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State-of-the-art report with focus on thermal energy storage

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Abstract

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Report

Industrial energy storage

State-of-the-art report with focus on thermal energy storage

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Report

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Abbreviations

BTES	Borehole Thermal Energy Storage
CAES	Compressed Air Energy Storage
DST	Decision Support Tool
EIP	Eco-industrial parks
EUC	Electric Utility Companies
FC	Fuel Cells
GHG	Greenhouse Gas
HT	High-Temperature
LNG	Liquified Natural Gas
PCM	Phase Change Materials
PHS	Pumped Hydro Storage
TES	Thermal Energy Storage
UTES	Underground Thermal Energy Storage

Summary

This report presents an overview and state-of-the-art on energy storage technologies for the industry. The focus is on thermal energy storage, however relevant electricity storage technologies are discussed as well. The report presents an overview of energy-storage technologies suitable for improving the efficiency of processes within the plants; as well as of storage technologies suitable for enabling energy exchange between industrial plants, or between external energy networks and industry. Case examples of industrial applications of the presented technologies are also included. Finally, non-technological barriers hindering the implementation of energy storage systems in the industry, and enablers promoting their deployment, are briefly discussed.

For improving process efficiency, latent heat storage in the form of phase change materials (PCMs) is a promising technology, in particular for process heat applications. Pilot-scale industrial implementations exist with PCM storage systems at up to 1 MW capacity, at temperatures up to 300°C. For larger-scale, higher temperature applications, such as utilization of industrial waste heat for space heating purposes, sensible heat storage technologies are well-proven and available. The main barriers hindering the utilization of such large-scale storage facilities are non-technological barriers, related to location, financing and ownership of the required infrastructure. Electricity storage is well developed and available, but rarely used by or relevant for the industry.

To promote the implementation of energy storage technologies in the industry, it is essential to identify specific cases and specific needs for energy storage in different industrial segments. For this purpose, models and simulations demonstrating efficient thermal energy storage technologies are needed. Temperature levels, cycle durations, thermal capacity, and storage dimensions are all important parameters to be defined for each case, and these parameters are more easily studied by simulations than through physical installations. Following the simulations, laboratory test rigs approaching industrial scale, and pilot projects are required to enable industrial implementation of the most promising technologies. Furthermore, control and optimization strategies need to be developed, to enable companies to fully exploit the potential of energy storage.

1 Introduction

Energy supply is fundamental for sustainable industrial production and manufacturing. All forms of production requires energy in some form; as thermal energy, electrical energy or as energy stored in feedstocks. Stable and robust access to inexpensive electrical energy has been a key driver for the development of energy-intensive industries, including steel, aluminum and alloy production, thereby defining the geographical distribution of these industries. The ever increasing focus on energy efficiency and decarbonization, together with more competitive and dynamic industries, emergence of new products and supply chains, and industrialization of developing countries, changes and puts pressure on the energy production systems. From sources to sinks, all parts of energy value-chains strives to minimize losses and utilize potential surplus energy. To this end, energy storage technologies may prove to be monumental in shaping future efficient energy systems.

This report focuses on *industrial* energy storage. There are several reasons why the industry should invest in energy storage:

- Energy storage may directly reduce plant's energy consumption by enabling exchange and reuse of surplus energy from other processes or plants. Energy storage may enable valorization of for instance side streams, gaseous emissions, surplus heat or by-products, thereby facilitating industrial symbiosis (Chertow, 2007; Guo et al., 2017).
- Energy storage may be used for supplying necessary peak power demands (both thermal and electrical) for time-varying production and manufacturing processes, often referred to as peak shaving. These time-variations may both be inherent for the processes, e.g. batch a semi-continuous processes (Atkins et al., 2010b; Fernández et al., 2012), or result from adaptation to changing market demands. Using energy storage to provide peak power-demands may save investment costs for companies by decreasing the necessary capacity of the energy-supply infrastructure, as well as reduce the demand for costly peak energy sources.
- Energy storage may facilitate load shifting from high-price to low-price periods (Kousksou et al., 2014; Zhang et al., 2015).
- Energy storage may also hedge against shortage in energy supply, thereby increasing security of supply and provide operational security for industrial plants.

Energy storage is most commonly installed to reuse surplus energy from other processes and plants, in particular surplus heat (Ammar et al., 2012; Fernández et al., 2012; Miró et al., 2016), or possibly through feedback from a particular process itself. Yet, pertaining to the motivation for storing energy mentioned in the paragraph above, plants with highly dynamic and adaptive production processes may for economic reasons utilize storage facilities also for storing energy supplied from a market. Both thermal, electrical and chemically bounded energy may be stored. Industrial plants may utilize stored energy both in the particular form the energy is stored, e.g. as heat or steam, or through conversion processes (Geidl et al., 2007), e.g. as heat-to-power through Rankine cycles (Lovegrove et al., 2004) or as power-to-gas (Götz et al., 2016).

The main objective of this report is to provide an overview and state-of-the-art on energy storage in the industry, particularly focused towards the Norwegian industry. The report does not target to be an exhaustive review on existing examples and case studies of industrial energy storage. Instead, we seek to present a unified overview of suitable energy storage technologies for integration in industrial production and manufacturing, put in the context of industries' potential and demands for energy storage (section 3). Moreover, we present a set of industrial applications of energy storage (section 4), and elaborate on barriers and enablers for increasing the use of industrial energy storage (section 5).

Notation

In the sequel, we refer to industrial processes in a broad sense, including both processes in food production such as drying and cooling, metallurgical processes such as melting of raw materials in furnaces, and classical chemical processes such as production of ammonia. We use the terms manufacturing and production interchangeably, although the manufacturing normally refers to the process of transforming raw materials into final products, while production is more general and refers to processes converting inputs materials to not necessarily salable output products. Moreover, by thermal output, we refer to a “thermal power” or thermal energy stream in the sense of $\mathrm{kW}_{\mathrm{thermal}}$.

2 Levels of industrial energy-storage integration

Surplus energy may be integrated and utilized at many levels in industrial production and manufacturing. As a means of providing a systematic description of the application, motivation and need for industrial energy storage, we consider two levels of integration:

- **Inter-plant** or plant-to-plant energy storage, sometimes referred to grid level storage.
- **Intra-plant**, plant-level or process-to-process energy storage, i.e. energy storage within a process or between separate processes within a plant.

For some industries, it may be adequate to consider also intra-process energy storage (Chaturvedi and Bandyopadhyay, 2014), that is, intermediate energy storage *within* a particular production or manufacturing process. However, as the distinction between intra-plant and intra-process energy storage may be ambiguous, intra-process is included in the intra-plant level of integration.

The categorization above does not exclude cross-integrations. In some industries, e.g. large diaries (Atkins et al., 2011), energy storage may be utilized both between and within plants. Notwithstanding, to assess inter and intra-plant energy storage, we attribute the following:

1. Definition and principle of the energy exchange.
2. Characteristics of energy exchange constituting a need for intermediate storage.
3. Media relevant for energy exchange.
4. Reported case studies from the literature.

2.1 Inter-plant energy storage

Energy exchange between industrial plants may take place when one or several plants have surplus energy of some form and sufficiently high grade which the plant is unable to utilize itself, and/or it is economically viable to distribute the energy outside the plant. Moreover, it requires that one or several other plants are able to integrate and utilize the surplus energy in their production or manufacturing. Inter-plant energy storage can hence be defined as the availability of an energy storage utility and infrastructure between two or more plants exchanging energy. An illustration of possible types of energy exchange with a storage is shown in Figure 1.

The motivation for investing in inter-plant energy storage facilities may come as a combination of the points mentioned in the introduction. An additional reason for inter-plant energy storage may be cases where several units supply surplus energy with different characteristics (e.g. temperature level of steam), with each end-user (sink) of the surplus energy requiring the stream supplied in a particular form or with certain properties. The highest potential for inter-plant energy storage and exchange comes with clustering or co-localization of industries with different energy profiles and demands. Still, both stored sensible heat (Chiu et al., 2016) and chemically bounded energy, either as by-products or as produced chemical products, may be stored and transported between geographically

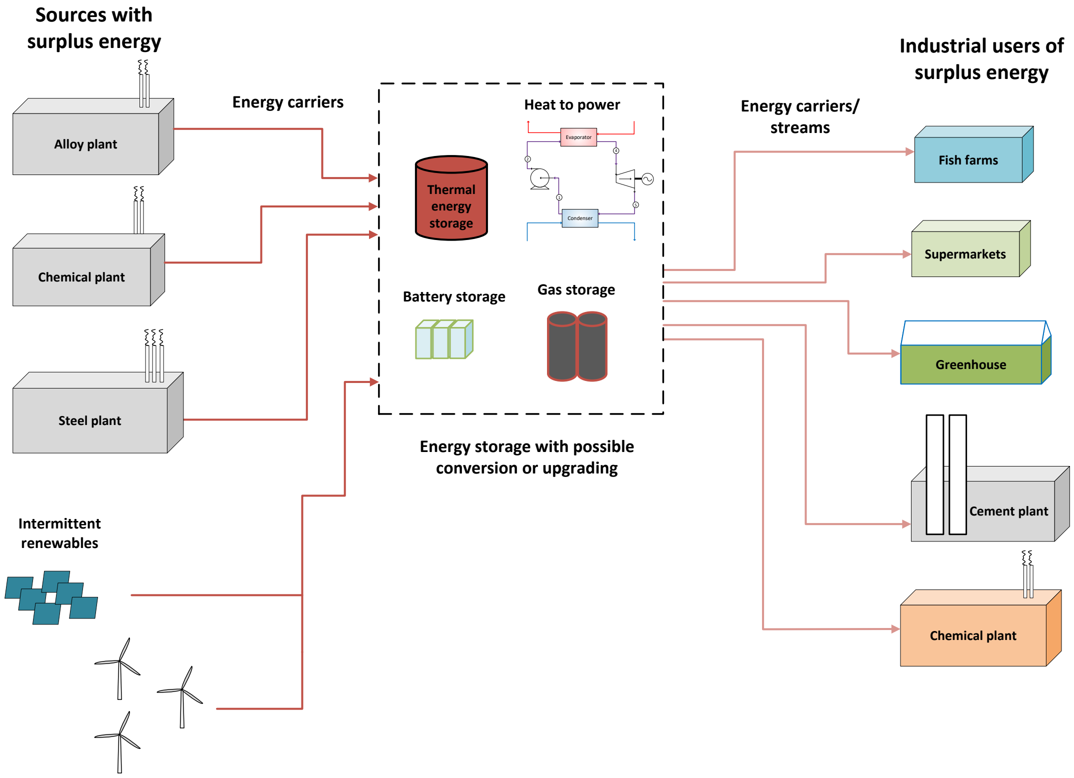


Figure 1: Illustration of a multi-carrier inter-plant energy storage infrastructure.

spread plants (Digernes et al., 2017). An example of the latter is hydrogen, either produced through steam-methane reforming, as a chemical by-product or produced by electrolysis of water from excess renewable electricity. Hydrogen may either be stored and transported subsequent to pressurization or liquefaction, or converted to methane or synthetic natural gas in a power-to-gas process with additional processing to enable transportation (Guney and Tepe, 2017). Meanwhile, chemical energy storage approaches the use of surplus energy as a commodity or feedstock. As such, one may consider also biomass and biogas (Denholm, 2006; Guney and Tepe, 2017) within the scope of inter-plant energy exchange with intermediate storage.

