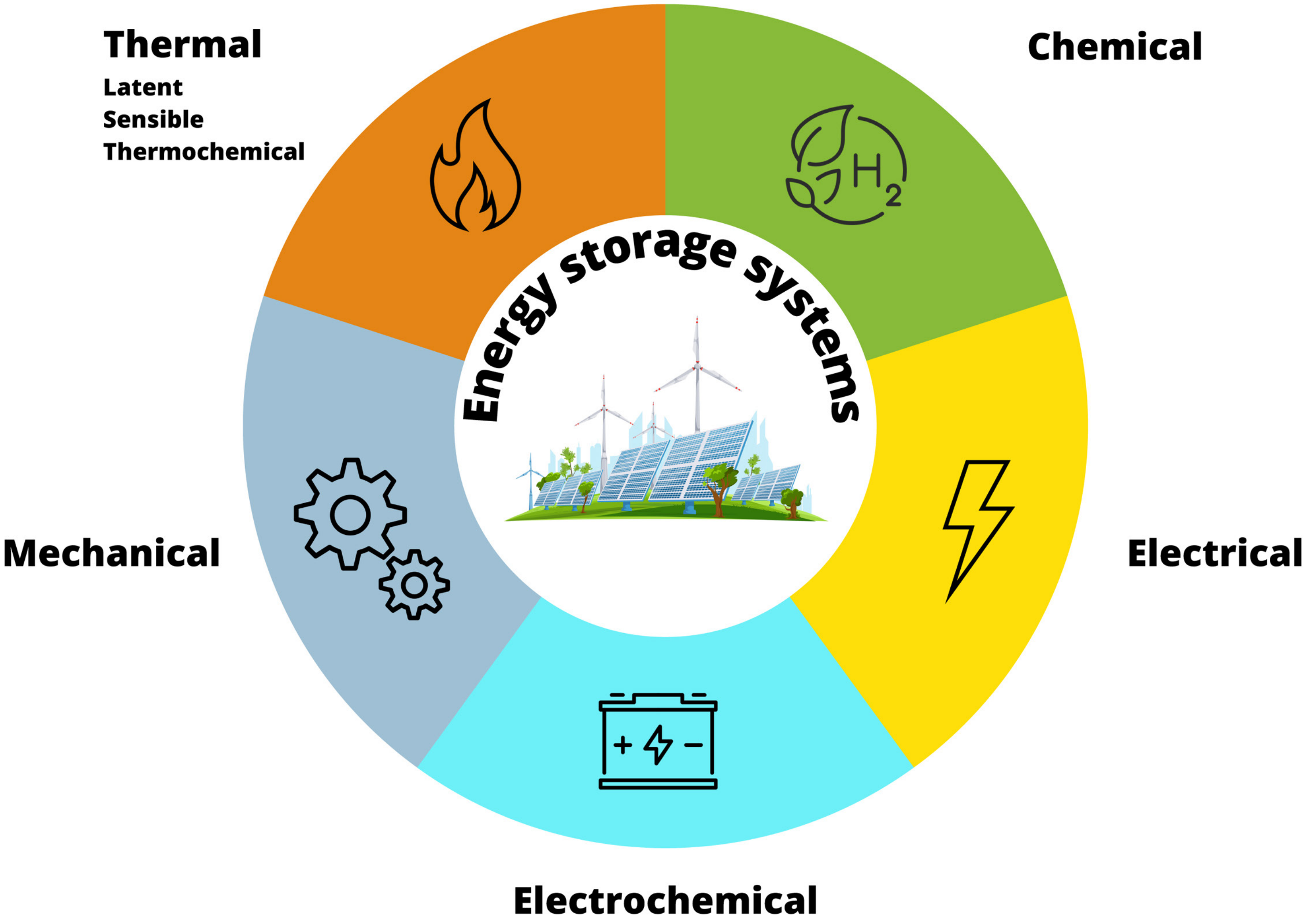
HEAT CIRCULATION INNOVATION PLATFORM
NORTH SAVO HCIP-NS-PROJECT

ENERGY STORAGE SYSTEMS: A STATE-OF-THE-ART STUDY



SAVONIA
University of Applied Sciences

12/2023

RESEARCH AND DEVELOPMENT

EDITOR: Raquel Mier González

European Union
European Regional
Development Fund

Leverage from
the EU
2014–2020

HEAT CIRCULATION INNOVATION PLATFORM NORTH SAVO
HCIP-NS-PROJECT

ENERGY STORAGE SYSTEMS

A state-of-the-art study

Raquel Mier González

Kuopio 2023

Savonia University of Applied Sciences
Julkaisutoiminta
PL 6
70201 KUOPIO
julkaisut@savonia.fi

1st edition

ISBN 978-952-203-323-9 (PDF)
ISSN 2343-5496

Savonia University of Applied Sciences serie 12/2023

Publisher Savonia University of Applied Sciences
Design and Page layout Tapio Aalto
Cover image Shutterstock

CONTENTS

ABSTRACT

A high-level penetration of intermittent renewable energy sources such as wind and solar into the grid will require new solutions to control the temporal mismatch between supply and demand. Long duration energy storage (LDES) is a promising solution to enhance grid flexibility. The principles of several LDES technologies are described in this review. Sensible heat storage technologies, including aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), tank thermal energy storage (TTES), pit thermal energy storage (PTES), cavern thermal energy storage (CTES) and fractured thermal energy storage (FTES) methods, are reviewed. Additionally, latent heat storage (LHS) systems as well as thermochemical storage (TCES) are discussed. The review also describes mechanical storage systems such as novel pumped hydro storage (PHS), compressed air energy storage (CAES), liquid air energy storage (LAES), pumped heat energy storage (PHES) and gravity-based energy storage technologies. Finally, Power-to-X technologies such as Power-to-Hydrogen are briefly reviewed.

This state-of-the-art study on energy storage systems has been written within the project Heat Circulation Innovation Platform North-Savo (HCIP-NS) realized from 1.8.2021 to 30.10.2023. The project was realized by Savonia UAS Energy Research Centre organisation at Varkaus Campus.

List of Figures

List of Tables

ABBREVIATIONS

A-CAES	Adiabatic compressed air energy storage
ARES	Advanced rail energy storage
ATES	Aquifer thermal energy storage
BESS	Battery energy storage system
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
CAES	Compressed air energy storage
CAES	Compressed air energy storage
CaL	Calcium-Looping
CCS	Carbon capturing and storing
CES	Cryogenic energy storage
CHP	Combined heat and power
CSP	Concentrated solar power
CTES	Cavern thermal energy storage
D-CAES	Diabatic compressed air energy storage
DH	District heating
DOE	Department of Energy of USA
ESS	Energy storage system
EIA	Energy Information Administration
EVRC	Energy vault resiliency centre
FTES	Fractured thermal energy storage
GES	Gravity-based energy storage
GHG	Greenhouse gas
HCIP	Heat Circulation Innovation Platform
HTF	Heat transfer fluid
I-CAES	Isothermal compressed air energy storage
IEA	International energy agency
IFPSH	International Forum on Pumped Storage Hydropower
IPCC	Intergovernmental panel on climate change
IPHROCES	Integrated pumped hydro reverse osmosis clean energy system
ISPT	Institute for Sustainable Process Technology
KIUC	Kaua'i Island Utility Cooperative
LAES	Liquid air energy storage
LDES	Long duration energy storage
LHS	Latent heat storage
Li-on	Lithium-ion
MGES	Mountain gravity energy storage
MIT	Massachusetts Institute of Technology
NA or N/A	Not available
NREL	National Renewable Energy Laboratory
ORC	Organic Rankine Cycle
OSF	Official Statics of Finland
P2A	Power-to-Ammonia
P2G	Power-to-Gas
P2H2	Power-to-Hydrogen
P2M	Power-to-Methane
P2X2P	Power-to-X-to-Power
PCM	Phase change materials
PHES	Pumped heat energy storage
PHS	Pumped hydro storage
PTES	Pit thermal energy storage
PV	Photovoltaics
R&D	Research and development
SHS	Sensible heat storage
SPHS	Seawater pumped hydro storage
SwRI	Southwest Research Institute
SWRO	Seawater reverse osmosis

TCES	Thermochemical energy storage
TES	Thermal energy storage
TPV	Thermophotovoltaic
TTES	Tank thermal energy storage
TUPH	Thermal underground pumped hydro
UPHS	Underground pumped hydro energy storage
UTES	Underground thermal energy storage
UW-CAES	Underwater compressed air energy storage
VRE	Variable renewable energy

SYMBOLS

a_m	Fraction of the melted material
$Ca(OH_2)$	Calcium hydroxide
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CH_3OH	Methanol
CH_4	Methane
Cl_2	Chlorine
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Cp	Specific heat capacity [J/(kg·°C)]
Cpl	Specific heat capacity of the liquid phase [J/(kg·°C)]
Cps	Specific heat capacity of the solid phase [J/(kg·°C)]
H_2O	Water
K_2CO_3	Potassium carbonate
m	Mass of the storing material [kg]
n	Amount of reactant A [mol]
Na	Sodium
NaCl	Sodium chloride
NH_3	Ammonia
Q	Heat stored [J]
sCO_2	Supercritical carbon dioxide
Tf	Final temperature [°C]
Ti	Initial temperature [°C]
ΔH	Reaction enthalpy [kJ/mol]
Δhm	Enthalpy of fusion [J/kg]

1 INTRODUCTION

Climate change is the greatest health and environmental threat facing humanity. The Intergovernmental Panel on Climate Change (IPCC) has concluded that in order to reduce the risks and impacts of climate change, global warming must be limited to 1.5°C above pre-industrial levels. (World Health Organization 2021.) To achieve this temperature goal, global carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions need to rapidly decrease to net-zero by 2050 and 2070, respectively (Climate Action Tracker 2022). The power sector is the single largest source of greenhouse gas emissions worldwide. In 2018, power sector accounted for 27% of the GHG global emissions and 37% of CO_2 global emissions (European Commission 2020). Therefore, the decarbonization of the power sector is crucial to mitigate climate change impacts. In practice, achieving a decarbonized power sector requires the transition from fossil fuels to renewable energy.

Renewable energy share in global power generation has increased significantly over the last two decades and it is expected to continue to grow in the coming years. The electricity generation systems of the future will be based largely on the use of solar and wind energy. In many European countries, energy produced with these renewable forms of energy is already the cheapest in terms of production costs. However, their disadvantage is their dependence on the weather for production. (Huhtinen 2021.) The daily and seasonal fluctuations in renewable energy production will require new solutions to control the temporal mismatch between supply and demand.

Energy storage systems (ESS) can help solve this issue by enhancing grid flexibility. Beside facilitating the integration of renewable energy sources, ESS can offer additional grid-related advantages including: frequency regulation and voltage support to ensure proper operation of the grid; peak shaving and load shifting to offset peak demand; and cost reduction in upgrades and expansions of transmission and distribution networks (Das, Bass, Kothapalli, Mahmoud & Habibi 2018; Bowen, Chernyakhovskiy & Denholm 2019).

One of the most important parameters of an energy storage system is its duration or discharge time, i.e., the time that it can sustain power output at its maximum discharge rate (EIA 2020). This parameter dictates the suitability of the energy storage for a specific application. Based on the duration, ESS can be roughly divided into two categories: short-duration and long-duration energy storages. In general, in the literature short-duration energy storage range from seconds to 4 hours and long-duration energy storage (LDES) range from 4 hours to multiple days.

Battery energy storage systems (BESS) are a well-suited option for short-term flexibility needs. The most popular BESS at this moment include lithium-ion (Li-on) batteries. This type of battery is the most competitive option due to their technological maturity and higher energy density, higher voltage capacity and lower self-discharge rate than other rechargeable batteries. However, existing BESS cannot provide long-duration storage. The main reason is that batteries offer low cost per megawatt but high cost per megawatt-hour for long duration storage above 2-6 hours. Each additional megawatt-hour of energy stored increases cost significantly because both energy and power scale by adding cells. Moreover, BESS entail other drawbacks such as rare-earth material sourcing, degradation, and no viable recycling option. (Allison 2020.)

Long-duration energy storage technologies are needed to store energy for prolonged periods. As LDES Council states, LDES energy capacity can be scaled without scaling up power capacity which makes it cheaper to increase the amount of electricity stored without significantly compromising the power supply (LDES Council 2022). In this review, the principles of several LDES technologies that can provide energy over several hours, days, or even weeks are described. Some of these technologies are under investigation and others are already commercially available.

The present review also includes several examples of selected energy storage technologies, with the focus on Finland and other Nordic countries. In countries at high latitudes, like Finland, there is a big variation of power demand as well as a large difference of solar irradiance between winter and summer. Therefore, energy storage systems that storages heat or cold for periods of up to several months, also known as seasonal storage, would be the next step towards a more flexible power production.

