BTES) system that has been in operation since 2007. Initiated and owned by the regional health authorities in the southeast, this thermal energy storage system includes ground source heat pumps connected to 228 borehole wells. These wells are drilled to a depth of 200 meters.

This system was originally built in order to meet the country's national goal that renewable energy resources be used to provide at least 40% of heating and cooling demand. It was expanded in 2010 and now supplies 85% of total heating demand (40% of total energy demand) for the Baerum heating district. (Midttømme, Banks, Ramstad, Sæther and Skarphagen, 2008; ECES IA 2007) At a total cost of USD 19.5 million for the BTES system – including the 8MW combined ground-source heat pump and ammonia chiller system – the project has an estimated payback period of less than 10 years.

Nydalen Industrial Park

Completed in 2004, the Nydalen Industrial Park BTES was built in response to the Norwegian National Policy Guidelines, which requires the use of renewable energy in new buildings. This system includes 180 borehole wells drilled to a depth of 200 meters and uses a series of ground-source heat pumps. In total, it carries 6 MW of heating capacity and 0.5 MW of cooling capacity.

This USD 10.5 million project is financed and currently operated by the Avantor Company. It is designed to heat and cool a school campus, hotel, and an assortment of commercial and residential buildings and now supplies 80% of these facility's heating requirements. In total, these buildings represent an area of 180,000 m². Since it began operation, this BTES system has reduced the park's external energy use by 50%.

Pit Storage

Project Example – Marstal district heating system (Denmark)

In Denmark's SUNSTORE 4 project, pit storage is used to support a solar thermal power plant that is used to meet 55% of local heat demand on an annual basis. The remaining 45% of demand is met using biomass (willow wood chips). The system is comprised of a 15 000 square meter solar system, combined heat and power system with a 4 MW low emission wood chip thermal oil boiler and a 750 kW_{el} organic rankine cycle unit, and a 1.5 MW_{thermal} heat pump that uses CO₂ as a refrigerant. In 2010, an additional 75 000 cubic meters of pit storage with a floating cover were added to the facility at a cost goal of approximately USD 46 per cubic meter. This system is used to store excess summer heat for use in the winter. The project is co-financed by the European Commission under the Seventh Framework Programme for Research (FP7). (SUNSTORE 4, 2010)

Molten Salts

Project Example – Gujarat Solar One (India)

At India's Gujarat Solar One facility in India, the 25 MW parabolic trough concentrating solar power (CSP) project currently under construction will be equipped with nine (9) hours of thermal storage using molten salts. These salts will be maintained as liquids in two tanks onsite. The project is being developed by Cargo Solar Power and is expected to cost approximately USD 750 million. (Gujarat Power Corporation Ltd, 2014)

Project Example – Gemasolar Plant (Spain)

Gemasolar is the first commercial-scale concentrated solar power (CSP) plant to use a central tower receiver and fifteen (15) hours of thermal storage using molten salts. Located near Andalusia, the project spans over more than 450 acres, the system consists of 2 650 heliostats and a molten salt storage tank, which makes it capable of supplying electricity for 6,500 hours per year. The system was brought online in 2011 has an estimated annual electricity output capacity of 110 MWh/year. It cost approximately USD 419 million.

Solid Media Storage

Project Example – Electric Thermal Storage Heaters in Kentucky (United States)

Electric thermal storage heaters use electric heating elements, insulation and high-density ceramic bricks to store heat in residential homes at a relatively small additional cost compared to heaters without storage. In these systems, off-peak electricity is used to heat the elements and this heat is then stored in the ceramic bricks for later use in heating the home. The release of this thermal energy is facilitated with a fan assembly that is turned on when heat is needed in the home. This fan moves air around the bricks and facilitating the transfer of energy from the hot bricks to the colder surrounding air. As with other heating units, electric heaters with thermal storage are sized according to the heating needs of the building in which they are used.

In the United States, the South Kentucky Rural Electric Cooperative offers a 40% discount on electricity rates for electric thermal storage heaters through a time-of-use type pricing system. Similar programs exist in Canada, with Nova Scotia Power's electric thermal storage financing program.