There exists a large number of industrial parks and clusters world wide where energy as well as other resources and commodities are exchanged towards the goal resource and energy efficient industrial ecology (Chae et al., 2010; Kastner et al., 2015). This co-localization and coordination of different industries is often termed eco-industrial parks (EIPs). In Scandinavian context, Kalundborg is by far the most well-known and developed EIP (Ehrenfeld and Gertler, 1997; Kalundborg Symbiosis, 2017). In Norway, Mo Industrial park has infrastructure both for exchange of CO gas and for heat exchange (Mo Industripark, 2017). Moreover, Nydalen has installed energy storage facilities (International Energy Agency, 2014a). Maes et al. (2011) presents a thorough review on energy exchange and management in industrial parks in Flanders. For other examples of energy exchange in EIPs, we refer the reader to Kastner et al. (2015) and Guo et al. (2017). Examples of inter-plant energy exchange outside EIPs include integration of a biogas and cement plant studied by Ellersdorfer and Weiss (2014), biomass drying using surplus heat from process industries (Li et al., 2012), and exchange of CO rich gas from a manganese alloy plant to a neighbor ammonia factory in Porsgrunn, Norway (Digernes et al., 2017; Eramet Norway, 2013)

While energy storage in particular may facilitate energy exchange between industrial plants with different production patters, it may also enable non-industrial utilization of surplus energy. A common example is use of low-grade surplus heat for heating homes and businesses via a district heating network(Ammar et al., 2012; Meneghetti and Nardin, 2012; Viklund and Johansson, 2014).

2.2 Intra-plant energy storage

Intra-plant or plant-level energy storage is used to intermediately store surplus energy from one process or production unit in a plant prior to supplying the energy to another process or unit within the same plant. Energy storage can be utilized both for storing energy targeted directly for one or several other processes in the plant, or for other purposes within the plant, for instance for fuel-supply to trucks or for building heating in the plant. In the latter cases, energy storage can be used to distribute the energy resource over time. The main purpose of intra-plant energy storage is to leverage time-variations between un-utilized energy streams and the energy demands of other processes within the plant (Anastasovski et al., 2015; Atkins et al., 2010a,b; Fernández et al., 2012). Yet, companies may also invest in energy storage utilities in their plant for resilience purposes, in order to decrease the process interdependency that would result from direct integration of energy streams.

The most widespread use of intra-plant energy storage is for indirect heat integration between processes, in particular for batch and non-continuous processes (Anastasovski et al., 2015; Atkins et al., 2010b; Chen and Ciou, 2008). In chemical process plants, high-grade (high-temperature) heat streams are often utilized directly through heat or process integration Ammar et al. (2012); Chaturvedi and Bandyopadhyay (2014); Chew et al. (2013). As a result, a major part of available surplus heat is at relatively low temperatures (Ammar et al., 2012; Li et al., 2012). Too low heat source temperature may require upgrading the heat stream, either before or after storage (Li et al., 2014). The most efficient sequence of storage and upgrading depends on the storage medium, temperature levels and whether both or only one of the sources and sinks exhibit time-variations. DECHEMA (2017) states that many chemical processes demand low and medium temperature steam, currently to a large extent generated by burning fossil fuels or with electricity. For chemical-process plants it may hence be interesting to explore the economical and technical feasibility of investing in energy storage and upgrading equipment for utilizing low to medium temperature surplus heat streams for steam generation.

On the other hand, for multiple, energy-requiring sub-processes that are intrinsically *connected* and which constitute the manufacturing of some product, it may be unnecessary and in fact suboptimal to intermediately store the heat since all storage comes with some losses. Examples on such processes may be sequenced cooling or heating in food processing or production of some chemical product.

Intra-plant energy exchange with storage exists with several different energy carriers, including hot water and steam for thermal energy exchange, flue and off-gases for heat generation with combustion chambers, and as solid feedstock-like carrier such as hydrogen or biomass. Where possible with respect to safety and available infrastructure, hydrogen may be a future pathway for intra-plant energy storage (Lowesmith et al., 2014). This is particularly relevant in chemical and petrochemical industries, with processes producing hydrogen in various degrees of purity as side streams (DECHEMA, 2017). Stored hydrogen may be used to produce on-demand electricity through a fuel cell, or used as feedstock in other processes. Intra-plant level energy storage may also include storing energy on site from a source outside of the plant itself. As an example, energy-intensive industries may invest in renewable energy production facilities mainly for supplying electricity to their own processes. Energy storage facilities may then be utilized for hedging against market price-fluctuations of the company's products, or to provide ancillary services to electric utility companies during non-productive periods.

There have been conducted numerous studies of intra-plant energy storage, and only a few are mentioned here. Atkins et al. (2010b) studied a milk powder plant in New Zealand utilizing using heat storage to reduce energy consumption. Boer and Bach (2006) presented a case study from an existing production facility of organic surfactants, studying the potential of different thermal storage systems for operating temperatures between 110 and 160°C. Muster-slawitsch et al. (2011) studied heat-integration networks with thermal storage tanks as a part of project for integrating renewable energy and reduce fossil energy usage breweries. Biglia et al. (2017) adopted steam storage for a case study on batch process for debacterisation of cocoa beans. Finally, we mention an interesting, recently conducted case study by Bailera et al. (2017), where the authors studied a hybrid power-to-gas electrochemical plant, utilizing renewable surplus electricity for hydrogen production, which may be intermediately stored in tanks, or used as a continuous stream in ammonia or synthetic natural gas production.

For a thorough review on case studies on industrial thermal energy storage, we refer the reader to Miró et al. (2016).

3 Energy storage technologies

A major part of the studies concerning energy storage focuses on electrical energy storage on an electricity grid level for enabling the introduction of more renewables. This is characterized as a key element for assisting the transition to a low-carbon society (Castillo and Gayme, 2014). Energy storage at an industrial level is however not widely used, due to several factors. Lack of knowledge, uncertain costs, unknown amount of surplus heat, and challenging operational implementation can be some of the reasons. However, the interest in energy storage is increasing, and the industry is requesting more relevant technologies and knowledge regarding implementation of storage facilities. The *International Energy Agency* has also identified thermal energy storage as a technology with potential to reduce surplus heat, which is characterized as an underutilized resource (International Energy Agency, 2014b).

Thermal storage is today mainly utilized within heating of buildings and hot water. The most common technologies include hot water tanks, underground thermal energy storage (UTES) and ice storage for cooling. All of these technologies are relatively inexpensive, but have significant space requirements, and the main focus of R&D today is at developing more compact storage technologies, such as systems using phase change materials (PCM). The same technologies may be applicable in industrial systems, but higher capacities and often higher temperature levels are often required. Investments in development of TES technologies is recognized as a key to solving the future challenges within a more energy efficient industry, especially when integrating fluctuating renewable energy sources, both thermal and electrical.

In the following sections, the most relevant energy storage technologies for industrial use will be presented, along with a qualitative assessment of their strengths and weaknesses. This is not a complete list of the applicable technologies, and every industrial case requires its own recommendations. However, the aim is to provide a good starting point for further discussion and evaluation in each case.

3.1 Technology selection

Considering the installed capacities of different energy storage technologies on a global level, pumped hydro storage (PHS) makes up a vast majority of the large scale energy storage installations. In USA, PHS provides more than 98% of the installed energy storage capacity (see Figure 2) (Aneke and Wang, 2016).

The International Energy Agency (2014b) classifies the applications for energy storage with respect to energy output, size, discharge duration and cycles. For industrial use, the applications *Seasonal storage*, *Demand shifting and peak reduction* and *Waste heat utilization* have been identified as the most relevant for industrial use. *Seasonal storage* may also be relevant in some cases in countries where the ambient temperature varies significantly with the seasons.

Important factors to consider when reviewing storage technologies include discharge duration, capacity, temperature range, cost, and area or volume. In Figure 3 the capacity range of the different storage applications is shown as a function of duration. The identified applications are found in the minute-day region up to 1-10 MW, apart from the seasonal storage, which differs from the rest with a huge capacity need over longer periods.

For industrial use of storage technologies, an important aspect is the payback period. The payback

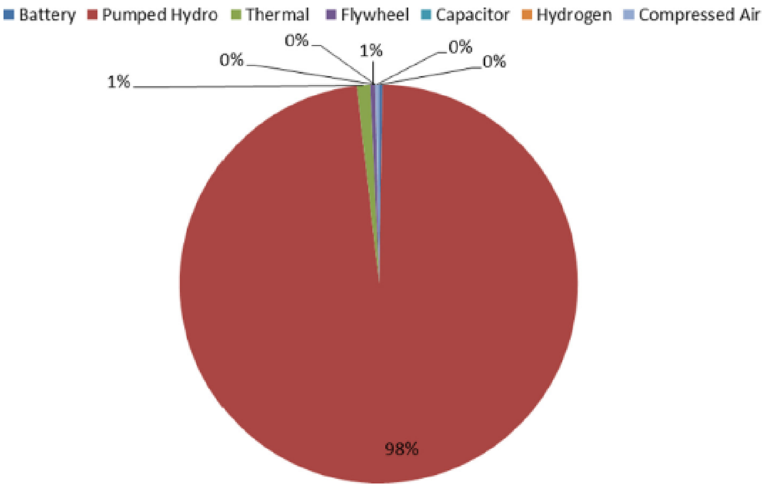


Figure 2: Technology share of quantity of energy stored globally. (Aneke and Wang, 2016).