According to the national climate change policy, Finland aims to reach carbon-neutrality in 2035 and reduce its greenhouse gas emissions by at least 80% by 2050 from the levels in 1990 (Finnish Government s.a). Finland also aims to increase the share of renewable energy to at least 51% of the total energy consumption (Finnish Government 2019). This share has increased significantly in the last decade and according to Official Statistics of Finland (OSF), the share of renewables was already 44.6% of the total energy consumption in 2020 (Official Statistics of Finland 2020). To achieve these goals as well as to balance the above-mentioned power demand and irradiance variations between winter and summer, it will be necessary the increase of energy storage capacity. In this scenario, improving the existing energy storage technologies and developing new ones will play a key role.

1.1 Heat Circulation Innovation Platform

Markku Huhtinen

This state-of-the-art study on energy storage systems has been written within the project Heat Circulation Innovation Platform North-Savo (HCIP-NS) realized 1.8.2021 – 30.10.2023. The project, with 290 k€ budget, was financed mainly (76%) by European Regional Development Fund (ERDF), granted by Regional Council of North-Savo. The rest of financing came from Savonia UAS and industrial partners.

The goal of Finland's energy policy is to gradually decrease the use of fossil fuels in energy production and move towards an emission-free energy system. In the district heating sector, the goal is to promote non-combustion heat production, to promote the use of related technologies such as waste heat recovery, heat storage and heat pump technologies. This is also the main goal of HCIP-NS-project.

HCIP-NS-project consisted of two parts: development project and investment project. Within the investment project was built in Savonia UAS Energy Research Centre a reactor for testing thermochemical energy storing reactions. All the other activities have been carried out in the development project.

The target groups of the project were:

- Companies generating waste heat in their production.
- Companies developing energy-efficient solutions and services.
- Companies interested in energy-efficient equipment deliveries.
- All stakeholders interested in the efficient use of energy.
- Decision makers of cities, municipalities, and other public organizations.
- Owners of companies and properties in different industries.

The goal of the project was to find out the sources of waste heat in North Savo and possibilities to utilize these sources in heat production promoting to reach at the regional level set target to create a carbon neutral in North-Savo by 2035. The goal of the project was also to promote business opportunities of North Savo Energy Cluster companies in this context.

Companies participating this project were Sumitomo SHI FW Energia Oy, Savon Voima Oy, Varkauden Aluelämpö Oy, HögforsGST Oy, Kuopion Energia Oy, Stora Enso Oyj, Suomivalimo Oy, Lamit.fi Oy.

The project was realized by Savonia UAS Energy Research Centre organisation at Varkaus Campus. As project manager worked:

- Markku Huhtinen 1.8.2021-6.3.2022.
- Kirsi Kinnunen 7.3.2022-10.10.2022.
- Petteri Heino 11.10.2022-30.10.2023.

The research work was realized by:

- Raquel Mier-González; state of art reports, measurements.
- Leena Pöntynen; state of art report (Large heat pumps).
- Arto Luukkonen; design, construction and tests with TCES-reactor.
- Jukka Huttunen; design of TCES-reactor.
- Janne Ylönen; measurements.
- Kirsi Tukiainen; project assistant.

HCIP-NS-project was broken down into four work packages, the content of them is described in below.

1.1.1 WP1 Waste heat recovery

A lot of heat is generated in industrial production, some of which can be recovered and utilized. In many cases, however, waste heat is not utilized and recovered but is released into the environment with cooling water or process gases. Most waste heat is typically generated in the pulp and paper -, chemical – and metal industries.

The work package collected information on waste heat recovery opportunities and good case examples both as a literature review and from waste heat recovery studies realized by FINHCIP-UAS-network. The found good case examples have been published on webpage of HCIP-NS-project for the benefit of those interested.

In certain industrial sectors (including industrial painting, timber drying and foundry processes) with possibilities to new innovations, the possibilities for heat recovery were examined in more detail by means of an energy audit, estimating the amount of investment required and the repayment period.

In general, it is worthwhile to utilize waste heat in same process, but the energy companies involved in the project are ready to recover the waste heat into the district heating network as well.

1.1.2 WP2 Large heat pumps

Heat production with heat pump technology is becoming more and more common in Finland. More than one million heat pumps have already been installed in Finland (Sulpu), companies in North Savo are well involved in the value chains and equipment deliveries of small heat pumps throughout Finland.

The profitability to use large or medium size heat pumps (100 kW- 2,000 kW) to recover heat from industrial processes has also improved so that there are several realized installations also in the area of North-Savo. There are Finnish suppliers for these devices, but at the moment they are not working in the area of North-Savo. There would be possibilities for the North Savo Energy Cluster equipment manufacturers to act as component, e.g., heat exchanger manufacture in these value chains.

In district heating, large heat pumps are also becoming more common. Large coal-fired power plants in coastal cities are planned partly to be replaced by tens of megawatts of heat pumps. At present, Finnish companies are not significantly involved in manufacturing of equipment related to large heat pumps or their deliveries, even if the products are well suited for the North Savo Energy Cluster equipment manufacturers.

In connection with this, the project investigated equipment manufacturers in connection with large heat pumps. The ultimate goal was to find out how equipment manufacturers in the North Savo energy sector could be involved in value chains related to the supply of large heat pumps.

Another state-of-the-art report published within the HCIP-NS-project relates to utilization of large heat pumps in industrial and district heating systems.

1.1.3 WP3 Energy storage

Several companies involved in HCIP-NS-project are particularly interested in the use of water reservoirs or soil as an energy storage connected to district heating network and on the other hand in thermochemical energy storage methods. In Varkaus it is investigated by Varkauden Aluelämpö Oy possibilities to store surplus energy from Riikinvoima power plant from summer to winter. In HCIP-NS-project it has been monitored the progress of the project. Also possibilities to store heat in the soil at the Savonia UAS Varkaus Energy Research Centre through the ground source heat pump system has been studied in the project.

This state-of-the-art study on energy storage systems has been written as part of this work package to give a comprehensive review to thermal energy storage, mechanical energy storage and chemical energy storage systems.

Within the investment project was built in Savonia UAS Energy Research Centre a reactor for testing thermochemical energy storing reactions. Because of the delay of components of the reactor so far only preliminary tests to find out the amounts of energy released and recovered in the reaction have been carried out with selected materials such as Na + Cl and CaO + H_2O.

1.1.4 WP4 Dissemination

A platform has been created on the webpage of HCIP-NS-project (https://lampokiertoon.fi/en/heat-circulation-innovation-platform-hcip-ns/) to present comprehensively non-combustion heat production and heat recovery technologies, their implementers and the experiences gained. The aim was to provide answers to questions how energy consumption and costs could be decreased in companies, industrial processes, and buildings by utilizing elsewhere piloted innovations related to:

- Energy storage.
- Waste heat recovery.
- Heat pumps.

During the project a FINHCIP-UAS network has been established. To the network belong applied universities who are interested have carried out waste heat recovery, energy storage or heat pumps related research and case study projects. The current members of the FINHCIP-UAS network include the following UAS: Savonia, Xamk, Turku UAS, Novia, Centria, SAMK, and VAMK. The network arranged the first common seminar at Varkaus 10.5.2021. The presentations of that seminar are available on the webpage of HCIP-NS-project. There are also list and links to webpages of research projects carried out by UAS of the FINHCIP-UAS-network.

By arranged seminars and newsletters posted by Savonia-UAS to North-Savo companies they were informed of the results of the project and raised their awareness of their own waste energy flows and advised on the use of the data on the webpage of the HCIP-NS-project.

1.1.5 Conclusion

Savonia UAS Energy Research Centre at Varkaus is specialized in research related to environment friendly combustion technology. However, in this Heat Circulation Innovation Platform North-Savo (HCIP-NS)- project the goal was to promote non-combustion heat production, to promote the use of related technologies such as waste heat recovery, heat storage, and heat pump technologies.

A platform has been created on the webpage of HCIP-NS-project https://lampokiertoon.fi/en/heat-circulation-innovation-platform-hcip-ns/ to present comprehensively non-combustion heat production and heat recovery technologies, their implementers and the experiences gained. For example, there are collected information on

- good examples (related to energy storage, waste heat recovery and heat pump solutions)
- FINHCIP-UAS-network partners and their projects
- in the project organized seminars and webinars and their presentations

Within the HCIP-NS investment project it is improved Savonia UAS Energy Research Centre possibilities to carry out TCES (thermochemical energy storage) research by building a test reactor for these purposes.

During the project a FINHCIP-UAS network has been established. To the network belong applied universities who are interested and have carried out waste heat recovery, energy storage or heat pumps related research and case study projects. The aim is to continue this co-operation after this project aiming to international networking and preparation of new research openings and projects.

2 OVERVIEW OF DIFFERENT ENERGY STORAGE TECHNOLOGIES

Every energy storage system comprises three processes: charging, storing, and discharging. Generally, the ESS is charged when surplus energy from intermittent renewable energy sources such as solar or wind is available, and it releases that energy at a later time when needed. Energy storage technologies can be classified in five categories based on the form the energy is stored: thermal, mechanical, electrochemical, chemical, and electrical. The different technologies shown in Figure 1 present very particular characteristics, which makes them suitable for different applications.

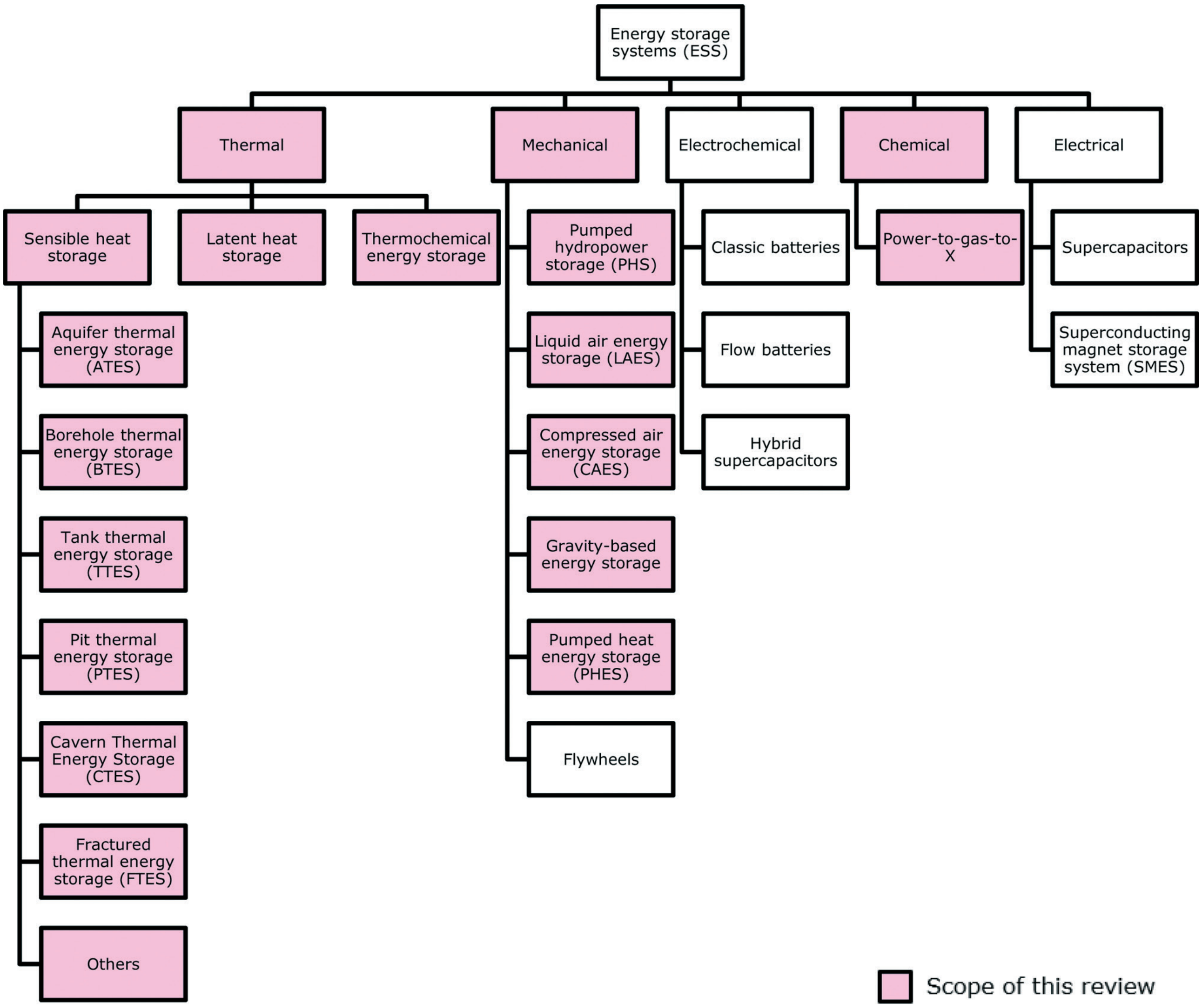


Figure 1. Classification of energy storage systems (Adapted from The European Association for Storage of Energy 2021; LDES Council 2022).