Hot and Cold Water Storage

Project Example – Shanghai Pudong International Airport (China)

China's first large-scale cold water storage demonstration project was installed in June 2008 at the Shanghai Pudong International Airport's Terminal 2. This airport experiences 180 cooling-degree days per year and it was hoped that the demonstration project would prove effective in reducing overall cooling costs for the facility. This system has a total storage tank volume of 11,600 m³ for a cooling area of 185,000 m² and was designed to maintain the terminal building at 18-24 deg C. It cost approximately USD 17 million to construct and USD 4 million per year to operate. Over a year of operation, the system proved its ability to store thermal energy at an effective total cost of 0.01 USD/kWh.

Project Example – Residential Water Heaters (France)

In France, the thermal energy storage in existing electrical water heaters is currently used to reduce the winter peak electricity demand by an estimated 5 GW (5%). Electrical water heating has been widely used in many countries and is responsible for approximately one-fifth of total residential water heating usage in EU countries and the United States.

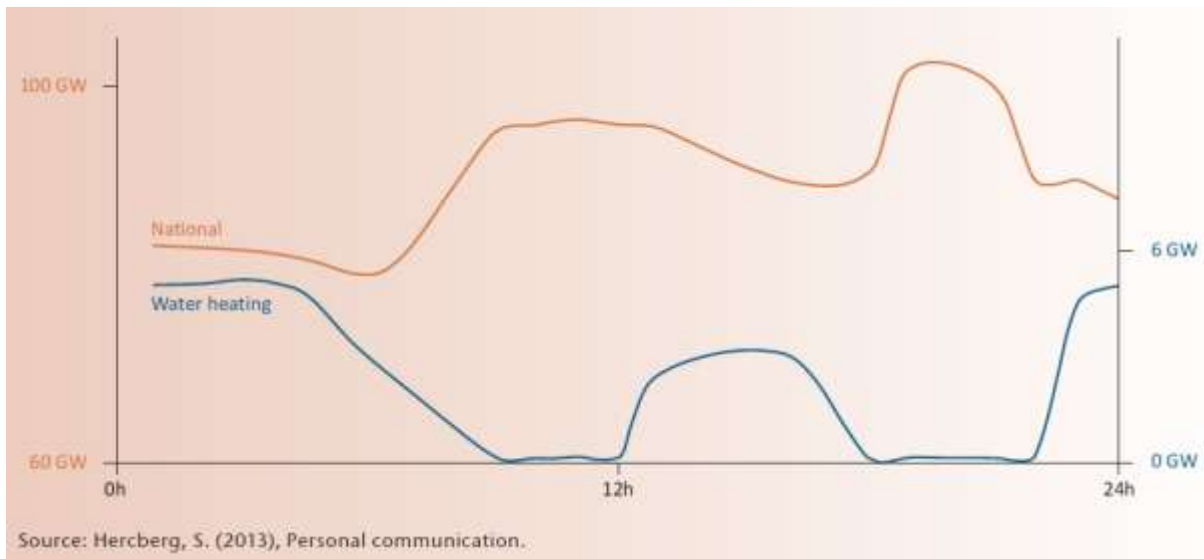
Table 2: Electric water heating: residential consumption

2010	Electricity use for water heating (TWh)	Share of residential electricity use (%)
European Union	93	22
Germany	23	27
France	20	43
Italy	7.4	25
United Kingdom	6.1	9
Spain	5.8	11
Belgium	3.3	29
Czech Republic	2.9	31
Netherlands	2.1	13
Ireland	1.8	34
Austria	1.8	21
Sweden	1.8	20
Finland	1	19
Greece	1.3	38
United States in 2005	123	20

Source: Enerdata (2011), Odyssee, the Europe Energy Efficiency Project, (database), Grenoble, France, <http://enerdata.net/enerdatauk/solutions/data-management/odyssee.php> and EIA (Energy Information Administration) (2013), Annual Energy Outlook, Washington, D.C.

In France, more than one-third of households use electrical water heaters equipped with a “2-period meter,” which allows these water heaters to be used as distributed thermal storage resources (Enerdata, 2011; EIA, 2013). These meters also allow customers to respond to the country’s peak-pricing structures, which were first implemented in the 1960s. In 2013, EDF quoted off-peak electricity prices at EUR 100/MWh versus EUR 130/MWh for peak electricity.