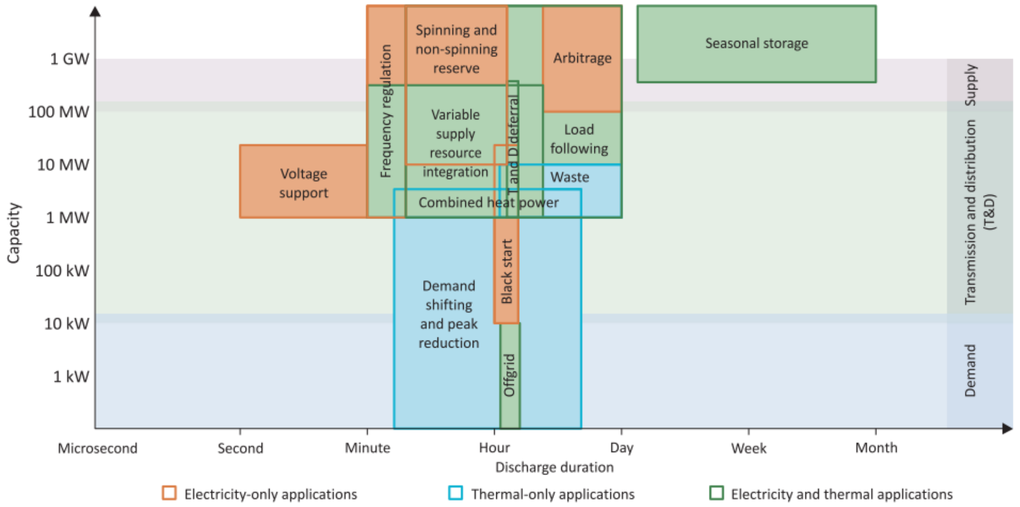


Figure 3: Thermal output/capacity requirement versus discharge duration for some applications of energy storage in today's energy system (International Energy Agency, 2014b).

period is the period of time required to recoup the investment cost. For the industry, the demanded payback period is normally 2-3 years, setting strict requirements for the profitability of an investment. The investment cost of an energy storage system depends on the type of energy storage, the area used, installed capacity and infrastructure costs. The profitability of a technology will depend on how much energy can be saved, and how much that energy would cost to produce or buy from other sources. An important factor to consider is the number of charging/discharging cycles, as a higher cycle frequency implies more energy saved, hence increasing profitability.

In the further evaluation of technologies, special attention will be paid to the investment cost, capacity and temperature level, as these are key factors when considering relevant technologies for an application. Space requirements, cycle length, efficiency, and necessary infrastructure are also important aspects, and will be discussed for each technology.

3.2 Thermal energy storage

Thermal energy storage (TES) builds upon the principle of storing surplus heat in a storage media for later use during periods with a heat deficit. TES technologies can be characterized by temperature, storage time, storage materials or other characteristics. Low-temperature TES has previously been extensively developed and investigated in several applications, while high-temperature has a future potential especially within surplus heat recovery and solar heat collection. TES has also been recognized as an enabler to shift the electrical loads from high-peak to off-peak hours, an important feature for high intensity industries (Kousksou et al., 2014). TES is normally divided into the following groups:

- Sensible TES
- Latent TES
- Chemical TES

Table 1 shows a comparison of some important parameters for the different types of thermal energy storage. As we can see, the energy intensity rises from left to right in the table, but so does the cost and the remaining need for research before the technology is commercially available. Both latent TES and chemical TES are considered to be promising technologies. The different technologies are further described in the following sections.

Table 1: Comparison of different types of thermal energy storage (Haji Abedin (2010); Zhang et al. (2016)).

	Sensible TES	Latent TES	Chemical TES
Temperature range	Up to: • 120°C (water tanks) • 50°C (aquifers and ground storage) • 400°C (concrete)	• 0-1000°C	• 20-1000°C
Storage density	Low (with high temperature interval) 50 kWh/m^3 (for typical water tanks)	Moderate (with low temperature interval) 80-140 kWh/m^3	Normally high 110-800 kWh/m^3
Lifetime	Long	Often limited due to storage material cycling	Depends on reactant degradation and side reactions
Technology status	Available commercially	Available commercially for some temperatures and materials	Generally not available, but undergoing research and pilot project tests
Advantages	• Low cost • Reliable • Simple application with available materials	• Medium storage density • Small volumes • Short distance transport possibility	• High storage density • Low heat losses • Long storage period • Long distance transport possibility
Disadvantages	• Significant heat loss over time • Large volume needed	• Low heat conductivity • Corrosive • Significant heat losses	• High capital costs • Technically complex

3.2.1 Sensible thermal storage

In sensible thermal energy storage, the heat is stored simply by heating or cooling a solid or liquid media. For instance water, concrete, sand and rocks are used as storage media for sensible TES. The

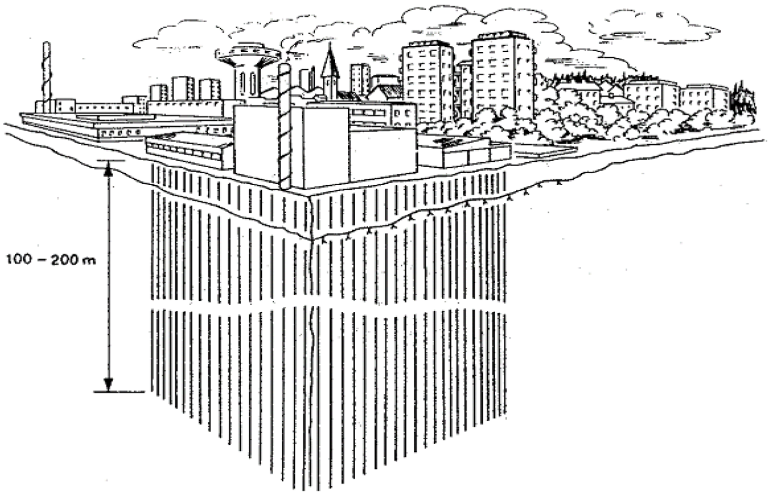


Figure 4: UTES system using boreholes for storing thermal energy. (Paksoy, 2013)

temperature difference per heat input/output is directly related to the heat capacity of the media used, through the relation

$$Q = mC_p\Delta T \tag{1}$$

where m and C_p denote the mass and heat capacity of the medium, while ΔT is the temperature difference for a given heat input/output Q.

Sensible thermal storage is the most mature form of TES, and many technologies have reached a high level of maturity and deployment. Water is undoubtedly the oldest, and still the most common form of thermal storage. This is for a good reason: water has extremely high specific heat capacity and high thermal conductivity, and it is cheap, abundant, and safe and simple to use. Sensible heat is also the cheapest technology, but with the lowest energy density of the TES technologies.

Underground Thermal Energy Storage

General: Underground thermal energy storage (UTES) is a large scale TES technology, and may provide benefits especially in areas with significant surplus heat resources. UTES involves pumping of heat or cold into the ground, for use at a later time. UTES is normally used for a long-term or seasonal storage of large amounts of thermal energy, and include pumping heat or cold into already existing caverns, boreholes and aquifers. UTES can be applied in buildings' heating systems or district heating.

Temperature: UTES systems are well developed and commercially available at temperatures up to approx. 40°C. For higher temperatures, demonstration projects exist up to around 90°C, and can be very interesting in industrial applications (European Technology Platform on Renewable Heating and Cooling, 2012).

Development & cost: UTES is already at a commercial level, at both low-temperature and medium-temperature applications. Some of the challenges with the UTES systems today are related to system efficiency and investment cost. Large energy amounts are needed to make an investment in a UTES system economically feasible. Especially within district heating grids, UTES is quite commonly used today, often in a combination with solar collectors. For industries with lots of surplus heat available in the summertime, and residental areas with large heat demand nearby, UTES may be applied to store the heat in the summertime to be utilized in the winter.

The International Energy Agency (2014b) specifically mentions the improval of thermal and economic efficiency of UTES systems as key actions for future thermal energy storage at temperatures

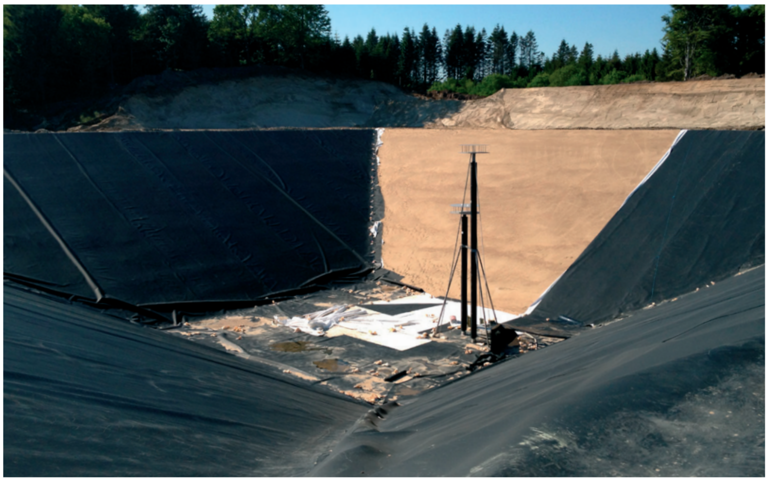


Figure 5: Construction of Dronninglund pit storage for solar heated district heating system (PlanEnergi, 2016).

from 10°C to 250°C. UTES for applications above 250°C is also mentioned as a critical area to develop on a longer term.

Pit storage

General: Pit storage is suited for smaller-scale TES, and is based on digging shallow pits and filling them with a storage medium. The storage medium can be gravel and water, and is covered by an insulating material. This is then used as a heat storage, where hot or cold water is pumped out of or into the pit.
Temperature: Pit storage is mainly applied in temperatures up to a maximum of 80°C (Solar Heating and Cooling Programme, 2015).
Development & cost: Pit storage is perhaps the furthest developed TES technology. Pit storage is used throughout Denmark's district heating system today (Solar District Heating, 2016). Pit storage is one of the TES technologies with the lowest investment cost.

Molten salt

General: Molten salts are solid at room temperature and ambient pressure, while they liquefy when heated or pressurized. The molten can be used to store, and in some cases also transport, heat. TES systems using molten salt are commonly used in power tower systems where solar energy is concentrated to heat the salt, and the salt is used to produce steam to run a power plant (Solar Reserve, 2017). The salt can then be stored and used when needed. They are also used in chemical and metallurgical industries to transport heat as a fluid, hence providing experience and knowledge of the use of the salts (Kousksou et al., 2014).
Temperature: Molten salts typically have a melting point around 100°C, and can be heated to approx. 500°C. They can therefore be a good alternative for storage at higher temperatures, but they are still quite space-consuming. Molten salts have typically an energy density of 30-100 kWh/m^3.
Development & cost: European Technology Platform on Renewable Heating and Cooling (2012) mentions molten salts as a possible solution for the industrial need of low-viscosity, non-corrosive fluids for storing large quantities of heat at low pressures. The technology is more expensive than pit storage, but generally provide high efficiencies, reported at over 90% (Sevault et al., 2017).