Thermal energy storage systems store thermal energy in a liquid or solid medium, and they are classified in sensible heat storage, latent heat storage, and thermochemical storage. *Mechanical energy storage systems* store potential or kinetic energy, and the most well-known technologies include pumped hydro storage (PHS), liquid air energy storage (LAES), compressed air energy storage (CAES), and flywheels. *Chemical energy storage systems* store energy in the bonds of chemical compounds such as hydrogen, ammonia and methanol, with hydrogen being one of the most attractive alternatives. In electrochemical energy storage systems, the electrical energy is converted to chemical energy, and it is stored in this chemical form. In this category are included batteries of different chemistries. Finally, *electrical energy storage systems* store energy in the form of an electric field or a magnetic field. Supercapacitors and superconducting magnetic energy storage technologies belong to this last category.

As stated before, an energy storage system is defined by its discharge time. In addition, the combination of power and capacity is another important characteristic of the energy storage technology. Together these parameters establish the suitability of the ESS for a specific application. The graphic below (Figure 2) represents several energy storage technologies according to their discharge time and power. As can be seen, each ESS has a suiTable application range, which in the case of LDES is from 1 MW to over 1 GW of power and from minutes to months of discharge time.

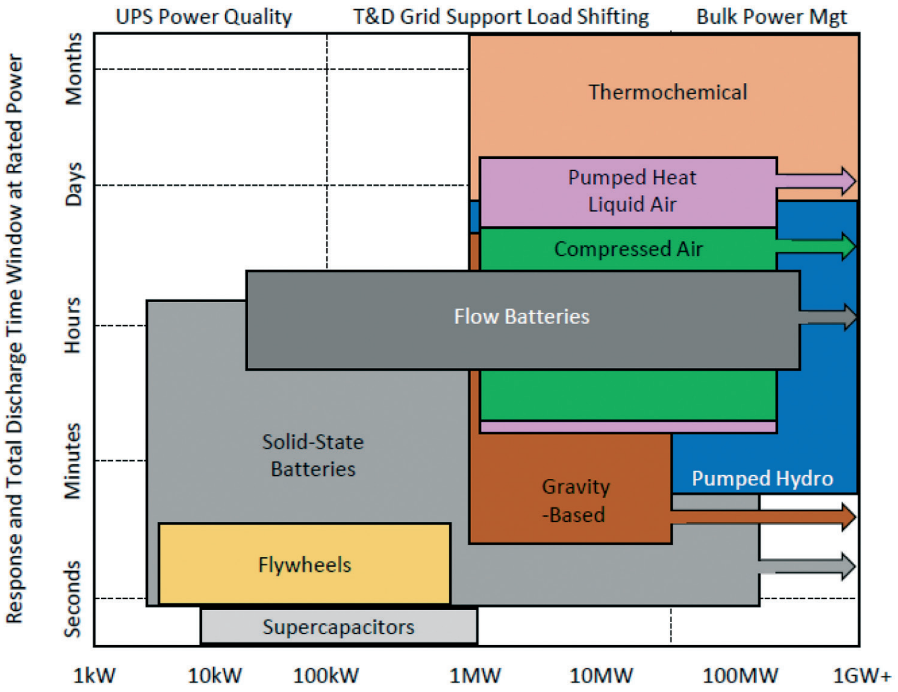


Figure 2. Power and discharge time of different energy storage technologies (Allison 2020).

DOE Global Energy Storage Database offers various statistics of energy storage installations that can be filtered based on technology, year and country, as well as a map that shows energy storage installations worldwide (Figure 3). According to this database, it is estimated that in 2021 pumped hydro accounted for 181 GW of installed energy storage capacity, which corresponds to over 94% of the global energy storage capacity. The other 6% includes mainly batteries, compressed air energy storage, sensible heat storage and flywheels. (Department Of Energy of USA 2022.)

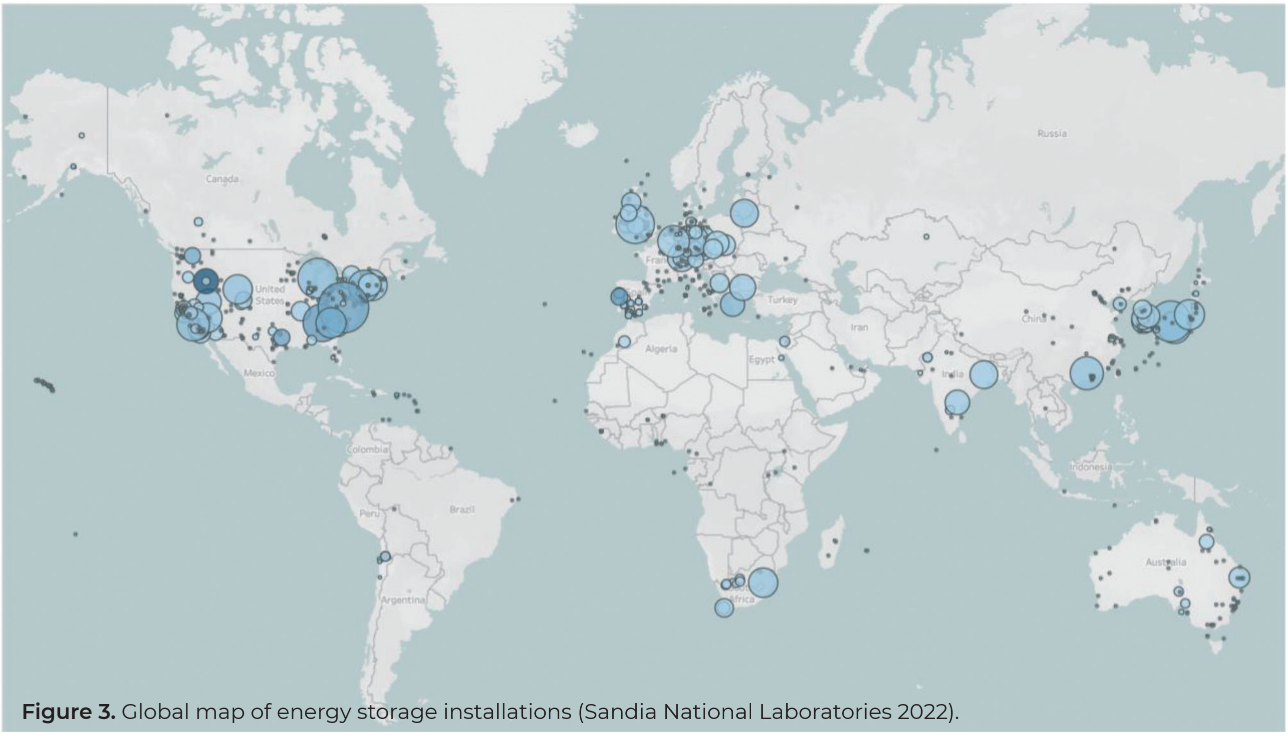


Figure 3. Global map of energy storage installations (Sandia National Laboratories 2022).

3 THERMAL ENERGY STORAGE SYSTEMS

Thermal energy storage (TES) systems store thermal energy in various types of materials, so that it can be use at a later time on demand either for heating and cooling applications or for power generation. There are three different types of TES: sensible heat storage, latent heat storage, and thermochemical energy storage (Figure 4). In Table 1 are compared these different types of thermal energy storage systems.

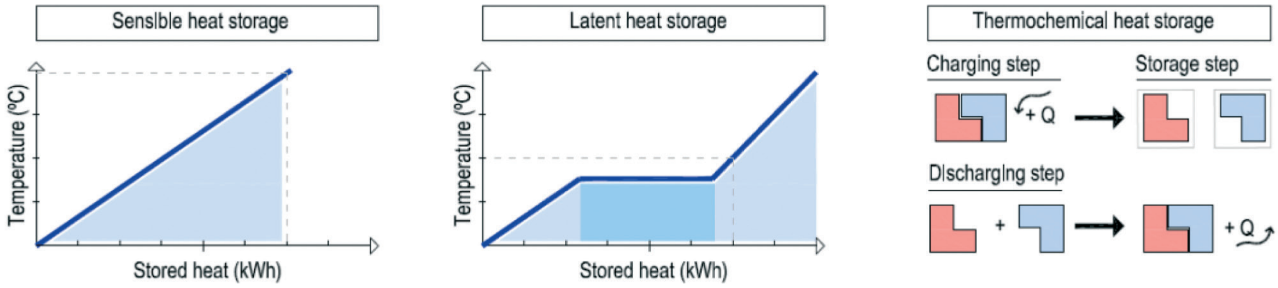


Figure 4. TES types: sensible heat, latent heat, and thermochemical heat (Lizana, Chacartegui, Barrios-Padura & Valverde 2017), used under CC BY-NC-ND 4.0.

Sensible heat storage (SHS) involves storing thermal energy by heating or cooling a liquid or solid storing material. The amount of heat stored, Q[J], is given by the formula 1:

$$Q = m \cdot C_p \cdot (T_f - T_i) \tag{1}$$

where m is the mass of the storing material [kg], C_p is the specific heat capacity [J/(kg·°C)], T_f is the final temperature [°C] and T_i is the initial temperature [°C].

Latent heat storage (LHS) or phase change storage implies the use of phase change materials (PCMs), which release or absorb thermal energy when they undergo phase transition. For a solid-liquid PCM, the amount of heat stored, Q[J], is given by the formula 2:

$$Q = m \cdot C_{ps} \cdot (T_m - T_i) + m \cdot a_m \cdot \Delta h_m + m \cdot C_{pl} \cdot (T_f - T_m) \tag{2}$$

where m is the mass of the PCM [kg], C_{ps} is the specific heat capacity of the solid phase [J/(kg·°C)], Cpl is the specific heat capacity of the liquid phase [J/(kg·°C)], a_m is the fraction of the melted material, Δh_m is the enthalpy of fusion [J/kg], T_m is the melting temperature [°C], T_f is the final temperature [°C] and T_i is the initial temperature [°C].

Thermochemical energy storage (TCES) is based on a reversible endothermic/exothermic reaction between reactants and products. In the charging process, energy is applied to decompose the reactant A into the products B and C, which are then store separately. When energy is needed, B and C react together releasing the energy. The amount of heat stored, Q [J], is given by the formula 3:

$$Q = n \cdot \Delta H \tag{3}$$

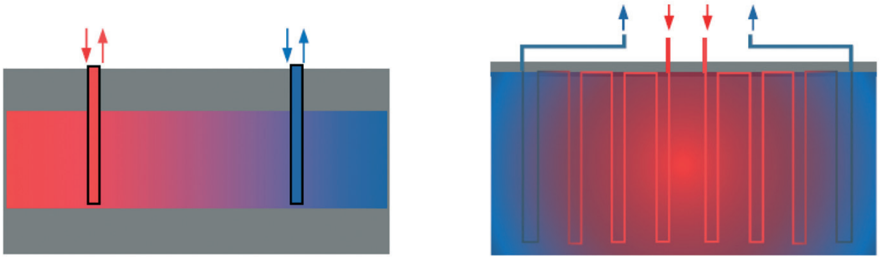
where n is the amount of reactant A in mol and ΔH is the reaction enthalpy in kJ/mol. Sorption processes are also considered a form of thermochemical energy storage. (Sarbu & Sebarchievici 2018.)

Table 1. Thermal energy storages comparison (adapted from Abedin & Rosen 2011; Alnaimat & Rashid 2019).

Criteria	Sensible heat storage	Latent heat storage	Thermochemical energy storage
Storage density	Low	Medium	High
Storage duration	Days/months	Hours/months	Hours/days
Technology maturity	Available commercially	Available commercially just for some temperatures and materials	Not commercially available, but undergoing investigation and pilot project tests
Lifetime	Long	Often limited due to storage material cycling	Depends on reactant degradation and side reactions
Storage temperature	Wide range	Phase transitions temperatures	Ambient temperature
Heat losses	High	Medium	No heat losses
Complexity	Low	Medium	High

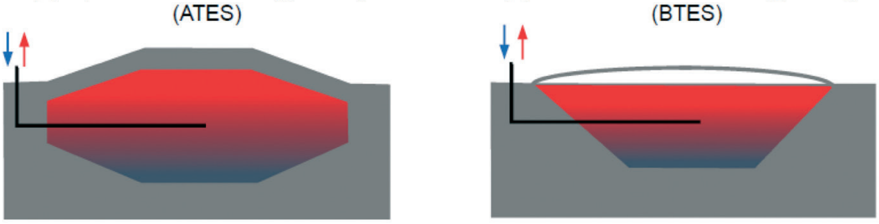
3.1 Sensible heat storage: Underground thermal energy storage (UTES)

Underground thermal energy storage systems are a type of sensible heat storage that involves the use of the ground for both heat and cold storage. The storage medium can be geological strata or water. UTES are a promising solution for seasonal storage due to the high heat capacity as well as low thermal conductivity of water and certain soils. The available UTES technologies (Figure 5) include aquifer (ATES), borehole (BTES), tank (TTES), pit (PTES), cavern (CTES), and fractured (FTES) thermal energy storage. From these technologies, ATES, BTES and CTES are the most common ones and are already commercially available. (Janiszewski 2019.)