Figure 3: Stylised French load curves (cold weekday in winter)



This reduction was achieved in part thanks to consumer information campaigns on electricity pricing structures (peak versus off-peak pricing) and a remote start/stop function option that allows grid operators to remotely control these water heaters. As a result of this peak reduction, French utilities claim that thermal energy storage has helped the country optimise its use of the nation's generation capacity. At the same time, it has helped France reduce its energy-related CO₂ emissions by limiting the use of expensive fossil fuel-fired peak generation plants (Hercberg, 2013).

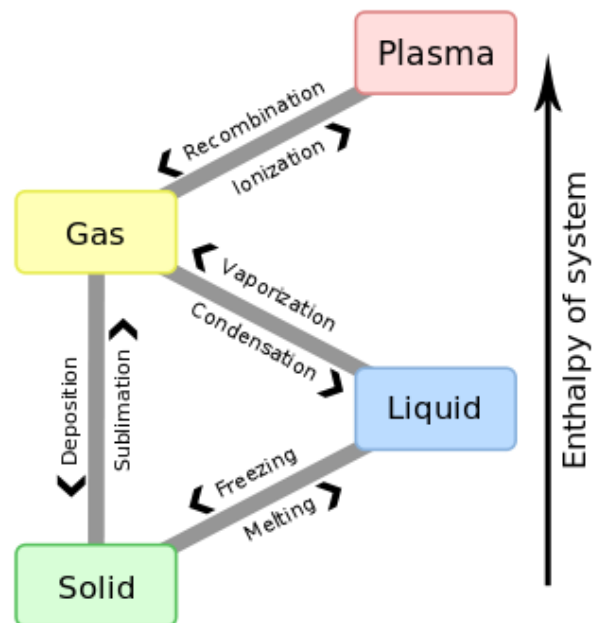
Project Example – Tahoe Center for Environmental Sciences Building (United States)

The Tahoe Center for Environmental Science Building project (TCES) in the United States uses hot and cold water storage tanks to reduce the building's total energy use and increase its usage of local renewable energy resources. For the hot water tanks, domestic hot water is pre-heated using solar hot water panels and then stored in an insulated hot water tank in the building's basement. A natural gas-fired water heater is then used to provide any additional heating requirements.

For the cold water tanks, water is cooled through evaporation during the night via a cooling tower and then collected in two 25 000 gallon underground tanks. The cold water is then circulated through a heat exchanger to decrease the temperature of the building's incoming air. Combined with radiant floors in the lobby, radiant ceiling panels in offices and induction coils (i.e. "chilled beams") in the building's laboratories this cooling system eliminates the building's need for refrigerants.

Thermal Energy Storage - Latent Heat¹¹

Latent heat storage is the use of a storage material that undergoes a phase change as it stores and releases energy. A phase change refers to transition of a medium between solid, liquid, and gas states. This transition can occur in either direction (i.e. from a liquid to a solid or vice versa), depending on if energy is being stored or released. The freezing and melting of a material is a form of latent heat storage and subsequent energy release. This type of thermal energy storage can offer storage densities 3 to 15 times greater than sensible storage. Further, the energy discharge temperature can be targeted to the desired application. Today, commonly used phase change materials include water, sodium acetate trihydrate (a colourless salt), and paraffin. (IEA-ETSAP and IRENA 2013)



Ice storage is a form of latent heat storage, where energy is stored in water that is frozen and then subsequently melted to release this stored energy.

Project examples: Ice Storage in Tokyo (Japan)

Phase change material (PCM) slurries use mixtures with higher thermal energy storage capabilities than water, particularly for air-conditioning applications.

Project examples: Clathrate hydrate slurry (CHS) for air-conditioning (Japan)

¹¹ Graphic of the nomenclature of the phase changes of a system in English by F l a n k e r and penubag exists in the public domain en.wikipedia.org/wiki/File:Phase_change_-_en.svg

Ice Storage

Project Example – Ice Storage in Tokyo (Japan)

The Tokyo Denki University's Tokyo SANYO Campus, both ice and liquid water storage tanks have been used since 2011 to provide energy storage capabilities with the primary goal of reducing energy-related CO₂ emissions on the campus. The project's three secondary goals included increasing the campus's overall energy efficiency, reducing campus peak demand, and providing an uninterrupted energy supply for resiliency in the face of energy grid disruptions. The system is owned by the University and operated by a facility management company.