Solid Media Storage

General: Solid media storage systems include storing heat or cold in solids such as bricks, rock, concrete and similar. Solid media storage lacks difficulties related to corrosion, pressure and other

Figure 6: Use of molten salt in a concentrated solar power system, where the molten salt is circulated through the power tower in the middle, stored in insulated tanks (Solar Reserve, 2017).

limitations related to processing fluids, but a critical element is the heat transfer. Efficient heat transfer between the source/demand and the storage is crucial, and is one of the limitations of solid media storage. In many countries, electric heaters include solid media storage, and also wood stoves may include solid media storage to distribute the transfer of heat over a longer period of time (International Energy Agency, 2014b). Solid Media is also being developed to be used in solar thermal power plants.
Temperature: Solid media storage can be used to store thermal energy in a large temperature span, depending on the storage media. Stone, concrete and metals have different applications, and can store heat at high temperatures. Commercial projects using concrete for storage up to 427°C exist (EnergyNest, 2017), and metals can be used at even higher temperatures.
Development & cost: Solid media storage is well developed, and is already commercially available. The investment cost depends on the storage medium chosen, but is generally low. A challenge is the space requirement, as the energy density is low compared to liquid storage media.

Hot and cold water tanks

General: Storing water in hot or cold water tanks is perhaps the most common example of sensible heat storage, and is found in both residential and industrial buildings worldwide. The simplest form of using water as thermal storage is in the form of large accumulator tanks, a technology which is widely used for instance by the district heating branch.
Temperature: Storage of water is naturally limited to 0-100°C at ambient pressure, however with pressurized tanks, higher temperatures can be applied. Hot water tanks are generally primarily suited for short-term, diurnal thermal storage owing to heat losses to the environment. The Dutch company Ecovat is however designing large-scale stratified accumulators buried underground, enabling to store heat at around 90 °C over a period of over 6 months, promising heat losses lower than 10% over this period (Ecovat, 2017).
Development & cost: As mentioned, hot water tanks are commonly used throughout the world today, and the technology is fully developed and commercialized. It is mainly used for short-term storage at relatively low capacities, but is easily scalable and cheap.

3.2.2 Latent thermal storage

Latent TES is based on the latent heat of phase change of a material between liquid to solid or liquid to gas at a constant temperature level. Latent TES is typically called phase change materials (PCM),

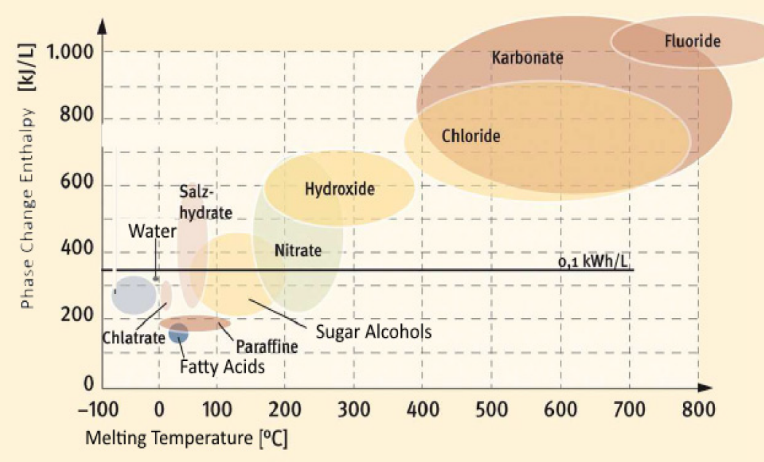


Figure 7: Temperature range and phase change enthalpy (latent heat of fusion) per unit volume for some common PCM groups (ZAE Bayern, 2017).

and is characterized by the ability to store energy at a higher density. It is also beneficial for several applications to be able to extract heat at a constant temperature. The storage capacity of PCMs can be calculated by

$$Q = mL \tag{2}$$

where L is the specific latent heat of phase change of the material.

Typically the phase change between solid and liquid state is applied, due to the large change in volume between liquid and gas phases. Energy density is one of the main advantages of PCMs compared to sensible heat storage, but another important feature is the constant temperature of the heat charge and discharge. While sensible heat storage changes temperature during storage and release, the phase changes takes place at a constant temperature. A drawback of PCMs is the thermal conductivity, which normally is lower than for sensible heat storage media. This requires large heat exchanger surfaces in order to achieve fast charging and discharging rates, making the technology more complex and expensive.

Due to the high energy density of PCMs, studies have also been performed to investigate the possibility of transporting surplus heat from one location to another. This can give great advantages in areas where the surplus heat and the heat demand are not co-located, such as in Norway, where the industries are often not located in areas with dense populations. In one test project, trucks filled with molten PCM have been used to transport up to 2 MWh from a biogas facility to a district heating network approx. 6km away (Miró et al., 2016). A few studies, and some demonstration projects regarding such mobile TES have been performed, but few have shown promising results, especially regarding the total CO_2 emissions (Miró et al. (2016) and Kaizawa et al. (2008)).

Latent thermal storage is generally divided into four types:

- Organic
- Inorganic
- Metallic (sometimes categorized as a subgroup of inorganic PCMs)
- Eutectic

These groups of materials are discussed briefly below; a more detailed discussion can be found in separate reports ((Drexler-Schmid and Kauko, 2017) and (Sevault et al., 2017)).

Organic PCMs

General: Organic PCMs, characterized by having carbon atoms in their structure, are among the most commonly applied PCMs (A.S. Fleischer, 2015; Pereira da Cunha and Eames, 2016). Organic PCMs exhibit relatively high latent heats (in the range of 100-200 kJ/kg), are physically and chemically stable, affordable, readily available, and easy to work with. However, their thermal conductivity is typically low (in the order of 0.1-0.7 W/(m·K) (Pereira da Cunha and Eames, 2016)), and this has to be taken into consideration in the heat exchanger design. Furthermore, organic PCMs have relatively low densities and do not exhibit a sharp phase transition at the melting temperature but rather an extended transition taking place around the melting temperature (A.S. Fleischer, 2015).
Temperature: 0-170°C (Pereira da Cunha and Eames, 2016)
Development & cost: Organic PCMs are widely studied for low-temperature applications: paraffins for thermal management in electronics, and fatty acids for applications related to thermal comfort, e.g., in residential buildings (A.S. Fleischer, 2015). Their practical applications are apparently still few. Incorporation of polymers to heat exchangers for different applications in the industry has been studied by Zauner et al. (2016); however, this application is still at a low TRL level. Prices of organic PCMs vary from around 45 NOK/kWh for fatty acids to 250 NOK/kWh and beyond for amides and other less common PCMs (Pereira da Cunha and Eames, 2016). Note that the price only includes the price of the material, excluding the costs of the heat exchanger system, storage tank and other infrastructure.

Inorganic PCMs

General: Common inorganic PCMs for higher temperature applications include salts and salt hydrates. Salt hydrates are combinations of members of the inorganic salt families (oxides, carbonates, sulphates, nitrates and halides) with water molecules, following a specific ratio (A.S. Fleischer, 2015). Salts and salt hydrates are the most commonly applied PCMs in the high-temperature range. Inorganic PCMs have sharp phase transitions at the melting temperature, latent heats comparable to those of organic PCMs, and higher thermal conductivities. Furthermore, they have higher densities, and exhibit smaller changes in volume during the phase change than organic PCMs. However, salts and salt hydrates tend to degrade over repeated thermal cycling, and are corrosive, hence not compatible with most materials. Moreover, they have a tendency for supercooling, meaning that the PCM might solidify at a temperature below the actual melting temperature. This problem may however be tackled with adding nucleating agents into the PCM.
Temperature: Salt and salt hydrates can be found with melting temperatures ranging from 10 to 900°C (A.S. Fleischer, 2015).
Development & cost: Salts and salt hydrates are commonly suggested for TES in e.g. concentrated solar power applications Xu et al. (2015), and some pilot installations exist (see section 4). Salts and salt hydrates are inexpensive; the prices range from 11 to 45 NOK/kWh for the salt hydrates listed by Pereira da Cunha and Eames (2016).

Metallic PCMs

General: Metallic PCMs are little studied but promising group of materials for high-temperature applications, such as surplus heat recovery from hot exhaust gases (Maruoka and Akiyama, 2006). Metals and metal alloys are the only groups of PCMs that do not suffer from low thermal conductivities, and most of them are safe and easy to work with. Their main drawbacks are their low latent heat and high density, which results in a high mass for the thermal storage. In the low-temperature regime, the latent heats of gallium and cesium are one order of magnitude lower than the organic PCMs with similar melting temperature. In the high-temperature ranges, however, metallic PCMs exhibit similar latent heats as salts and similar melting temperatures.
Temperature: Most potential for high-temperature applications, from 400 to >1000 °C (A.S. Fleischer, 2015; Maruoka and Akiyama, 2006).

Development & cost: It seems that the use of phase change metal alloys for high-temperature TES has been underestimated by researchers though they are superior to salts in many respects (Kenisarin, 2010). Some studies on using metallic PCMs for surplus heat recovery from hot exhaust gases are presented in section 4. No price information was found for this group of PCMs.

Eutectic PCMs
General: Eutectics are generally defined as alloys or mixtures exhibiting a distinct melting point for the whole mixture, which is lower than that of any other alloy or mixture composed of the same constituents in different proportions (A.S. Fleischer, 2015). Commonly applied eutectic PCMs are mixtures of salts and water, applied for operation temperatures close to/below 0°C (Oró et al., 2012). Furthermore, binary and ternary mixtures of inorganic salts have been widely studied for high-temperature applications (Pereira da Cunha and Eames, 2016). Due to their high density and stability in the liquid state, they have been used widely in high-temperature sensible thermal storage systems (thermonuclear energy, concentrated solar thermal power).
Temperature: Mixtures of salts and water are applied for operation temperatures close to/below 0°C. Eutectic mixtures of inorganic salts appear promising in the range from 130°C up to 1250°C (Pereira da Cunha and Eames, 2016).
Development & cost: Application of aquatic salt solutions as PCMs for cold thermal storage are commercially available (Oró et al., 2012). The application of eutectic mixtures as PCMs for high-temperature applications is on the research stage. Prices range from 16 to 340 NOK/kWh (Pereira da Cunha and Eames, 2016).