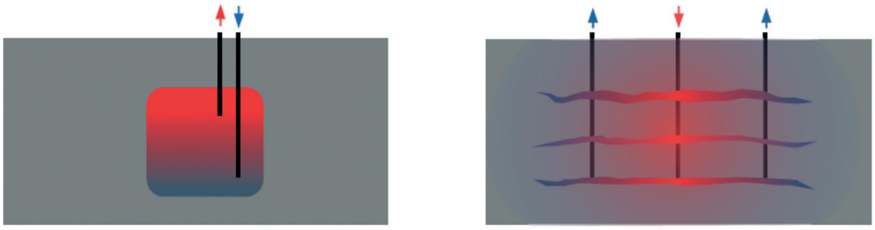
(a) Aquifer Thermal Energy Storage (ATES)

(b) Borehole Thermal Energy Storage (BTES)



(c) Tank Thermal Energy Storage (TTES)

(d) Pit Thermal Energy Storage (PTES)



(e) Cavern Thermal Energy Storage (CTES)

(f) Fractured Thermal Energy Storage (FTES)

Figure 5. UTES technologies (Janiszewski 2019).

Table 2 shows a technical comparison of four key UTES. In the following sections, UTES systems are described in more detail and examples of these technologies in Finland and other Nordic countries are given. Currently, only a few UTES systems are active in Finland: 1 ATES, 50-100 BTES, and 3 CTES.

Table 2. Comparison of UTES systems (Adapted from Doczekal 2019; ur Rehman 2020).

Criteria	ATES	BTES	TTES	PTES
Storage medium	Ground material and groundwater	Ground material	Water	Water / Gravel-water
Specific capacity (kWh/m3)	30-40	15-30	60-80	60-80 / 30-50
Storage temperature (°C)	<25	5-90	5-95	5-95
Duration	Seasonal storage	Seasonal storage	Seasonal storage and short-term	Seasonal storage and short-term
Investment costs	Medium	Low	High	Low
Geological requirements	• High yield aquifer • Aquifer thickness 20-50 m	• Drillable ground • High heat capacity • High thermal conductivity • Low hydraulic conductivity • 30-100 m deep	• Stable ground • Preferably no groundwater • 5-15 m deep	• Stable ground • Preferably no groundwater • 5-15 m deep
Advantages	• Lower costs than other technologies • Used for both heating and cooling	• Flexible and cost effective in terms of location • Lower costs than other technologies • Used for both heating and cooling	• High charging /discharging capacity • High heat capacity	• High charging /discharging capacity • Low losses • Lower costs than other technologies
Disadvantages	• Low temperature • Low energy density • High heat losses • Requires a high yield aquifer	• Low charging /discharging capacity • Low energy density • High heat losses	• High construction and maintenance costs • Leakage risk	• Requires stable ground • Large area requirements • Top cannot be used for other purposes • Leakage risk

3.1.1 Aquifer thermal energy storage (ATES)

Aquifer thermal energy storage are systems that make use of natural aquifers to store energy in the form of heat and cold. ATES are usually operated as low temperature seasonal storage for space heating and cooling (Figure 6). In summer, groundwater is extracted from the cold well and is used to cool the building via a heat exchanger. During this process the groundwater is heated, and it is later injected back into the aquifer, but in the warm well. In winter, flow direction is reversed so that the groundwater is extracted from the warm well, is used to heat the building and is injected back into the cold well of the aquifer.

In 2017 there were around 3,000 ATES systems in the world. They are mostly located in the Netherlands (2,500), followed by Sweden (220), Denmark (55) and Belgium (30). From these 3,000 ATES projects, about 100 are large scale systems integrated in district heating and cooling networks. However, in Finland there is not a significant number of ATES systems yet. (Todorov, Alanne, Virtanen & Kosonen 2020.) In this Nordic country, the ATES suitability based on geo-hydrological conditions is estimated as 3-4 out of 10, although it is expected to increase in the next decades (Bloemendal, Olsthoorn & van de Ven 2015).

Examples

In *Askonalue, Lahti (Finland)* a geothermal system with one well was being used to cool buildings with groundwater, and the efficiency of the system was increased by drilling another well in 2018. When completed, the two wells system can be used as a real ATES system for both cooling and heating. The finished ATES system comprises 2 wells of 43 m deep, with an output of 0.3 MW. A total amount of 160 MWh of cooling and 1,900 MWh of heating is produced. (Hirvonen 2020.)

In the publications by Todorov et al. (2020) two case studies are presented, where the ATES integration within the existing district heating networks in Pukkila and Kupittaa (Turku), Finland, is investigated. It was concluded that combining heating and cooling, with seasonally reversible

ATES operation and annually balanced pumping volumes, has a low long-term environmental impact on the aquifer and is economically feasible. The energy production cost is expected to be below 42 €/MWh and 30 €/MWh in Pukkila and Kupittaa case study, respectively.

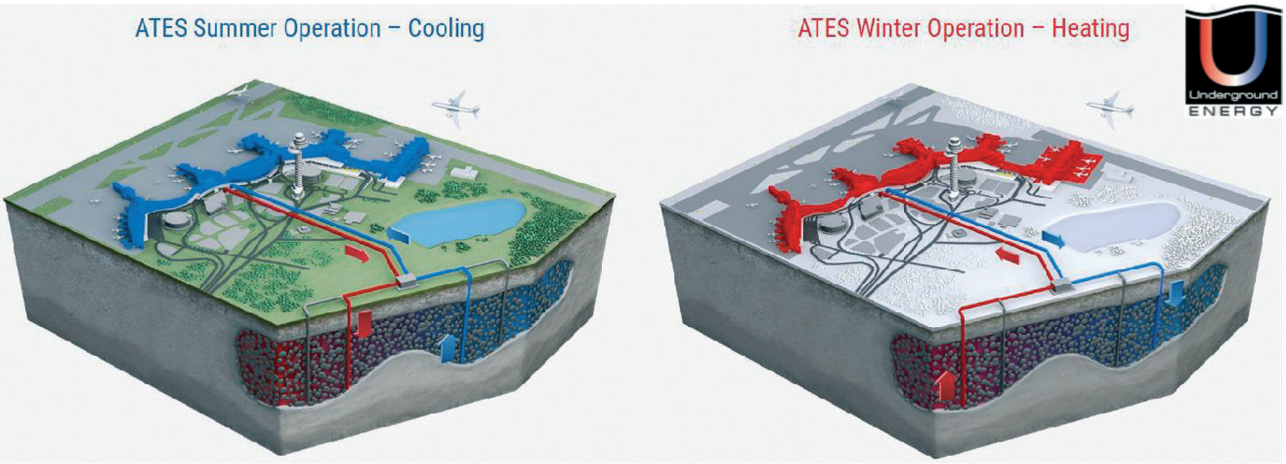


Figure 6. ATES system in Arlanda Airport in Stockholm, Sweden (Underground Energy 2017a).

A good example in the Nordic countries is the ATES system of Arlanda Airport in Stockholm (Sweden) shown in Figure 6. The airport features an ATES system consisting of 5 cold wells and 6 warm wells. The system was taken into operation in 2009 and it has allowed the airport to reduce its annual energy consumption by 19 GWh. In summertime, the cold groundwater is pumped into the airport's district cooling network saving up to 4 GWh yearly. On the other hand, during wintertime, the groundwater is extracted from the warm well and used to melt snow on the pavement in aircraft apron areas and to preheat the ventilation air in the building, which reduces the district heating use by 15 GWh. (Cabeza 2015.)

3.1.2 Borehole thermal energy storage (BTES)

Borehole thermal energy storage systems store thermal energy in the ground material surrounding the boreholes that compose the BTES system (Figure 7). The thermal energy is exchanged by the means of borehole heat exchangers (BHEs) installed in the boreholes, through which a heat carrier fluid is circulated. There are different construction designs of BHE: single U-tube, double U-tube, or coaxial heat exchanger, being single U-tube the most common type (Figure 8) (Raos, Ilak, Rajšl, Bilic & Trullenque 2019). BTES are usually operated as seasonal storage for heating and cooling of buildings.

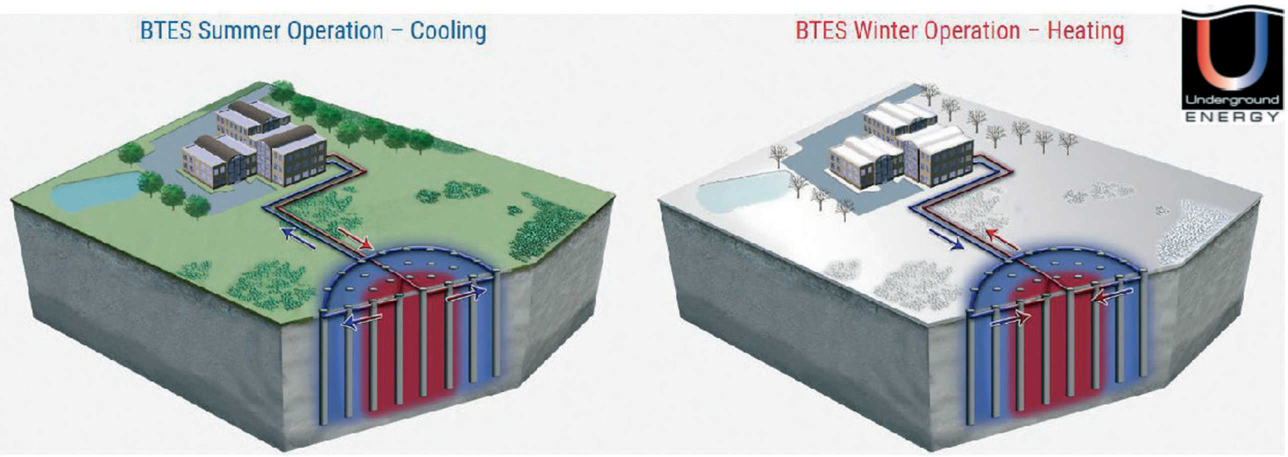


Figure 7. BTES system: summer operation (left) and winter operation (right) (Underground Energy 2017b).

There are many countries with thousands of BTES systems, ranging from one borehole to up to a few hundred boreholes (Cabeza 2015). In Finland, it is estimated that there are about 50-100 BTES systems. This technology is more widespread in Sweden, where the first large scale BTES systems were built together with solar district heating plants for seasonal storage around 1980. (Janiszewski 2019.)

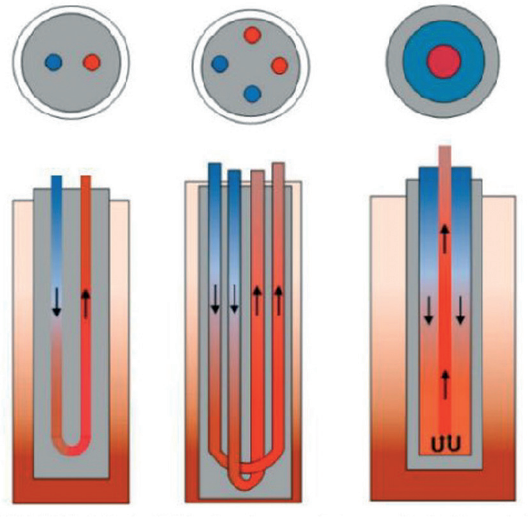


Figure 8. BHE designs. From left to right: single U-tube, double U-tube, or coaxial heat exchanger (Raos et al. 2019), used under CC BY 4.0.

Examples

The company *Finn Spring Ltd in Sykäräinen (Finland)*, which is dedicated to the bottling of spring water for commercial use, features a BTES system by Heliostorage to store excess heat from both production and solar thermal collectors. The BTES system was commissioned in 2018 and consists of 63 boreholes, about 50 m deep, which provide 500 MWh of energy storage. The stored heat is used in wintertime to heat the office space and a swimming hall. The same technology is used since 2020 in *Kaustinen Evangelical School in Kaustinen (Finland)*, where heat from solar thermal collectors is stored in the underground soil and is used during winter to heat the building. The BTES system comprises 21 boreholes and presents an energy storage capacity of 25 MWh. (Heliostorage 2020.)

The biggest BTES system in Finland is located in *Sipoo (Finland)*. The system consists of 150 (+ 159 in phase 2) vertical borehole heat exchangers, which present an average depth of 300 m. The BTES system, that is situated in granitic gneiss bedrock, has been in operation since 2012 and produces heating and cooling energy for a large logistics centre (Gehlin 2016). Another example in Finland is the waste incineration facility in *Korvenmäki, Lounavoima (Finland)*, where the waste heat is integrated to district heating with BTES. When completed, the system will consist of 6 boreholes 2,000 – 3,000 m deep, although the initial plan was to build 530 boreholes 150 m deep. (Hirvonen 2020.)