This campus-wide system is comprised of an ice-on-coil storage system (latent heat storage) combined with a series of water tanks (sensible heat storage), located in campus buildings. A 13 degree Celsius temperature difference is seen between the two tanks. In the ice-to-coils portion of the system, cheaper off-peak electricity is used to freeze water that is subsequently melted to meet cooling requirements in 400 m³ ice storage tanks. The ice is frozen in cylinders along steel coils and is tied to water storage tanks (690 m³) installed at higher elevations in the campus's buildings. These vertically-linked tanks are capable of storing a combination of liquid water and ice, though they practically only hold a mixture of 1-2% ice. In practice, this system is a daily charging and discharging of energy for air-conditioning purposes. (Momota, Ibamoto, Hayashi, and Nakamura, 2014)

This project was publically funded by the Japanese Ministry of Land, Infrastructure, Transport and Tourism. In total, USD 9 million was given to pay for the campus's entire energy system infrastructure, including this thermal storage system plus all other campus energy system infrastructure. It is difficult to separate the cost of this thermal storage system, as it is wholly integrated with the building energy system.

The award of this funding was motivated strongly by the Great East Japan Earthquake (March 2011) and the resulting cessation of all nuclear power plants in Japan, which resulted in serious electricity shortages. The final goal for annual CO₂ emissions for this campus is 37.0 kg per m². During the first year of operation (April 2012 – April 2013), the buildings achieved an overall CO₂ emissions level of 46.1 kg per m². While it missed its CO₂ target in its first year, the project is considered a success as an energy conservation effort.

PCM Slurries

Project Example - Clathrate hydrate slurry (CHS) for air-conditioning (Japan)

In Japan, CHS was used at the JFE Engineering Company's headquarters in Yokohama. Starting in 2005, the system used a 35 cubic meter thermal storage tank to reduce the building's peak energy demand. Over the course of June 2005 to May 2006, the system facilitated a 25% reduction in primary energy consumption at the facility compared to the previous year. As a result, the facility reduced its total CO₂ emissions by approximately 25% in 2006, 2007, and 2008.

This type of slurry was chosen as an energy storage medium primarily due to its higher phase change temperature compared to water. The aqueous solution used in the CHS system transitions from liquid to solid at 45 degrees Fahrenheit (7 degrees Celsius) and has approximately twice the storage density of liquid water. Other considerations in the decision to use this solution in the Yokohama project included safety and ease of reuse compared to alternatives.

Versions of this CHS system have been used in office and other commercial buildings in cities including Tokyo, Yokohama, Kawasaki, Okayama, and Fukuoka. The concept has also been explored in the United States by the California Steel Industries, Inc. as a part of a Thermal Energy Storage Air-Conditioning system for their corporate office building near Los Angeles, California.

Thermal Energy Storage – Thermochemical

Thermochemical storage uses reversible chemical reactions to store heating or cooling capacity in the form of chemical compounds. Energy is stored via endothermic reactions and released in exothermic reactions, achieving energy densities 5 to 20 times greater than sensible storage. Thermal energy can be discharged at different temperatures, uncoupled from phase change critical temperatures, dependent on the properties of the thermochemical reaction. Due to its relatively high energy density potential, significant research and development effort is currently being focused on developing this type of thermal energy storage.

Project example: Thermochemical Energy Storage for Concentrated Solar Power Plants (Germany)

Project Example – Thermochemical Energy Storage for Concentrated Solar Power Plants (TCSPower) (Germany)

The TCSPower demonstration project began operation on 11 January 2011 and is scheduled to run for three years. It stores energy in reversible gas solid reactions using calcium oxide/calcium hydroxide at a temperature of 400-550 degrees Celsius and manganese oxide at a temperature of 750-900 degrees Celsius as the storage media. This project was funded by the European Commission under the Environment Theme of the Seventh Framework Programme for Research and Technological Development.