3.2.3 Chemical storage

General: Chemical TES uses reversible chemical reactions to store and release heat. Chemical TES has the potential to store energy at much higher densities, and is well suited for long-term storage. This technology is nevertheless at a lower technological readiness level, and significant research and development efforts are being focused on developing this type of thermal energy storage (Haji Abedin, 2010).

Chemical TES is based on using heat to excite a reversible endothermic reaction and releasing the heat in the reverse exothermic reaction. The principle is based on the following equation, C is a material absorbing energy and converted into two components A and B (Haji Abedin, 2010):

$$C + heat \Longleftrightarrow A + B \tag{3}$$

As illustrated in Figure 8, one of the main advantages of chemical energy storage is the possibility of storing the two components separately, reducing the heat losses from the storage to nearly zero. Thermochemical energy storage is therefore suitable both for short-term and long-term heat storage. In thermochemical energy storage, the material selection is the key issue. The reaction between the materials must be possible to control in a suitable way, and issues regarding corrosion, thermal conductivity, material degrading must be taken into consideration.

The absolutely main advantage of chemical energy storage compared to sensible heat and latent heat is the energy density. While the energy density of sensible heat and latent heat lie in the range of 50-140 kWh/m^3, chemical TES can achieve storage densities of 110-800 kWh/m^3, as shown in Table 1.
Temperature: A large number of materials can be used for thermochemical energy storage, enabling a large range of possible temperatures applied. Haji Abedin (2010) mentions a temperature range of 20-200°C, while Zhang et al. (2016) lists possible materials in the range of 300-1000°C. The challenge lies within the material selection and limitations in control systems and equipment.
Development & cost: Thermochemical energy storage is a highly attractive technology for future use, due to its high energy density and efficiency. It has nearly no losses during storage, and can be used both for short- and long-term storage. However, there is a long way to go before thermochemical storage

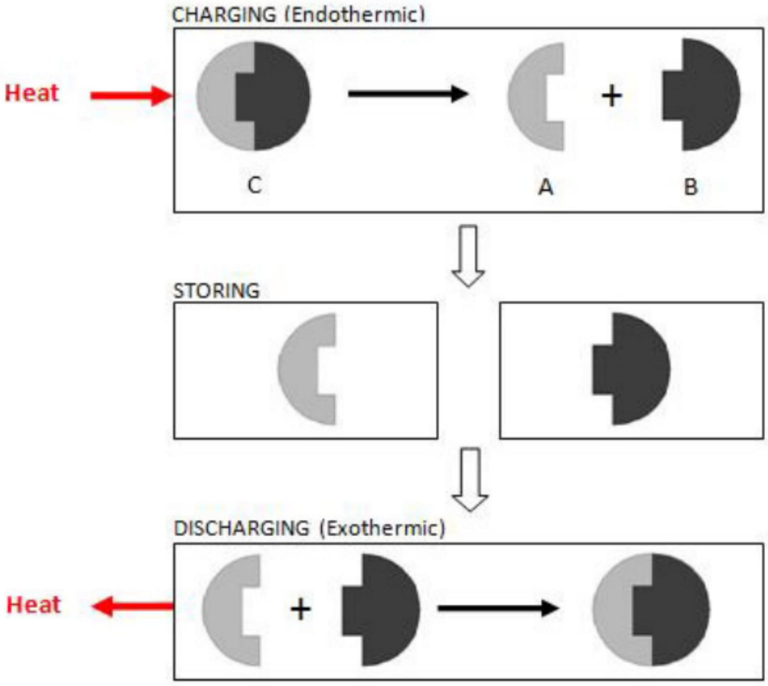


Figure 8: Processes involved in a thermochemical energy storage cycle: charging storing and discharging. (Haji Abedin, 2010)

is commercially available. Most studies today are related to the material stability and containment, and the control technologies. When the practical possibilities have been mapped, it will be easier to assess which applications will suit best for thermochemical storage. The cost of thermochemicals today is very high, and is at the moment not competitive to existing technologies (Kousksou et al., 2014).

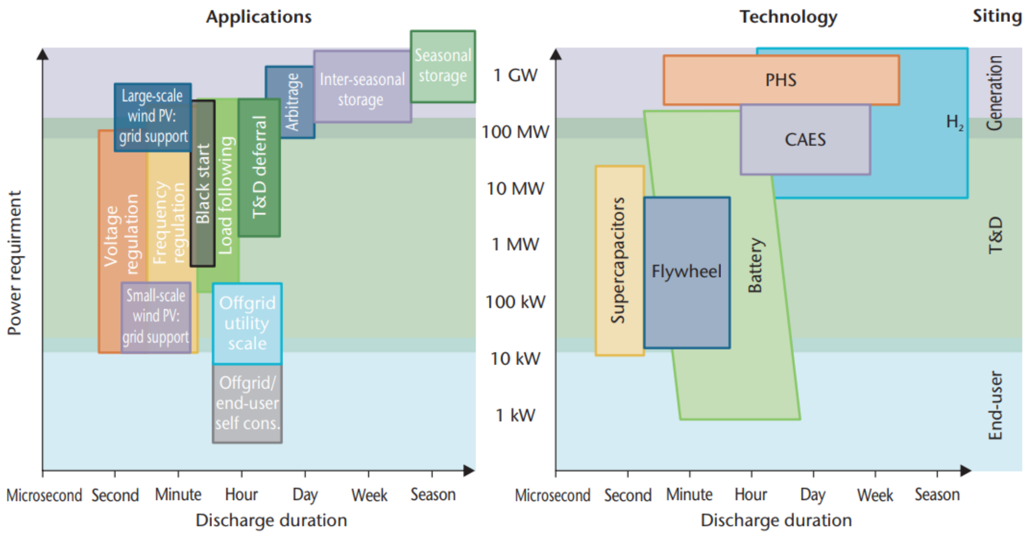
3.3 Electrical energy storage

There are several technologies which can be used to convert electricity to a storable form of energy and back to electricity again. Some are mostly for very short-term storage and load stabilizing, while others can be used for long term seasonal storage. In Figure 9 some of the electricity storage applications and technologies are listed. In section 3.1 the minute-hour range and capacities of 1-10 MW were identified as most relevant for industrial applications. Transferred to electricity storage, it seems few technologies are suitable for the demand, except some battery applications. Both pumped hydro storage, compressed air energy storage (CAES) and hydrogen storage have a potential within seasonal storage. These four technologies are briefly described in the following subsections. In addition, a concept regarding electicity storage using thermal energy is described, as an option without need for the significant infrastructure as PHS and CAES.

3.3.1 Pumped Hydro Storage

As shown in Figure 2, PHS is by far the most mature and implemented form of energy storage in the world today. PHS is efficient, responsive, and able to store huge amounts of energy. It is widely used to stabilize the grid, as well as providing a buffer capacity when the electricity system has a deficit or surplus production.

The main drawback regarding PHS is the significant infrastructure needed. In addition to the correct geographical placement with two reservoirs and a high enough elevation difference, building a hydro power station is a huge project requiring large investments and knowledge. The governmental regulations of water resources is also a major barrier for implementation. On a grid level, however,



Note: CAES = compressed air energy storage; PHS = pumped hydro energy storage.

Figure 9: Electricity storage applications and technologies. (International Energy Agency, 2015)

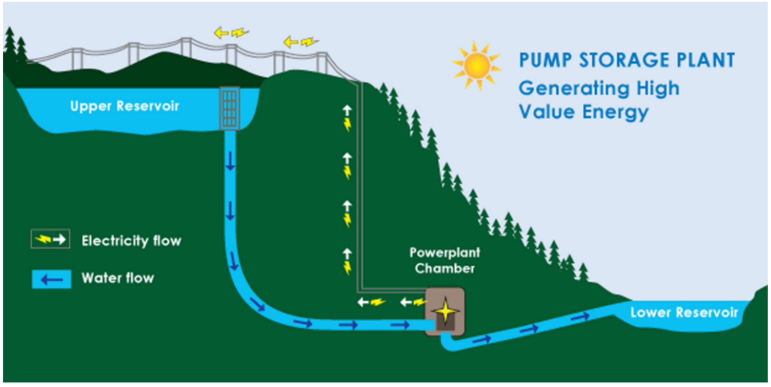


Figure 10: Schematic drawing of a pumped hydro storage facility (Aneke and Wang, 2016)

PHS receives increasing interest owing to the increasing introduction of intermittent renewables, and a lot of research is ongoing regarding the special pump-turbines required for the purpose. In Figure 10 a PHS facility is shown, in electricity production mode. In a storage mode, the electricity and water flow would be opposite. The figure gives an indication of the required infrastructure and complexity.

From an industrial point of view, PHS is only possibly relevant for a few major industries located in areas with the required geographical features and with the capability of actually investing in its own hydro power plant.

3.3.2 Compressed Air Energy Storage

CAES is another large scale energy storage solution. CAES uses off peak electricity to compress air and store it in a reservoir, typically under ground. During peak-hours, the compressed air can be heated, expanded and used to run a turbine to generate electricity. Different variations of the principle exists, where some one is shown in Figure 11. It is also possible to store the surplus heat from the compression in a thermal storage, and re-use the heat for heating air when the compressed air is expanded. CAES has an estimated efficiency of 70% and a lifetime of about 40 years today, but is not widely used (Aneke and Wang, 2016). Here as well, the infrastructure needed is significant, and it is a large investment to establish a CAES-system. Certain geographical constraints apply, and only a few CAES-facilities exist today. CAES is mainly relevant for grid-level applications.