Another UTES system that is relatively new and is based in BTES technology is energy piles, which use the building foundations as ground heat exchangers (Cabeza 2015). The parking hall under *Turku Market Square (Finland)* makes use of this technology since 2020 (Figure 9). During the summer, the fluid inside the piping installed on the market square surface collects passive solar heat and flows inside the energy piles, 50 m deep, transferring the heat into wet clay. During the winter, heat is extracted from the ground and used to heat the parking hall and keep the market square free of snow. The storage capacity of the system is 11.2 GWh and its maximum power is estimated at 6.6 MW. (Hirvonen 2020.)

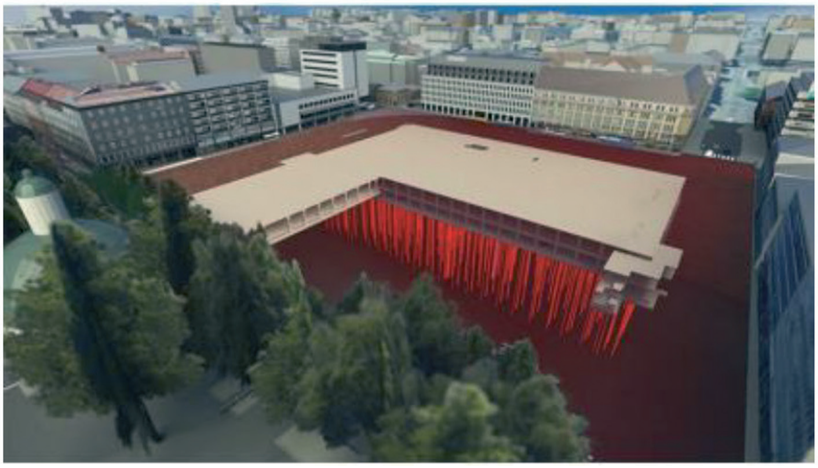


Figure 9. Energy piles in Toriparkki in Turku (NollaE 2023).

Energy piles have also been used in *Puuvilla shopping center in Pori (Finland)* since 2010. The system, which consists of 30 m deep energy piles, makes use of geothermal heat, waste heat and ground cooling to cover 98% of the heating and cooling needs of shopping centre. Energy piles with a depth of 30 m can be also found in the Technopolis Innova 2 building in *Lutakko, Jyväskylä (Finland)*. In this case, the system covers approximately 68-79% and 33-40% of the heating and the cooling needs, respectively. The same technology has been used in *Niskaparkki in Joensuu (Finland)* for preheating and cooling the air going through the ventilation system of a residential building. The system comprises 155 energy piles, which give a heating power of 34 kW and a cooling power of 21 kW. (Tahvanainen 2018.)

As stated before, Sweden is a frontrunner in large scale BTES system with about 50 BTES larger than 5,000 m drilling. One of the world's largest BTES systems for storage of industrial excess heat is the BTES at *Xylem's production plant in Emmaboda (Sweden)*, which was taken into operation in 2011. The BTES comprises 140 boreholes, 150 m deep, and stores heat recovered from two high-temperature ovens and the foundry ventilation air. During the period when the highest BTES efficiency was achieved, roughly 2.2 GWh and 0.4 GWh were injected into and extracted from the storage, respectively. (Nilsson & Rohdin 2019.) Another large scale BTES system in Sweden is located at the *Volvo Powertrain plant in Köping*. This system, which was commissioned in 2016, consists of 215 boreholes with an average depth of 270 m. The BTES system reduces the business's energy consumption by 5 GWh yearly. (Gehlin, Andersson & Rosberg 2021.)

Braedstrup district heating plant (Denmark) is an excellent example of efficient district heating production in Nordic countries. The plant features a solar collector field of 18,600 m2, a 1.2 MWth heat pump and a 10 MW electric boiler, although there is still a need for natural gas boilers as peak load. The plant also features a seasonal ESS consisting of accumulation tanks of a total of 7,500 m3 and a BTES system comprising 48 boreholes, 45 m deep (Figure 10). (PlanEnergi 2018.)

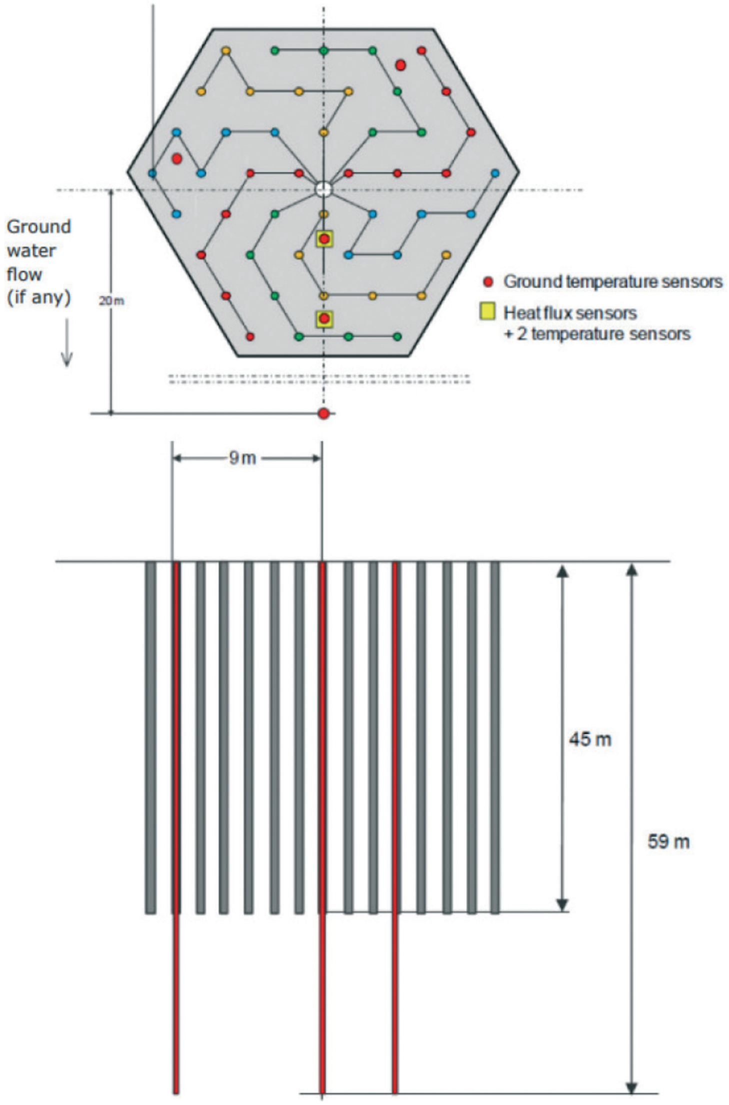


Figure 10. BTES system in Braedstrup, Denmark (PlanEnergi 2018).

3.1.3 Tank thermal energy storage (TTES)

Underground tank thermal energy storage systems store thermal energy in water in large tanks buried in the ground, as shown in Figure 11. These tanks are typically constructed onsite, by pouring concrete and then lining it with either a stainless steel or a plastic-based liner. The outside of the tank is then covered with a waterproof material to provide insulation. (Cruickshank & Baldwin 2016.) The main disadvantage of underground TTES is that the investment and maintenance costs are higher than other technologies. However, TTES presents high energy density as well as high temperature potential up to 95°C, and its efficiency can be further improved by ensuring optimal water stratification in the tank and highly effective thermal insulation (Sarbu & Sebarchievici 2018). An advantage of TTES over PTES is that the space above the buried tank might be used for other purposes, so their integration in urban areas is easier. (DoczekaL 2019; ur Rehman 2020.)

Figure 11. Tank thermal energy storage in Walnut, USA (Picture courtesy of DN Tanks).

Examples

There are no active TTES systems in Finland. However, in Germany there are few of them. In a *central solar heating plant in Munich* a tank thermal energy storage with 5,700 m³ of water volume and a heat capacity of 330 MWh was taken into operation in 2007. The tank is built from prefabricated concrete elements with inner stainless-steel liner, and it makes use of a stratification device and a thermal insulation system to improve its efficiency. The TTES provides energy to four large blocks of flats and eight smaller townhouses. (van den Heuvel 2020.)

In *Friedrichshafen* a 12,000 m^3 underground tank was built in 1996, and it provides energy for two residential zones. The tank is made of reinforced pre-stressed concrete and is lined with watertight 1.2 mm stainless steel sheets. The roof and vertical walls of the tank are insulated. (van den Heuvel 2020.)

3.1.4 Pit thermal energy storage (PTES)

Pit thermal energy storage systems store thermal energy in water or water/gravel in pits with an insulating floating lid. PTES systems have the advantages of operating as both seasonal and short-term storage and presenting high energy density as well as high temperature potential (up to 95°C). The disadvantages include that PTES systems require a large area of sTable ground and, although the investment costs are relatively low, they might be significantly increased by the insulating lid depending on the size of the pit. (Doczekal 2019; ur Rehman 2020.)

Examples

There are not PTES implementations in Finland yet. There was one PTES combined with BTES in *Kerava solar village*, that was operating between 1983 and 1985. The water pit of 1,500 m^3 volume was excavated in rock and was heated with solar energy. The pit was surrounded by 54 BHEs spread in two rings. Unfortunately, the tank was undersized, and the system was replaced by district heating. (Hirvonen 2020.)

Large pit thermal energy storage systems can be found in Denmark (Table 3), where they are combined with solar thermal heating and work as seasonal storage with water as storage medium. The largest of these Danish PTES, which was commission in 2015, is located in *Vojens district heating plant* and has a capacity of 210,000 m^3 with an operating temperature range of 40-90°C (Wyrwa, Raczynski, Kulik, Oluwapelumi, Mateusiak, Zhang & Kempka 2022).

Table 3. PTES in Denmark (Wyrwa et al. 2022).

Name	Year built	Temperature range (°C)	Capacity			(Dis)Charging power (MW)
			(m3)	(MWh)	(TJ)	
Sunstore 2 Marstal*	2003	35-90	10,000	638	2.3	6.51
Sunstore 3 Dronninglund*	2013	10-89	60,000	5,400	19.4	26.1
Sunstore 4 Marstal*	2012	17-88	75,000	6,000	21.6	10.5
Vojens**	2015	40-90	210,000	12,180	43.8	38.5
Gram**	2015	20-90	125,000	12,125	43.7	30.0
Toftlund**	2017	20-90	85,000	6,885	24.8	22.0

*Demonstration installations. **Commercial installations.

The pit thermal energy storage in *Marstal district heating plant* has a capacity of 75,000 m^3 (FIGURE 12. Left: Excavation of PTES at Marstal District Heating plant (Picture courtesy of Marstal Fjernvarme)). *Dronninglund district heating plant* PTES presents a similar design to the storage in Marstal, but while in Marstal the in- and outlet pipes enter through the side of the storage, in Dronninglund the pipes enter through the bottom. It also has a lower volume capacity of 60,000 m3. *Gram solar district heating plant* features a PTES of 122,000 m^3, and its design is similar to the storage in Marstal, too. These PTES systems are charged to about 80-90°C during summer and discharged down to about 10-20°C during winter. The storages are used directly and as heat source for the heat pumps. (PlanEnergi 2018.)

Figure 12. Left: Excavation of PTES at Marstal District Heating plant (Picture courtesy of Marstal Fjernvarme). Right: PTES at Gram District Heating plant (Picture courtesy of Gram Fjernvarme).

3.1.5 Cavern thermal energy storage (CTES)

Cavern thermal energy storage systems store thermal energy in water in underground caverns that may be man-made caves, abandoned mines or natural formations. The water is injected on the top and it is extracted from the bottom in order to maintain an optimal thermal stratification. The main disadvantages are the geological restrictions (e.g., it requires hard rock) and the high investment costs in case of man-made caverns. On the other hand, the advantages include large storage capacity and high charging and discharging capacity.

Examples

A rock cavern that previously operated as an industrial oil storage facility in Kemira factory area, *Oulu (Finland)*, became a heat storage in the late 1990s. The system is connected to Toppila's CHP plant and is used for optimizing heat production and as backup source of heat. The CTES consists of two parallel rock caverns with a volume of about 190,000 m³ and a storage capacity of 13.5 GWh. The charging and discharging capacity is 80 MW. (Yliluoto 2022.)