A consortium of seven organisations from Belgium, Germany, Israel, Spain and Switzerland oversees this project. In their three years of testing, researchers in this consortium aim to validate operations and performance characteristics of the system. Specifically, they hope to:

- characterise the hydroxide and oxide reaction system in terms of thermo-physical properties, thermodynamic equilibrium and reaction kinetics
- develop calcium hydroxide and manganese oxide materials with increased kinetics, improved heat transfer functionality and sufficient cycling stability for the desired temperature ranges
- identify and develop an efficient reactor concept for the hydroxide and the redox reaction system by detailed simulation
- validate the reactor concept for both reaction systems and evaluate performance in laboratory scale (100 Wh)
- investigate the more promising of the two reaction systems experimentally in a 10kW scale reactor with about 10 hours charging time corresponding to a stored thermal energy of 100 kWh
- develop a concept for efficient integration of the TCS hydroxide system into a DSG plant and of the redox system into a tower plant with central air receiver
- develop strategies for up-scaling of the TCS storage technology to industrial scale
- evaluate the overall technical and economic potential of thermochemical storage systems for next generation CSP plants

Other storage project examples

Electricity storage

- Mechanical
 - Pumped Storage Hydropower
 - Dinorwig Pumped Storage (United Kingdom)
 - Edolo pumped storage plant (Italy)
 - Entracque power plant (Italy)
 - Presenzano Hydroelectric Plant (Italy)
 - Roncovalgrande Hydroelectric Plant (Italy)
 - San Fiorano Hydro Power Station (Italy)
 - Flywheels
 - Ross Island PowerStore Flywheel Project (Antarctica)
 - Lakbarri Wind Farm Project PowerStore Flywheel Project (Australia)
 - La Gomera PowerStore Flywheel Project (Spain)
- Electrochemical
 - Lithium ceramic batteries: LESSY project (Germany)
 - Lithium ion batteries: Enel (Italy)
 - Lithium ion batteries: Los Andes (Chile)
 - Nickel metal hydride batteries: Minami Daito Island Frequency Regulation Project (Japan)
- Electrical
- Chemical - hydrogen
 - INGRID Hydrogen Demonstration Project (Italy)
 - EnBW Hydrogen Testing Facility (Germany)

Thermal storage

- Sensible heat
 - Underground thermal energy storage (UTES)
 - The Arlanda Aquifer Thermal Energy Storage (ATES) plant
 - Central Solar Heating Plant with Seasonal Thermal Energy Storage in Crailsheim (Germany)
 - Riverlight Apartments (United Kingdom)
 - Richard Stockton College ATES Project (United States)
 - Molten salts
 - KaXu Solar One (South Africa)
 - Diwikar CSP Plant (India)
 - Ice Bear – Redding Electric Utilities (United States)
 - Solid media storage
 - EnErChem (Germany)
 - Cold water storage
 - Jinan Ginza water storage heating reconstruction project (China)
 - Triton Square (Japan)

- Kompaktw und wirtschaftliche Latentwärmespeicher für Kühlprozesse im Niedertemperaturbereich (KOLAN) (Germany)
 - Hot water storage
 - Super-insulated sensible hot water long-term store (Germany)
 - Triton Square (Japan)
 - SmartHeat (Germany)
 - StoEx (Germany)
 - Jinan Ginza water storage heating reconstruction project (China)
 - Other sensible storage
 - Storage and transformation of industrial waste heat for air conditioning purposes using open cycle desiccant cooling by ZAE Bayern (Germany)
- Latent heat
 - Ice storage
 - Beijing international financial centre (China)
 - The China Pavilion for the Shanghai World Expo 2010 (China)
 - China Petrochemical Corporation Research and office room (China)
 - Other phase change materials
 - EnFoVerM (Germany)
 - Zentral (Germany)
 - FORETA Teilprojekt K - Mobile Wärmespeicherung zur Abwärmenutzung (Germany)
 - EnFoVerM (Denmark)
 - Project ProsperPLUS (Germany)
 - Chemische Wärmespeicher, CWS: Thermochemical Energy Storage for Concentrated Solar Power Plants, TCSPower (Germany)
 - Project ITES (Germany)

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