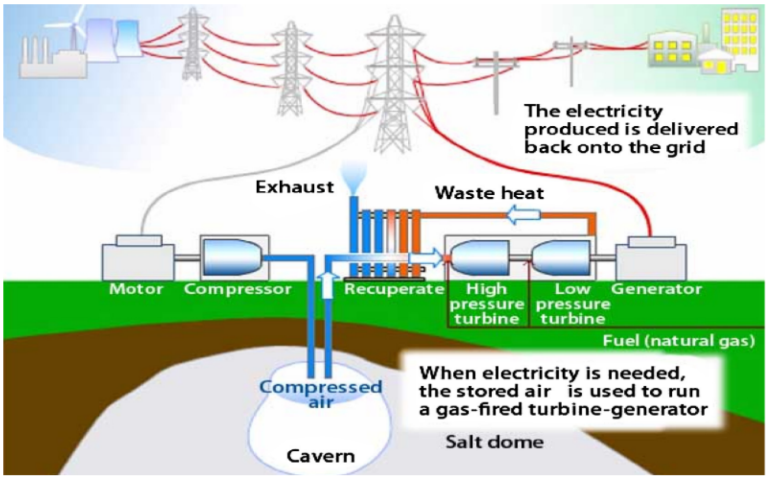


Figure 11: Schematic drawing of a CAES facility (Aneke and Wang, 2016)

3.3.3 Hydrogen storage

For many decades hydrogen has been a major feedstock in chemical and petrochemical industry (fertilizer production and upgrading of heavy fuel oils), in the food industry (fat hardening), in metallurgical industry, as well as in the glass industry (initiation). Hydrogen is expected to become a more important chemical energy carrier in the future as it enables to combine storage, re-electrification at the production side, or usage as energy carrier and implementation as transportation fuel, or conversion to heat. Comparing with other common energy carriers (e.g. oil, natural gas), hydrogen has by far the highest energy content per weight unit. The production of hydrogen from water through electrolysis, where water is split into oxygen and hydrogen, is restricted to locations with ample and cheap electricity or for very small scale on-site applications such as in research laboratories. For this reason, electrolysis only contributes to a miniscule share of all hydrogen produced today; most hydrogen is produced by natural gas reforming.

The end-user application governs the design profile for the relevant storage method (compressed gas, liquefied hydrogen, cryogenic compressed hydrogen, cryogenic adsorption, hydrides). To meet the requirements, established storage approaches often have to be customized to the application, or new technologies need to be developed. The use of fuel cells (FC) enables the back conversion towards electrical energy and heat without pollution of greenhouse gas emissions. Other conversion technologies are gas turbines or internal combustion engines however, the FC giving the highest electrical efficiency.

Hydrogen production, storage and re-electrification has a moderate cycle efficiency, typically in the order of 20-50% (International Energy Agency, 2014b). Present research efforts mainly focus on full hydrogen energy pathways, i.e. comprising hydrogen production, distribution and storage as well as its end-use. The main challenges of using hydrogen energy widely today result from its low volumetric energy density and its embrittling impact on conventional steels. Effective hydrogen storage technologies has been identified as a key technology to further facilitate the introduction of hydrogen as a sustainable energy storage and carrier, enabling to improve energy security, environmental quality and economic well-being simultaneously.

3.3.4 Batteries

The most commonly known technology for storing electrical energy is through chemical reactions in batteries. Batteries use chemical reactions in two or more cells to enable the flow of electrons, hence storing or releasing energy. The main advantages of battery technology is the relatively small need for extra infrastructure, their ability to react fast to load changes, easy scalability and relatively high efficiency, typically of 75-95% (International Energy Agency, 2014b). However, batteries have a low

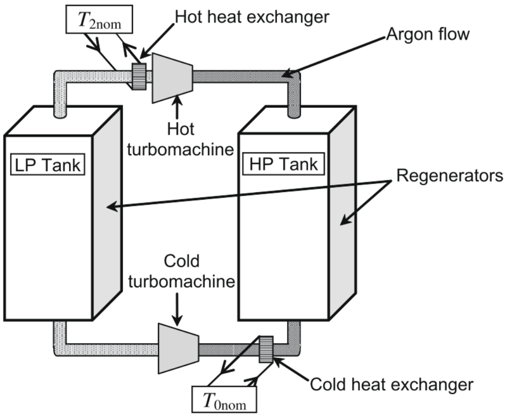


Figure 12: Schematic representation of the storage principle. (Desrues et al., 2010)

energy density and have some lifetime-issues regarding their ability to perform over time. There are few examples of industrial plants using batteries for storage of surplus energy, but several wind farms in the US have implemented batteries to be able to distribute the power output from intermittent renewables over time.

In an industrial context, batteries may be an option for industrial plants with their own energy production from wind or solar. There are examples of battery installations at wind farms with up to 36 MW peak power output, and 24 MWh total capacity (Duke Energy, 2015). Batteries are also mentioned as a possible technology for arbitrage applications, to store low priced energy during periods of low demand, and using or selling it during peak hours. PHS and CAES are also possible technologies in such applications, due to their high efficiency (Aneke and Wang, 2016).

3.3.5 Thermal-electric storage

Another option which has not yet recieved much attention is to store electricity as thermal energy, before converting it back to electricity when needed. Desrues et al. (2010) have developed a novel method for energy storage known as pumped thermal electricity storage, with a main focus of enabling energy storage from electricity in areas without the necessary geographical capabilities needed for PHS and CAES. In short, the principle builds upon creating a cycle with a hot and a cold thank with two turbomachines between, circulating Argon. During low demand periods, the turbomachines can store energy by heating the hot tank and cooling the cold tank, and opposite in peak-hours when electricity is needed. The principle is shown in Figure 12 with the low pressure and temperature tank to the left, and the high pressure and temperature tank to the right.

In their initial studies from 2010, Desrues et al. (2010) conclude that thermal-electric storage may be a potential technology to replace PHS and CAES in most areas, being able to obtain similar capacity, power and efficiency. White et al. (2013) investigated the same system with respect to power and energy density compared to the existing solutions of PHS and CAES. Compared to PHS, the new system has a significantly higher energy density, while the power density is lower. As no demonstration projects of this technology exists, several approximations have been done. In general, the results are promising, but the efficiency and storage density is highly affected by the temperature ratio, and hence the pressure ratio. High temperatures will imply difficulties in the different components.

The pumped thermal electricity storage system is an interesting technology, but it is far from commercialized.

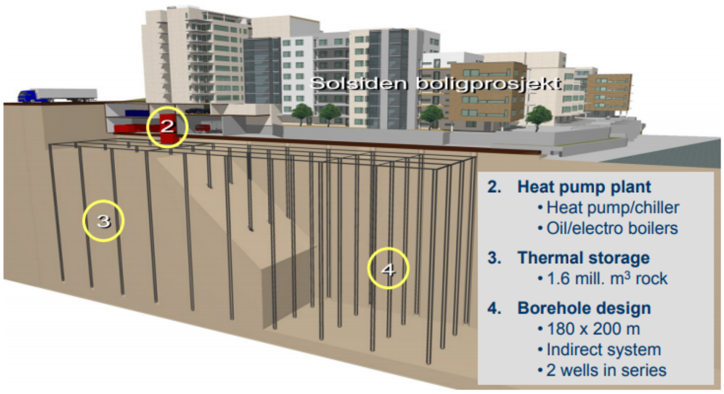


Figure 13: Sketch of the thermal storage system in Nydalen Industrial Park (Stene, 2006).

4 Applications

In this section examples of applications for the different technologies presented in section 3 will be given.

4.1 Thermal energy storage

4.1.1 Sensible thermal storage

Since most sensible thermal storage technologies are already widely applied, there are a lot of examples of applications for such technologies.

Underground Thermal Energy Storage
UTES at lower temperature levels is widely applied for buildings' heating and cooling systems, and can also be applied to store industrial surplus heat. An example of an application is the Nydalen Industrial Park in Oslo, Norway. The park has a borehole thermal energy storage (BTES) consisting of 180 borehole wells drilled to a depth of 200 meters and uses a series of heat pumps to upgrade the heat. A sketch of the system is shown in Figure 13. In addition to the heat pumps, the river is used to provide cooling and the total capacity of the energy central is 6 MW for heating and 9.5 MW for cooling. The energy central provides heating and cooling to a school campus, hotel, and an assortment of commercial and residential buildings. These buildings have a total area of 180000 m^2, and the BTES system supplies 80% of the required heating. The BTES system was completed in 2004, and since then it has reduced the park's external energy use by 50% (International Energy Agency, 2014a; Stene, 2006).

There are also examples of UTES systems at higher temperature levels. The Drake Landing Solar Community in Canada has a BTES system which supplies 90% of the heat demand for 52 single-detached homes. Solar heat is collected during the summer, stored in the ground and returned to the homes during the winter. The system includes 798 solar collectors with a total area of 2293 m^2 and a BTES system consisting of 144 boreholes with a depth of 35 m. By the end of the summer, the temperature in the ground is almost 70°C. In order to retain the high temperature level until the winter, the BTES area is covered with sand, high-density R-40 insulation, a waterproof membrane, clay, and other landscaping materials. During the winter, the heat is circulated to the homes in a district heating loop (Sibbitt et al., 2012).

UTES systems can also be used to store high-temperature surplus heat from industry. Since 2010 a high-temperature BTES has been in operation at a leading manufacturer of submersible pumps and mixers in Sweden. The BTES system consists of 140 boreholes á 150 m, and the aim of the BTES system was to reduce the dependence of district heating to a minimum. There are an internal heating system at the plant which provides space heating during the winter. Several surplus heat sources, such as cooling of the foundries and compressors, are connected to the heating system, in addition to an external district heating system. In periods with higher waste heat production than space heating demand, the surplus heat is stored in the BTES. The storage is designed for an annual heat injection of 3.6 GWh, and it is expected that 2.6 GWh can be recovered for space heating during the winter. The heat injection has been gradually increased since the start in 2010, and since July 2010 to March 2015 approximately 10 GWh has been injected, and only 174 MWh has been extracted. This has resulted in an increased temperature in the ground. It is expected that the system will reach steady state operation after a few years, with an annual heat extraction of 2.6 GWh. The system does not utilize heat pumps for heat extraction, but heat pumps could be used in combination with a lower storage temperature in order to increase the efficiency of the system (Nordell et al., 2015).

Pit Storage

A pit storage is used for instance at the Marstal district heating system in Denmark. The power plant consists of 15000 m^2 of solar collectors, a combined heat and power system with a 4 MW wood chip thermal oil boiler and a 750 kW_{el} organic rankine cycle unit, and a 1.5 $MW_{thermal}$ heat pump that uses CO_2 as working fluid. The pit storage was built in 2012 and is 75 000 m^3 and has a floating cover for insulation. It is used to store excess summer heat for use in the winter (SUNSTORE 4, 2013).

Molten Salts

An example of the usage of molten salt TES can be found at the Gemasolar concentrated solar power plant in Spain. The plant covers an area of approximately 1.8 km^2, and the system is comprised of 2650 heliostats and a molten salt storage tank. Gemasolar has an estimated annual electricity output of 110 MWh, and the cost was approximately 419 million USD (International Energy Agency, 2014a).

There are several examples of studies were molten salts has been proposed as a TES in industrial processes. Steinparzer et al. (2012) analyzed several TES systems that can be used to recover surplus heat from a steel making process, and found that molten salts was one of the best solutions due to a better dynamic capability when compared to high-temperature concrete. It was found that up to 24% of the energy existing in the exhaust gas could be recovered to generate process steam or electricity for on-site use, and the energy consumption could be reduced with between 60 and 80 kWh per ton of liquid steel. A test rig using 1500 kg of molten salts at 430°C was designed and implemented in order to experimentally test the concept (Miró et al., 2016).