In 2020, a CTES was put into operation in Vaskiluoto, Vaasa (Figure 13). The TES facility consists of two caverns, previously used as oil storage, that store excess thermal energy from a waste incineration plant. The system balances district heating production peaks and will enable a more flexible use of wind and solar energy in the future. The thermal storage caves have a volume of 150,000 m³ and 60,000 m³ (210,000 m³ in total), its charging and discharging capacity is 100 MW, and its storage capacity is about 7–9 GWh. The operating temperature is 45–90°C. (EPV Energia Oy 2020)

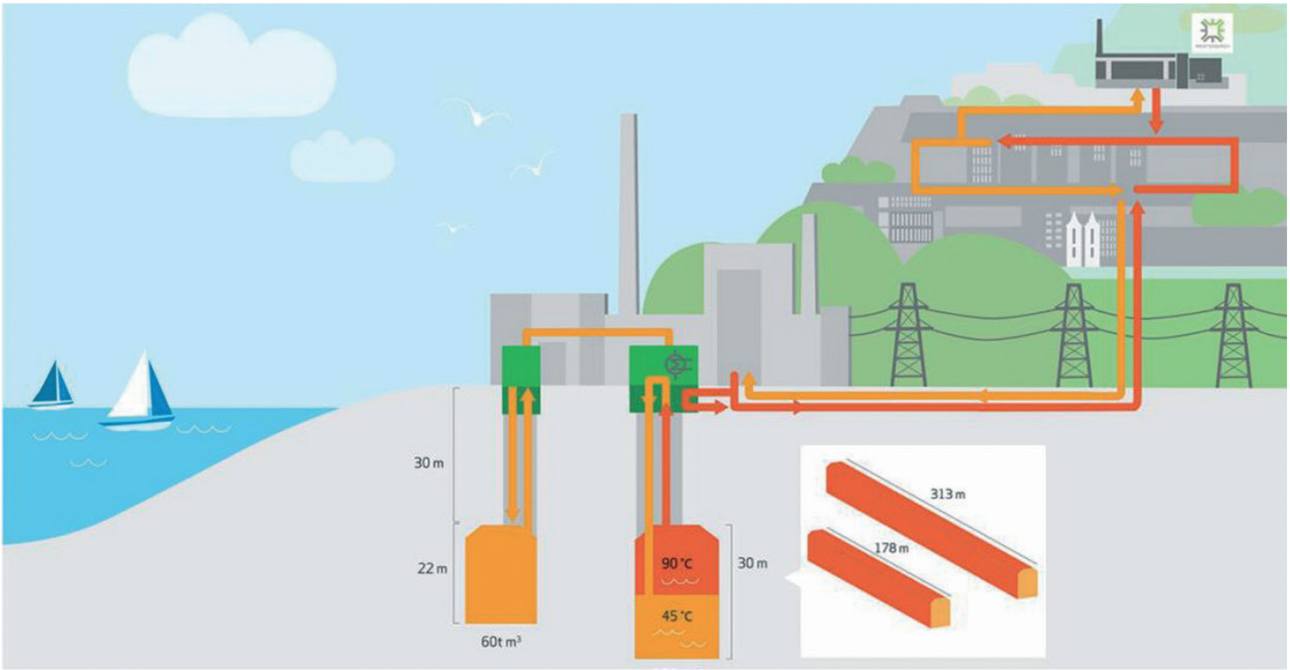


Figure 13. CTES in Vaskiluoto, Vaasa (Finland) (EPV Energia Oy 2020).

Finland's current largest CTES was built in the old oil caverns in Mustikkamaa (Figure 14). The system stores heat, e.g., waste heat from waste waters and properties, and releases it when necessary, balancing consumption peaks of the district heating network throughout the year. The planning of the Mustikkamaa CTES started in 2019 and the construction was completed in 2021. The amount of energy stored is 11.6 GWh, the charging and discharging capacity is 120 MW and the operating temperature is 45–100°C. The effective water volume in the heat storage facility is 260,000 m3. (Yliluoto 2022.)

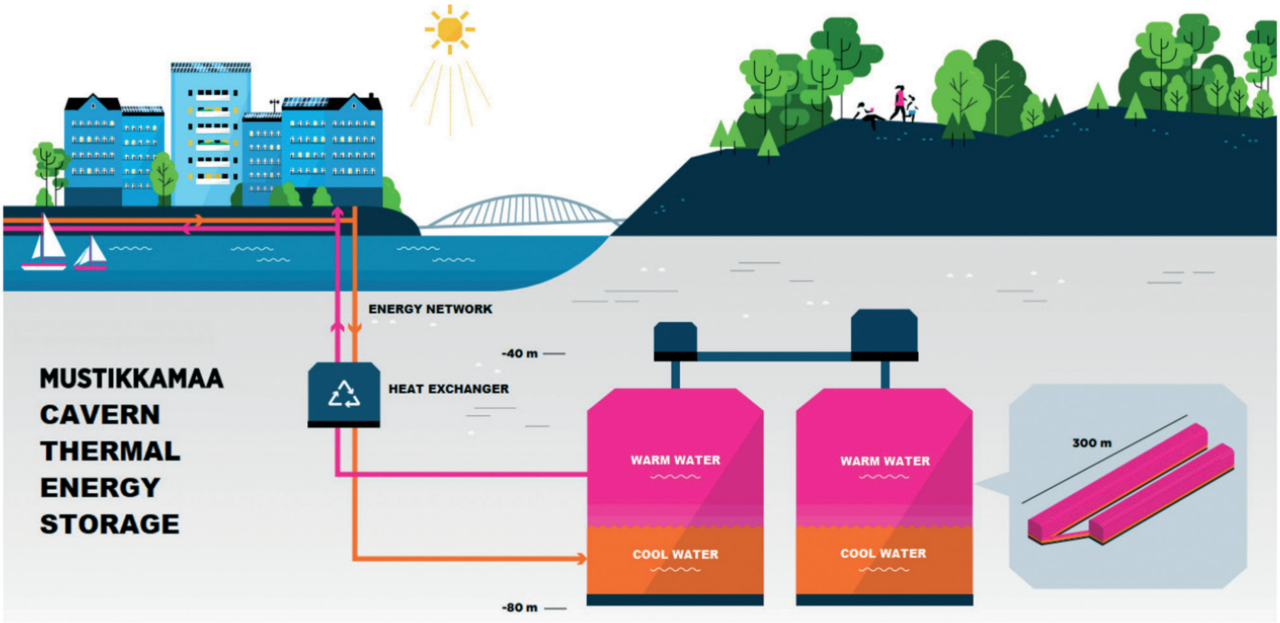


Figure 14. Mustikkamaa CTES (Picture courtesy of Heley Oy, Translated from Finnish).

Another CTES that will make advantage of an old oil storage facility are the *rock caverns under Kruunuvuori* (Figure 15). Planned completion of the project is in the mid-2020s. The caverns, which have a combined volume of 300,000 m3 and are about 50 meters below sea level, will be use as seasonal storage for Skanska's new residential area, with the goal of carbon neutrality during its life cycle. The caverns will be filled with sun-heated surface water collected in the summer, and it will be used as a heat source for heat pumps in winter. In the summer, the buildings' excess solar heat will be also collected. The annual production will be about 6-7 GWh, the discharging capacity 3 MW and the operating temperature 2–24°C. (Yliluoto 2022.)

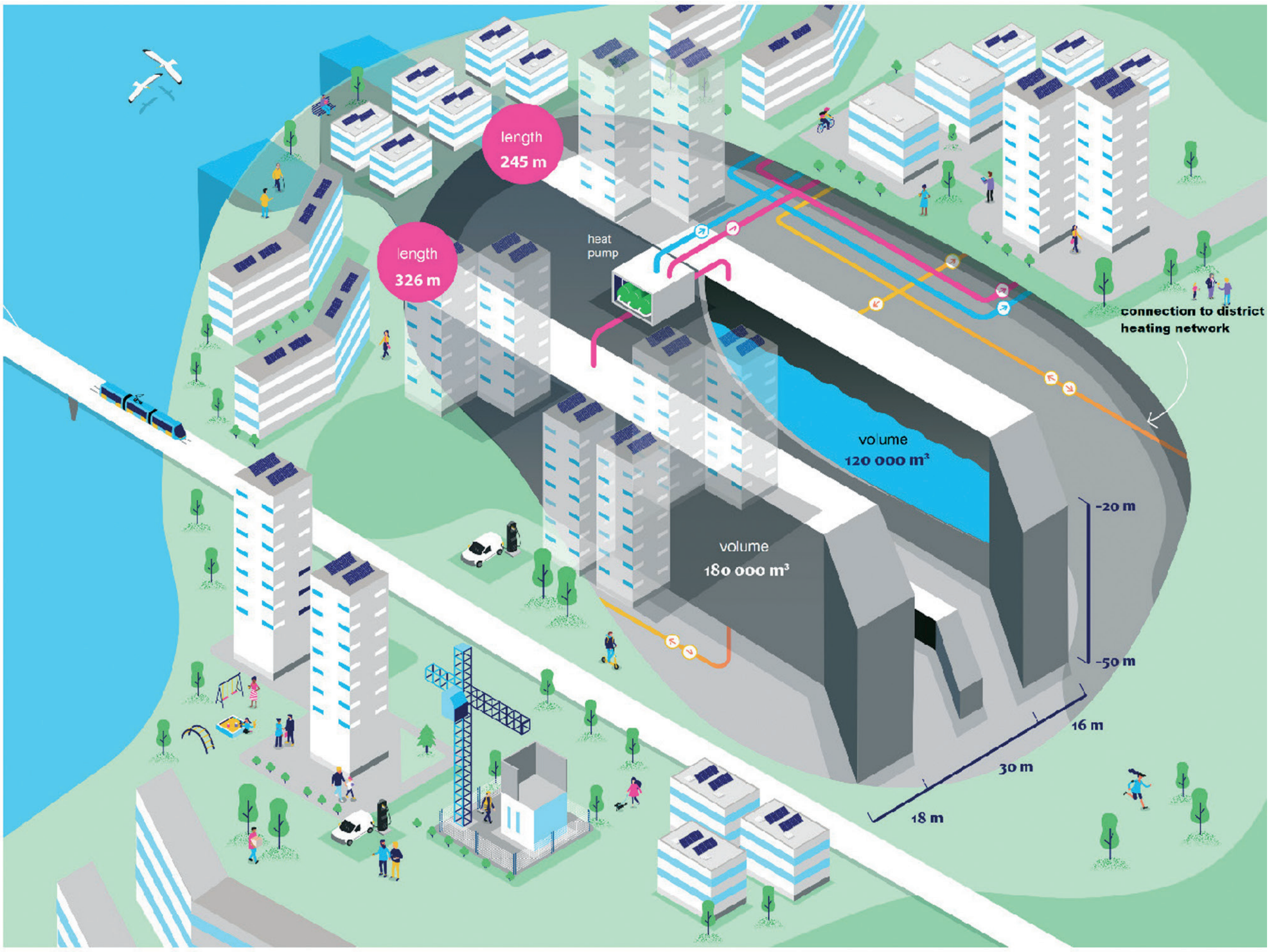


Figure 15. Kruunuvuorenranta CTES (Picture courtesy of Heley Oy, Modified and Translated from Finnish).

Another promising seasonal energy storage is *VECTES (Vantaa Energy Cavern Thermal Energy Storage)*. The facility, which is planned to be ready in 2026, will be the largest CTES in the world with 1,000,000 m^3 in size (Figure 16). The purpose of the CTES is to store renewable energy from wind, solar and geothermal sources as well as waste heat. The heat stored during summer, will be used in winter to produce district heat. The system will have a storage capacity of 90 GWh, a charging and discharging capacity of 200 MW and an operating temperature is 35–140°C. (Yliluoto 2022.)