Solid Media Storage

An example of an application of a solid media storage is found in Kentucky in United States. High-density ceramic bricks are used to store heat in residential homes with electric heating elements. Off-peak electricity is used to heat the elements, and a fan is used to release the heat when it is needed (International Energy Agency, 2014a).

In Germany, there is an ongoing project where researchers are testing an energy storage system for discontinuous industrial surplus heat of a furnace at a foundry. They are planning to use packed bed with rocks in direct contact with the heat transfer medium in order to store 10 MWh. The charging temperature of the storage is supposed to be up to 300°C, and the discharge temperature about 100°C. The storage time will be from hours to days. The aim of the project is to utilize the surplus heat as input heat for different furnace processes and for space heating at temperatures up to 100°C (Energie Speicher Forschungsinitiative der Bundesregierung, 2017).

During solidification of molten metal in foundries, almost all sensible and latent heat is lost to the sand surrounding the mold cavity. In order to utilize the heat released during this process, Selvaraj et al. (2015) investigated the use of aluminium shots embedded in the sand while casting. Some of the heat liberated during the solidification of the metal in the mold cavity was absorbed by the shots. Afterwards, the shots were removed from the mold and transferred to an insulated box where they heated the scrap metal by conduction. The scrap was then used as input to the furnace. The experiments indicate that at least 6.4% of the surplus heat could be recovered and reused.

EnergyNest is a Norwegian based company who has developed a novel technology for storing thermal energy in a concrete based storage medium which they have developed in cooperation with a concrete manufacturer. The technology is based on a module system consisting of integrated heat exchanger tubings in concrete elements. Several modules can be combined to achieve the necessary capacity, and are then insulated (EnergyNest, 2017). EnergyNest aim to serve both suppliers and consumers of energy, including industrial consumers. The system is based on converting electricity to heat, storing, and re-supplying as either heat or electricity at a later time. The optimal temperatures of storage are in the range of 300-427°C and a charge/discharge cycle time of 4-48+ hours is favored. Due to high thermal inertia of the storage material, a cycle length of less than 4 hours is not recommended. The storage capacity is approx. 2 MWh per module, and there is no defined maximum of number of modules. Each module is 48 m^3.

Hot and cold water tanks

A hot water tank is planned to be used in the district heating network in Trondheim, where a 5000 m^3 large accumulator tank filled with semi-pressurized water at 1.2-1.3 bar and 120°C will be built (Graver, 2016). Owing to the tank, usage of peak heating devices such as gas boilers can in many cases be avoided, leading to an increased heat production from the central combustion unit burning municipal solid waste by approximately 8 GWh per year. In addition, the tank will function as a pressure balancing device for the district heating network and a water reservoir in the case of leakages. In the future, with increasing electricity production from wind turbines in the region, the tank may be used as an energy storage also for the power grid in the case if excess power is available from the grid.

4.1.2 Latent thermal storage

For latent heat TES, process heat applications appear to be the most promising area of utilization in the industry. State-of-the-art TES for process heat applications (100–300°C) is the steam accumulator technology, which uses the sensible heat storage in pressurized saturated liquid water (Tamme et al., 2008). To maximize the storage efficiency, the temperature difference between working fluid and storage medium should be minimized. This requires isothermal storage media for processes using water/steam as a working fluid, PCMs being an obvious solution. Using PCM in steam accumulators could further help increasing the storage capacity, owing to the higher volumetric storage capacity of PCMs (in the range of 100 kWh/m^3 as opposed to 20-30 kWh/m^3 for water) (Steinmann and Eck, 2006). Different approaches for integrating PCMs in steam accumulators, aiming to overcome the problem with low thermal conductivity, have been suggested by Tamme et al. (2008) and Steinmann and Eck (2006).

Merlin et al. (2016) have designed, manufactured and tested a PCM TES system adapted to a sterilization process. The storage was based on an expanded natural graphite matrix, impregnated with a PCM. Paraffin RT82 was chosen as the PCM, with a phase change domain between 60 and 82°C. The system is well adapted to industrial applications with short-term cycles, including set ramp temperatures during heating and cooling phases. An economical study of the manufacturing of a 1.2 MW industrial storage resulted in a cost of about 2500 NOK/kW·h and a payback period of 500 days. Despite the encouraging results, they concluded that the long-term stability of the composite material still needs to be investigated to confirm the viability of the concept.

Laing et al. (2013) have demonstrated a high temperature PCM storage module for direct steam generation in a 1 MW test facility. Schematic illustration of the system is shown in Figure 14. Sodium nitrate salt ($NaNO_3$) was applied as the PCM ($T_m = 305°C$), and they used a finned shell-and-tube heat exchanger made of aluminium. The PCM was placed in the tank/shell side, and thermal oil was used as the heat transfer fluid. The operation of the PCM TES module for evaporating water in constant and sliding pressure modes was demonstrated successfully in three different operation modes.

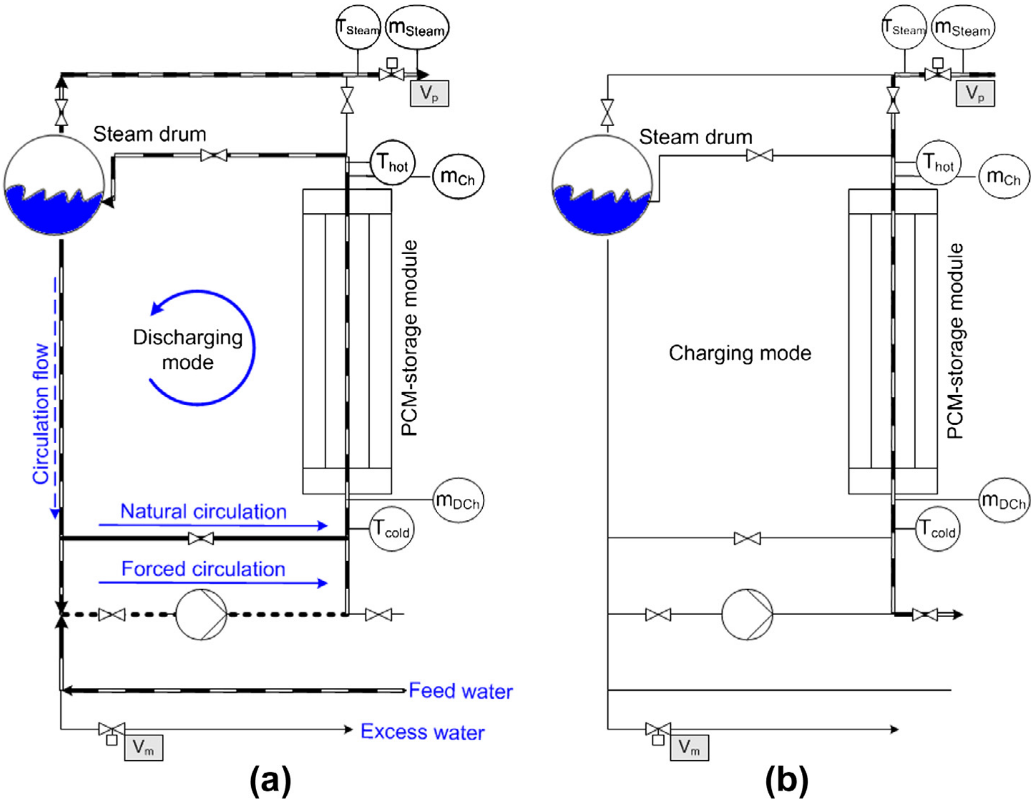


Figure 14: Schematic set-up of the PCM storage in a water/steam loop with circulation cycle by Laing et al. (2013). (a) Discharging mode shows the piping used in black/black-and-white for natural circulation and dashed/black-and-white for forced circulation; (b) charging is shown in once-through operation with black-and-white piping denoting used piping.

Regarding higher-temperature applications, Maruoka and Akiyama (2006) have suggested heat recovery from hot exhaust gas (> 1600°C) from steelmaking converter by utilizing both PCM and endothermic heat of reaction. The intermittently emitted heat from the converter was first transferred into a PCM storage, and then supplied to coke oven gas to induce the endothermic reaction of steam reforming of methane. In the proposed system, methanol was finally produced from the obtained gas. Copper spheres ($T_m = 1083°C$) encapsulated in nickel were applied as the PCM storage. Similar concept was studied to utilize the PCM copper spheres for exhaust gas surplus heat recovery and thereafter as catalysts in steam reforming of methane to produce hydrogen (Maruoka et al., 2002). The hot nickel surface of the copper spheres proved to be an excellent catalyst for methane reforming reaction at 1473 K.

4.1.3 Chemical storage

A thermochemical energy storage for concentrated solar power plants has been demonstrated in a project in Germany. In order to offer a concentrated solar power plant with full dispatchability, solar energy is being stored by means of reversible thermochemical reactions. For open operations, the redox reaction of manganese oxide at 700°C was used, since the reactive oxygen can be exchanged with the ambient. For steam power plants, calcium oxide could be integrated as it reacts reversibly with water vapor at a temperature range of 400-600°C. The reactor concept was validated in a pilot-scale system of about 100 kWh capacity, and the capacity can easily be increased by adding additional tanks to store the required amount of reaction material (CORDIS, 2016).

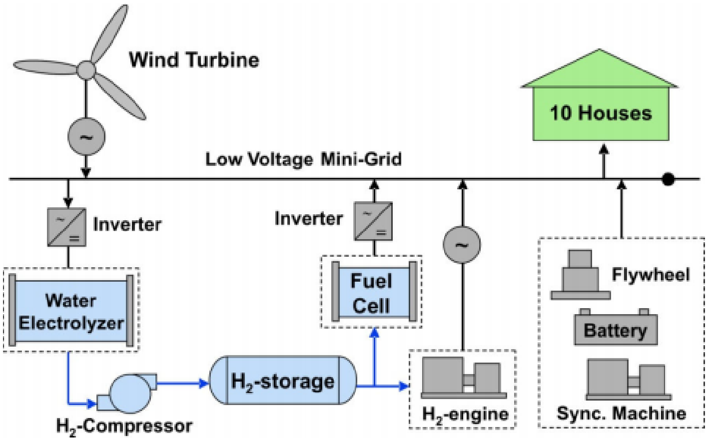


Figure 15: The energy system at Utsira (Eté and Ulleberg, 2009).