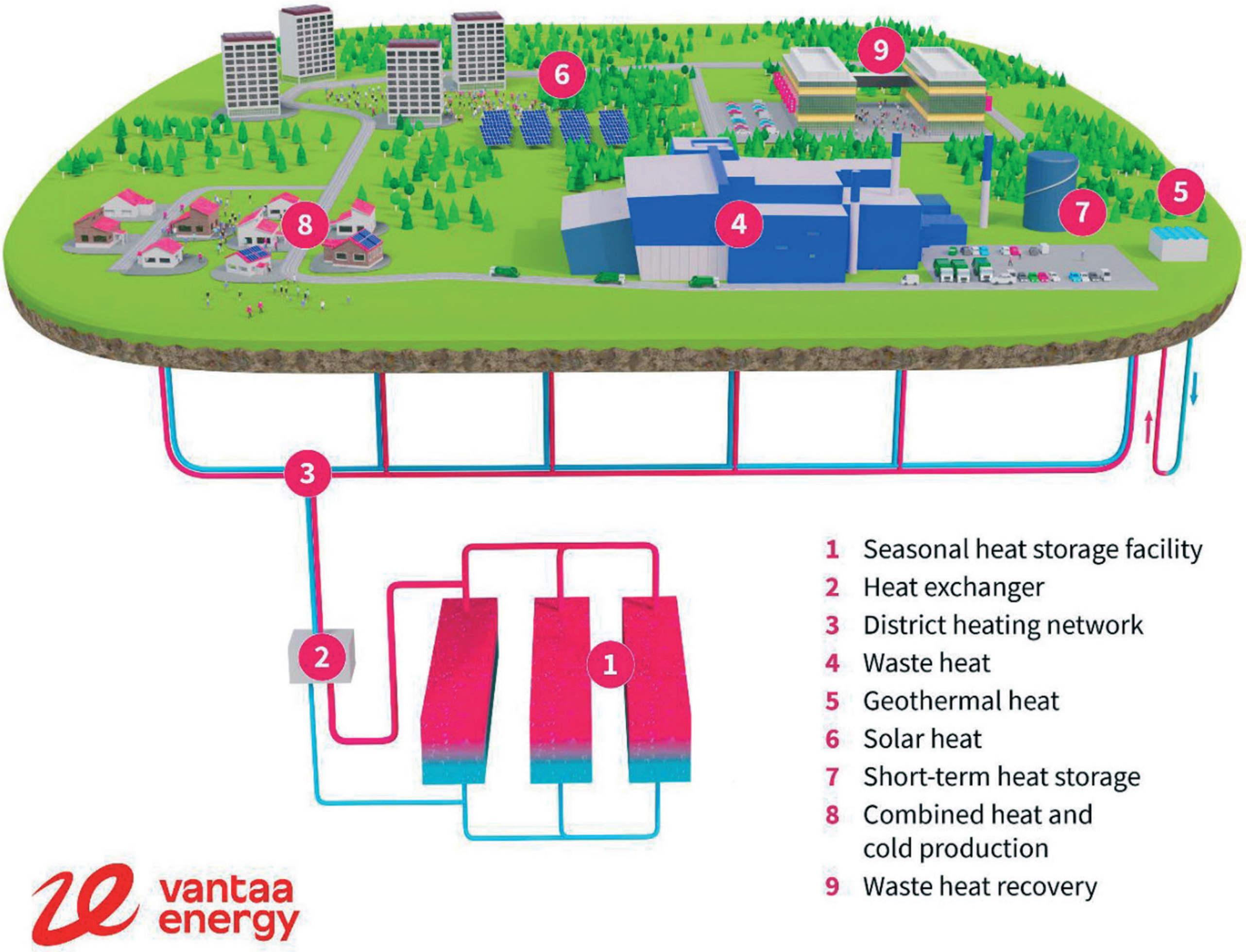


Figure 16. VECTES (Picture courtesy of Vantaan Energia).

The first CTES systems in the world were built in Sweden. In *Avesta* a CTES with a volume of 15,000 m^3 was built in 1981 as a short-term storage integrated with an incineration plant. In *Lyckebo*, a CTES with a volume of 115,000–120,000 m^3 was taken into operation in 1983 and is part of the Upp-sala district heating network. The CTES system is connected to a solar energy system that acts as a partial heater for the water in the cave thermal storage. The CTES in *Hornsberg*, with a volume of 70,000 m^3, was commissioned in 2009 and it balances district cooling production peaks. (Yliluoto 2022.)

3.1.6 Fractured thermal energy storage (FTES)

Fractured thermal energy storage systems involve the use of an artificial network of fractures in a rock mass to store thermal energy (Figure 17). Sub-horizontal fracture planes are created by hydraulic fracturing in vertical boreholes. To achieve the heat transfer, a hot fluid is circulated through the fractured storage medium. FTES systems can be a cost-effective alternative to BTES method as it may require a lower number of boreholes. Moreover, FTES systems have the advantage of high heat transfer rates and large storage capacities due to the extensive surface area provided by the fractures. However, these systems require homogenous rocks, and existing natural fractures may affect the results of the artificial fracturing. In addition, the presence of appropriate apertures in the fracture planes must be ensured in order to achieve the desired operation and performance of the fractured thermal energy storage system. (Janiszewski, Shen & Rinne 2018; Janiszewski 2019.)

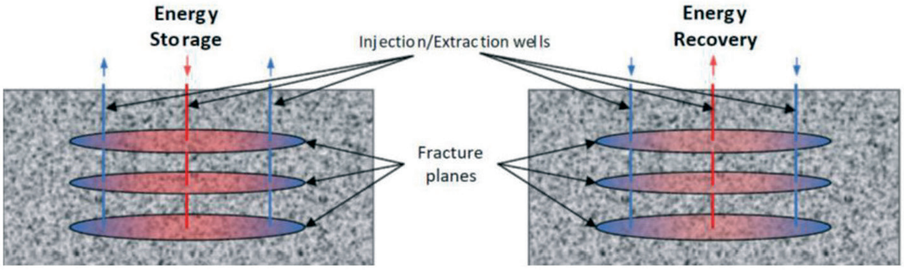


Figure 17. FTES charging (left) and discharging phases (right) (Janiszewski 2019).

One of the applications of the FTES method is HYDROCK by Hellström and Larson. Existing fractures or artificially created fractures in hard crystalline rocks are used to store thermal energy. During the charging phase, hot heat transfer fluid (HTF) is pumped into the central hole, and it heats up the surrounding rock while it flows through the sub-horizontal fracture planes towards the peripheral wells. During discharging phase, cold heat transfer fluid is pumped into the peripheral wells, and it heats up as it flows through the fractures. Finally, the hot HTF is extracted from the central well. (Janiszewski 2019.)

Examples

FTES technology is still in the research and development stage, and there are no active systems yet.

3.2 Other sensible heat storage systems

Besides the underground systems described in the previous section, there are other types of sensible heat storage systems. As stated before, these SHS systems store thermal energy by heating or cooling a liquid or solid storage medium. The most widely used storage material is water, since it is relatively inexpensive, easily available, chemically sTable, and it has a high specific heat capacity. However, its working temperature is limited due to the boiling point constraint to less than 100°C, unless the pressure of the system is increased. For this reason, water as storage medium is more suiTable for low temperature applications. (Sarbu & Sebarchievici 2018.)

Other storage materials besides water including sand, rock, concrete, molten salts and different types of bricks and organic liquids have been studied. Sarbu et al. (2018) made a comprehensive review on thermal energy storage, that collects information from several articles about different storage mediums for sensible heat storage. The main characteristics of these materials can be seen in Table 4.

Table 4. List of selected materials for sensible heat storage (adapted from Sarbu & Sebarchievici 2018).

Medium	Fluid Type	Temperature Range (°C)	Density* (kg/m³)	Specific Heat* (J/(kg·K))
Sand-rock minerals	Solid	200-1,300	1,700	1,300
Reinforced concrete	Solid	200-400	2,200	850
Cast iron	Solid	200-400	7,200	560
NaCl	Solid	200-500	2,160	850
Cast steel	Solid	200-700	7,800	600
Silica fire bricks	Solid	200-700	1,820	1,000
Magnesia fire bricks	Solid	200-1,200	3,000	1,150
Water	Liquid	0-100	1,000	4,190
Calorie HT43	Oil	12-260	867	2,200
Engine oil	Oil	≤ 160	888	1,880
Ethanol	Organic liquid	≤ 78	790	2,400
Propane	Organic liquid	≤ 97	800	2,500
Butane	Organic liquid	≤ 118	809	2,400
Isotunaol	Organic liquid	≤ 100	808	3,000
Isopentanol	Organic liquid	≤ 148	831	2,200
Octane	Organic liquid	≤ 126	704	2,400

*At 20°C.

3.2.1 Water tank storage

Unlike underground TTES described in section 3.1.3, these tank thermal energy storage systems store hot water in tanks installed at ground level. Normally, these tanks are made of steel and have a vertical cylindrical shape. The main advantages of above ground tanks over underground tanks are that they are a well-understood technology, are more economical to construct and are simpler to install. On the other hand, the disadvantages include that these water tanks are not designed to provide long-term storage, and that the tank is exposed to the elements, which might cause significant heat loss during cold months. This heat loss can be reduced by adding an effective insulation, but this solution increases notably the investment costs. (Cruickshank & Baldwin 2016.)

Thermal storage by hot water tanks is a major technology in all European countries. Tanks are mostly dedicated to residential applications, but they can also be found in large scale applications, e.g., as district heating batteries. In Finland, several tank thermal energy systems are connected to district heating networks (Table 5). The tanks are often located near the main boiler plant and are used to balance district heating production peaks.

Examples

In Helsinki, Helen Oy's *Salmisaari* power plant produces heat and electricity from hard coal and wood pellets. The power plant features an energy storage system consisting of two water tanks of 10,000 m^3 each installed in 1987, with an energy storage capacity of approximately 1,000 MWh. (Helen Oy 2014a.) *Vuosaari combined cycle power plants*, also Helen Oy's, produce electricity and district heat from natural gas. The water tank, which was installed in the plant in 1998, has a capacity of 25,000 m^3 and an energy storage capacity of approximately 1,250 MWh. (Helen Oy 2014b.)

Another district heating battery was taken into operation in 2020 at Kuopion Energia's *CHP plant in Haapaniemi, Kuopio* (Figure 18). The 15,000 m^3 tank can store approximately 13,500 m^3 of water and can transfer it to the district heating network as needed. The charging and discharging capacity is about 85 MW, and the maximum energy storage capacity is 800 MWh. (Sähköviesti 2021.) Also at Fortum's *CHP plant in Suomenoja (Espoo)* a water tank of about 20,000 m^3 works as a district heating battery and can store about 800 MWh of thermal energy (Fortum 2015). *Vatajankoski power plant* features two 1,500 m^3 district heating batteries, which store waste heat from Knauf Oy's drywall factory. The recovered heat is discharged into the district heating network's flow water via heat pumps. (Vatajankoski 2020.)

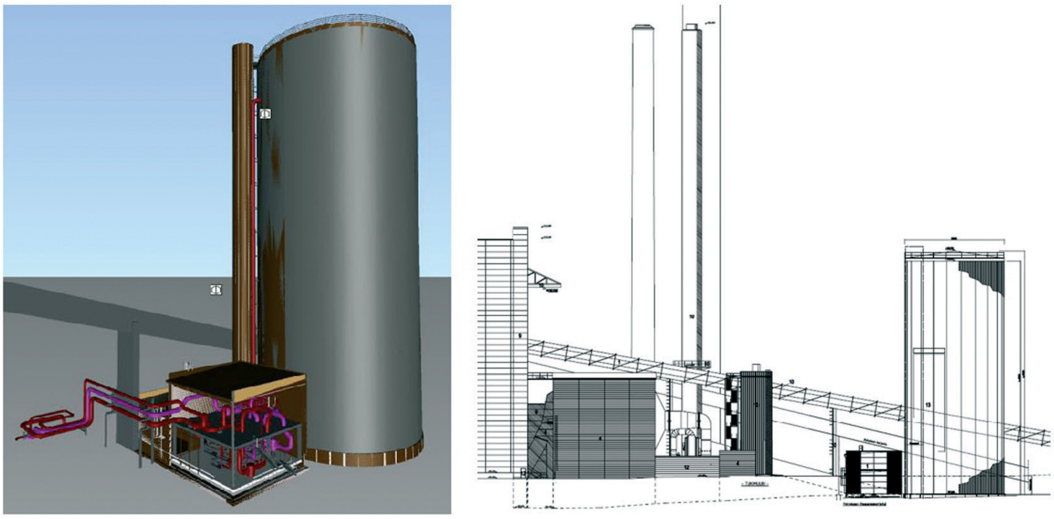


Figure 18. "District heating battery" at Kuopion Energia's power plant in Haapaniemi (Pictures courtesy of Kuopion Energia).

The biggest tank in Europe is under construction in Berlin (Germany). The tank is 45 m high and has a capacity of 56,000 m^3. Its maximum thermal output is 200 MW, and its energy storage capacity is 2,600 MWh. When completed, it will store district heating water at a temperature of 98°C and will use heat produced with renewable electricity coming from the grid. (Murray 2022.)