4.2 Electrical energy storage

4.2.1 Pumped Hydro storage

The biggest PHS in Norway is Saurdal hydroelectric power station located in Rogaland. The reservoir is Blåsjø located 465 m above the power station. The capacity of the power station in total is 640 MW, and the pumping capacity is 320 MW. Annually approximately 280 GWh is used by the pumps, while the average annual production is 1350 GWh (Rosvold, 2012).

4.2.2 Compressed Air Energy Storage

Huntorf power plant in Germany utilizes compressed air in order to store off-peak electricity. The total storage volume is 310000 m^3, divided into two underground cylindrical salt caverns. The capacity of the system is 321 MW, and the storage can release energy for up to two hours at full capacity. During periods of peak demand, the compressed air is used to burn natural gas in the combustion turbine. The overall efficiency of the power plant is 42% (Barbour, 2017; International Energy Agency, 2014a).

4.2.3 Hydrogen storage

At Utsira outside Haugesund in Norway there was a demonstration project for hydrogen storage going on in four years from 2004 to 2008. Excess power from two 600 kW wind turbines was converted into hydrogen using a 48 kW electrolyzer and fuel cells were used to produce electricity from the hydrogen. A sketch of the system is shown in Figure 15, and the system included a 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 fuel cell (Eté and Ulleberg, 2009; International Energy Agency, 2014a).

4.2.4 Batteries

Lithium-ion batteries are used as an energy storage at the AES Laurel Mountain wind power facility in the United States. The facility consist of 61 wind turbines with a total capacity of 98 MW, and the battery storage system has a capacity of 32 MW and can store up to 8 MWh. The system is used to match the generation and demand for electricity, and the battery plays a critical role in maintaining overall grid reliability with greater than 95% availability (International Energy Agency, 2014a).

5 Non-technological barriers and enablers

The technologies for storing energy at an industrial level clearly exist, as shown in Chapters 3 and 4. Energy storage technologies are however mainly applied in district heating systems or smaller heating/cooling systems for buildings, or at grid level when electrical storage is concerned, and very little in an industrial context. This section will discuss some of the main non-technological barriers together with enablers to accelerate the implementation of energy storage systems in the industry.

5.1 Economic barriers and enablers

Costs of energy storage systems is one of the biggest barrier limiting their implementation. Economic incentives are hence an important, while limited, enabler to promote implementation of energy storage within plants and processes as well as in inter-plant setting, with shared storage infrastructure. In the lack of supportive economic frameworks and energy policies, and unless the industries are driven by idealistic or environmental reason to exchange energy for reducing emissions (Tudor et al., 2007), then the parties organizing the energy exchange and storage must themselves ensure economic benefits of the investments and efforts.

Many countries and regions offer subsidiaries for technologies that can be documented to improve energy efficiency and reduce emissions. If the presence of such subsidiaries, companies may utilize these for investing in intra-plant energy storage. In the lack of such exogenous economic incentives, the companies must themselves ensure payback of investment costs for energy storage, either by means of explicit energy savings or market advantages. Several of the currently available technologies today are expensive, or suffer of low round-trip efficiencies, making the payback period too long. The cheapest and most developed technologies are also the ones with low energy density, making the space requirements significant.

Surplus energy sources, for instance hydrogen and organic rich flue gases, could in combination with storage infrastructure be exploited as a financial instrument similar to commodities (Secomandi, 2010). This type of trading with energy resources is performed today through regional and international markets for electricity (Yamin, 2004) and natural gas (Hittinger and Lueken, 2015; Knudsen and Foss, 2017). Association to energy markets may reduce the risk of investing in infrastructure, increase availability and distribution, and draw interest from diverse industries to participate in surplus energy exchange. Yet, this form of energy exchange requires an enterprise, distributor, shipper or authority to operate the storage facility, and often requires long-term contracts for ensuring the economic security to the party investing in the infrastructure.

5.2 Regulatory barriers and enablers

In a report by the United Nations (United Nations, 2007), it is emphasized that energy efficiency efforts, including implementation of energy storage, are more likely to succeed if a supportive framework of policies and regulatory environment exists. Governmental regulations may be both barriers or enablers. For large-scale storage infrastructure which significantly affects the surroundings, regulations may prevent full use of the available possibilities. Such regulations may be for instance environmental regulations related to utilization of ground water, drilling boreholes or building dams. Regulations can in some cases also promote implementation of energy storage, by setting requirements to re-use of energy and on how much heat may be released from a facility.(Gallo et al., 2016)

5.3 Organizational challenges

The organizational challenges related to energy storage are also a significant barrier, in particular for inter-plant energy storage. In applications where the heat is to be stored transferred between plants belonging to different companies, the complication regarding infrastructure, pricing and ownership is a major barrier of implementation. As it often is difficult to quantify the economic gain for the sales of surplus heat, the motivation for investing to the infrastructure may be low. Furthermore, the party investing to the infrastructure is not necessarily the the one gaining the profits from the energy savings.

5.4 Control and optimization strategies

Control and optimization is an essential part of both development of operations of industrial energy-storage facilities. During the decision making process for investing in energy storage facilities, numerical optimization may aid the decision makers in choosing the storage technology, the dimensions and capacity of the storage, which surplus energy streams to connect to, and the location of the storage. An example of such static type of superstructure optimization-problems can be found in (Majozi, 2009).

Upon investment and installation, efficient control and operational strategies may significantly increase the profitability of energy storage facilities[1]. Control strategies for energy storage facilities serve two purposes. The first is (automatic) control necessary to ensure safe and stable operations of both the energy storage itself, and its the integration in the production or manufacturing chain. This is essential for deployment in process industries (Knudsen, 2016), which often includes with exothermic reactions (DECHEMA, 2017). The second objective is control strategies for exploiting the operational flexibility energy storage provides, cf. Section 1. The flexibility of energy-storage, i.e. the maximum power and the response time from changing demands, clearly depends on the particular technology. Nevertheless, to maximize the utilization of energy storage for capitalizing on varying energy prices, supply or changing market demand of the products produced by the plant, optimization-based control strategy should be developed that accounts for variations and uncertainties in energy supply, storage levels and market demands.

Well developed control strategies should also minimize disturbances on the operations that may arise from energy exchange with intermediate storage (Miró et al., 2016). To this end, model predictive control (MPC) (Mayne, 2014) is a promising control strategy, which is frequently applied in process industries (Qin and Badgwell, 2003). Increased use of intelligent and advanced control such as MPC is highlighted by SPIRE (2013) and Cefic (2013) as key actions to harvest energy efficiency in industries. However, it appears to be limited exploited for industrial energy storage (Blasco et al., 2007).

6 Conclusions and outlook

The potential of energy storage systems for improving energy efficiency in the industry is widely recognized, however this potential is hardly exploited. The main technical barriers for today's thermal energy storage technologies is the large space requirement, and consequently the high investment costs. Technologies applicable for industrial use exist, and some of these have been used in commercialized projects, or in development projects. For low-temperature thermal storage, the sensible heat technologies are well developed. Despite the large space requirements, they are relatively inexpensive, easily implementable and scalable, and suitable for large-scale applications. Examples exist of using underground thermal energy storage for storing industrial waste heat at up to 60-65°C to be utilized for space heating purposes. For higher temperature applications, molten salts appear to be a promising alternative, and this technology is already widely used in concentrated solar power systems.

The problem with space requirements can be largely avoided with latent heat storage. The development of PCM thermal storage is fast, and the technology has potential for significantly higher energy density, higher temperatures and high round-trip efficiencies when compared to sensible heat storage.

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[1] Control and operational strategies may be used interchangeably, and essentially refer to the same task. Operations may be performed by human operators with support from a decision-support system in a control hierarchy (Darby et al., 2011; Engell, 2007), where there operator based on price and measurement analysis provides set-points to controllers, for instance a model predictive controller. In contrast, an operational strategy may also be fully automated with no human intervention during nominal operations.

There are already several industrial scale demonstration projects of PCM storage systems for temperatures up to 300°C, and the technology has a high potential especially for process heat applications. For higher temperatures, inorganic and metallic PCMs seem promising, and the potential of these materials should be investigated further. In particular, metallic PCMs have gained little attention so far, although they may be very attractive for high-temperature applications such as exhaust gas heat recovery. Chemical TES is so far little developed, and significant research efforts are needed to make this technology applicable for the industry. It is however an extremely promising technology, owing to the high energy density – exceeding that of PCMs – and low heat losses.

Electricity storage is well developed technically, but rarely used by the industry. Low energy density or low round-trip efficiencies are the main technological barriers. For e.g. metal industries with large electricity demands, with potentially intermittent electricity sources available, electrical energy storage might be relevant and some potential technologies exist. In most European countries however, the electricity grid is well developed, and the grid is also best suited to handle these irregularities.

Apart from the technological barriers, there are many non-technological barriers hindering the deployment of energy storage systems in the industry. Inter-plant energy storage creates and inherent dependency between the companies supplying and receiving heat to and from the storage. Companies generally refrain from creating such dependencies, both in terms of long-term economic perspectives and robustness. A particular enabler for inter-plant energy storage may hence be its ability increase resilience against time-limited shortage in energy supply. In this context, simulations and pilot projects demonstrating the benefits of storage systems are needed. An authority or third-party taking ownership of and operating the energy storage facilities may also be an enabler for promoting the use of inter-plant energy storage.

Intra-plant energy storage is in general easier to implement, and the direct economical benefits in terms of energy savings in processes are often more easily perceptible – and the company in charge of the investment costs is also the one gaining the profits from the energy savings. Furthermore, with only one company involved, organizational barriers are not an issue the way they are in the case of inter-plant energy storage. More demonstration projects showing the benefits of energy storage systems, and governmental incentives and policies supporting energy efficiency measures are needed to promote the use energy storage in the relevant industries.

To further the implementation of energy storage technologies in the industry, it is essential to identify specific cases and specific needs for energy storage in different industrial segments. For this purpose, models and simulations demonstrating efficient deployment of heat recovery systems incorporating energy storage are needed. Temperature levels, cycle durations, storage capacity and thermal output are all important parameters to define for each case, and these parameters are more easily studied by simulations than through physical installations. Awareness of the benefits of using energy storage in industrial applications need to be communicated better to make the implementation more attractive. As a means to quantify the benefits, economic evaluations should be performed in context with the case studies. Laboratory test rigs approaching industrial scale, and pilot projects are required to advance industrial implementation of the most promising technologies and applications, such as PCMs in process heat applications. Furthermore, control and optimization strategies need to be developed, to enable companies to fully exploit the potential of energy storage.

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