Table 5. Main water tank storages connected to district heating networks in Finland (Adapted from Aalto 2021, 269)

Company	Location	Volume (m3)	Capacity (MWh)	Maximum output (MW)	Year of commission
Helen Oy	Salmisaari, Helsinki	20,000	1,000	130	1987
Helen Oy	Vuosaari, Helsinki	25,000	1,250	130	1998
Fortum Power and Heat	Suomenoja, Espoo	20,000	800	50	2015
Vantaan Energia Oy	Martinlaakso, Vantaa	20,000	900	50	1990
Oulun Energia Oy	Oulu	15,000	800	80	1985
Lahti Energia Oy	Lahti	10,000	450	40	1985
Elenia Lämpö Oy	Hämeenlinna	10,000	320	50	1988
Napapiirin Energia ja Vesi Oy	Rovaniemi	10,000	450	30	1998
Turku Energia Oy Ab	Naantali	15,000	690	82	1985
KSS Lämpö Oy	Kouvola	10,000	420	72	1988
Etelä-Savon Energia Oy	Mikkeli	7,000	350	30	2016
Hyvinkään Lämpövoima Oy	Hyvinkää	10,000	350	50	1988
Kuopion Energia	Haapaniemi, Kuopio	15,000	800	85	2020
Vantaan Energia Oy	Ojanko	11,000	498	50	2014
Tampereen Sähkölaitos Oy	Tampere	2,300	104	50	N/A
Turku Energia Oy Ab	Turku	6,000	271	50	2002
Rauman Energia Oy	Rauma	2,000	90	50	N/A
Ekenäs Energi Ab	Tammisaari	700	31	50	N/A
Herrfors Oy Ab	Ylivieska	1,000	45	50	2003
Saarijärven Kaukolämpö Oy	Saarijärvi	350	20	50	1988
Vatajankoski Oy	Kankaanpää	1,500	N/A	N/A	2021

3.2.2 Molten salts -based energy storage

Molten salts -based energy storage is a type of sensible thermal energy storage that uses molten salts as storage medium. Currently, this technology is commercially used as heat storage in concentrated solar power (CSP) plants. The stored heat can later be converted to electricity via steam turbines. At the end of 2019, the worldwide power generation capacity from molten salt storage in CSP plants was estimated at 21 GWh. (Bauer, Odenthal & Bonk 2021.)

The most common molten salt used in sensible heat storage is a mixture of 60 wt.% sodium nitrate ($NaNO_3$) and 40 wt.% of potassium nitrate (KNO_3), also known as solar salt. Caraballo et al. (2021) studied the most promising next generation molten salts and compared them to solar salt (Table 6). It was concluded that nitrate-based materials were the best choice for low temperatures while chloride-based materials were best for high temperatures instead of fluoride- and carbonate-based materials, primarily because of their more affordable price. (Caraballo, Galán-Casado, Caballero & Serena 2021.)

Table 6. Promising molten salts for SHS (Adapted from Caraballo et al. 2021).

	Fusion temperature (°C)	Decomposition temperature (°C)	Density (kg/m³)	Specific heat capacity (J/kg·°C)	Specific cost ($/kg)	Energy storage cost ($/MJ)
Nitrate-based						
Solar Salt	240	565	2090 – 0.636T	1443 + 0.172T	1.3	2.65
Hitec	142	450	1938 – 0.732T	1560 – 0.001T	1.93	4.02
Hitec XL	130	450	2240 – 0.827T	1542.3 – 0.322T	1.66	3.58
$LiNaKNO_3$	118	550	2088 – 0.612T	1580	1.1	1.61
$LiNaKCaNO_3$	93	450	1993 – 0.700T	1518	0.7	1.29
$LiNaKNO_3NO_2$	97	450	2074 – 0.720T	1135.3 + 0.071T	N/A	N/A
Chloride-based						
KMgCl	430	>700	2125.1 – 0.474T	999	0.35	1.29
NaKMgCl	383	>700	1899.2 – 0.4253T	1023.8	0.22	0.68
NaMgCaCl	407	650	4020.57 – 2.7697T	12,382.2 + 0.040568T∧2–42.78T	0.17	0.57
NaKZnCl	204	>700	2625.44 – 0.926T	911.4 – 0.0227T	0.8	1.79
KMgZnCl	356	>700	2169.6 – 0.5926T	866.4	1	3.36
Fluoride-based						
LiNaKF	454	>700	2530 – 0.73T	976.78 + 1.0634T	2	5.11
NaBF	385	>700	2252.1 – 0.711T	1506.0	4.88	10.29
KBF	460	>700	2258 – 0.8026T	1305.4	3.68	11.75
KZrF	420	>700	3041.3 – 0.6453T	1000	4.85	17.32
Carbonate-based						
$LiNaKCO_3$	397	670	2270 – 0.434T	1610	2.02	4.15

Molten salts -based TES systems can be divided into four categories: single-tank indirect thermocline system, single-tank direct thermocline system, two-tank indirect system, and two-tank direct system (Figure 19). In direct systems, molten salt works both as heat transfer fluid and as storage medium, thus the investment costs are lower because there is no need of an extra heat exchanger. In single-tank systems, the separation of the hot and cold volumes is achieved by thermal stratification in a single tank, while in two-tank systems a hot and a cold tank are used. From these four different types, two-tank indirect system is the most widely used in CSP plants.

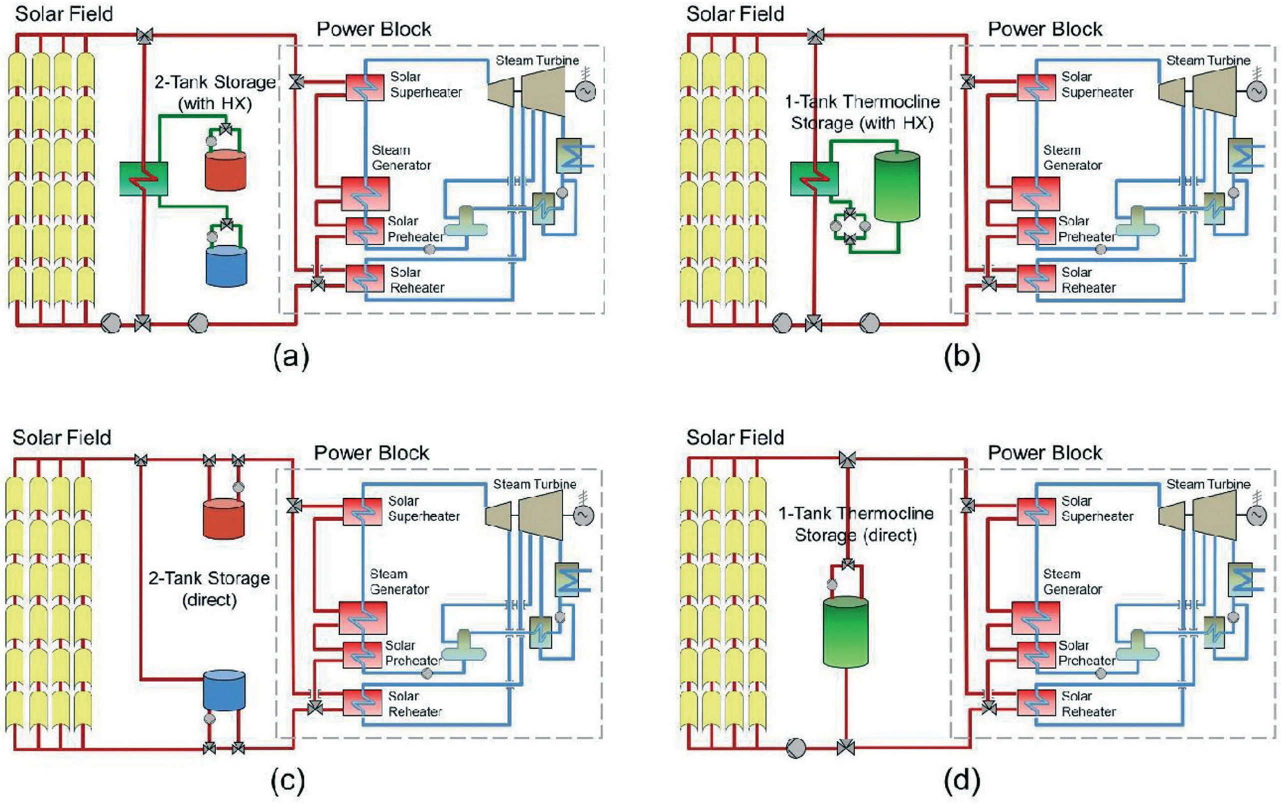


Figure 19. Different configurations of TES in CSP plants: (a) two-tank indirect, (b) single-tank indirect thermocline, (c) two-tank direct, and (d) single-tank direct thermocline system (Biencinto, Bayón, Rojas & González 2014).

Examples

Examples of solar thermal demo plants where two-tank concept using molten salt was successfully demonstrated are shown in Table 7. All these demo plants set the basis of commercial molten salt storage systems that are being installed worldwide. The first commercial large scale molten salt system in Europe was commissioned in 2008 for the ANDASOL plant in Spain, with a thermal capacity of about 1 GWh and a hot tank volume of 14,000 m3. Other commercial CSP plants with molten salt -based TES are listed in Table 8. (González-Roubaud, Pérez-Osorio & Prieto 2017.) Finland is not applying this technology yet.

Table 7. TES demo plant with two-tank system (González-Roubaud et al. 2017).

TES demo plant	Heat transfer fluid	Storage material	Cold storage temperature (°C)	Hot storage temperature (°C)	Hot tank volume (m^3)	Thermal capacity (MWh_{th})
CESA-1 (Spain)	Steam	HitecTM	220	340	200	12
Themis (France)	HitecTM	HitecTM	250	450	310	40
CRTF (USA)	Solar salt	Solar salt	288	566	53	7
Solar Two (USA)	Solar salt	Solar salt	290	565	875	105
Archimede (Italy)	Solar salt	Solar salt	290	550	25	4
TES-PS10 (Spain)	Synthetic oil	Solar salt	288	388	220	8.1

Table 8. Selected commercial CSP plants with two-tank TES system (adapted from NREL 2022).

CSP plant	Country	Heat transfer fluid	Energy storage type	Storage capacity (h)
Andasol 1 - 3	Spain	Thermal Oil	2-tank indirect	7.5
Aste 1A - 1B	Spain	Dowtherm A	2-tank indirect	8
Atacama I / Cerro Dominador	Chile	Molten Salt	2-tank direct	17.5
Bokpoort	South Africa	Dowtherm A	2-tank indirect	9.3
Crescent Dunes	USA	Molten salt	2-tank direct	10
CSNP Urat	China	Thermal oil	2-tank indirect	10
Extresol 1 - 3	Spain	Biphenyl/Diphenyl oxide	2-tank indirect	7.5
Gemasolar	Spain	Molten salts	2-tank direct	15
Kathu Solar Park	South Africa	Thermal Oil	2-tank indirect	5
Dacheng Dunhuang	China	Molten salt	2-tank direct	15
Manchasol 1 - 2	Spain	Biphenyl/Diphenyl oxide	2-tank indirect	7.5
NOOR I	Morocco	Dowtherm A	2-tank indirect	3
NOOR II	Morocco	Thermal oil	2-tank indirect	7
NOOR III	Morocco	Molten salt	2-tank direct	7
Shouhang Dunhuang Phase I	China	Molten salt	2-tank direct	15
Shouhang Dunhuang Phase II	China	Molten Salt	2-tank direct	11
Termosol 1 - 2	Spain	Thermal Oil	2-tank indirect	9

3.2.3 Sand-based energy storage

Sand-based energy storage is a high temperature thermal energy storage that uses sand or sand-like materials as its storage medium. Sand is a good option as a thermal storage medium and has been under investigation by several researchers because of its high availability, low cost, relatively high heat capacity, and high melting point. (Polar Night Energy 2022.) In the investigation by Diago et al., desert sand from the United Arab Emirates was studied and results showed that it was possible to heat the sand up to 800-1,000°C. Above 800°C, weak agglomeration effects started to become significant and above 1,000°C samples became solid. Therefore, abundant natural desert sand may be considered as a good candidate for sensible heat storage applications. (Diago, Crespo-Iniesta, Delclos & Soum-Glaude 2016.)

Examples

The company *Polar Night Energy* has designed and build the world's first commercial sand-based heat storage. The energy storage system has a heating power of 100 kW and an energy capacity of 8 MWh, and it will provide district heat for Vatajankoski's DH network in Kankaanpää (Finland). The technology is also being tested in a 3 MWh demonstration pilot in Hiedanranta, Tampere (Finland). The pilot is connected to a local district heating network, and it provides heat for a couple of buildings. (Polar Night Energy 2022.)

In Polar Night's energy storage system, surplus from wind and solar power is used to heat air by resistive heating. The hot air is then blown through a network of pipes inside of a sand-filled container heating the sand up to 500°C. When energy is required, cool air is forced through the pipes, and it heats up as it passes through the storage. This heated air can be utilized to convert water into steam for industrial processes or to heat water for district heating purposes in an air-to-water heat exchanger. Electricity can be generated if steam turbines are integrated into the system. (Polar Night Energy 2022.)

Another example of sand-based energy storage is the prototype *ENDURING energy system* (Figure 20) designed by the American National Renewable Energy Laboratory (NREL). ENDURING uses surplus solar or wind power to heat silica sand to 1,200°C by resistive heating. The heated particles are then stored in insulated concrete silos. When energy is required, these hot particles are fed to a pressurized fluidized bed heat exchanger, where a gas is heated and pressurized. This gas powers a gas turbine that converts the energy of the gas to mechanical energy, and a generator converts this mechanical energy into electrical energy. After the system is discharged, the chilled particles are returned to the silos to be stored until the conditions are suiTable for recharging. The system has the capacity to store a maximum of 26,000 MWh of thermal energy. (NREL 2021.)

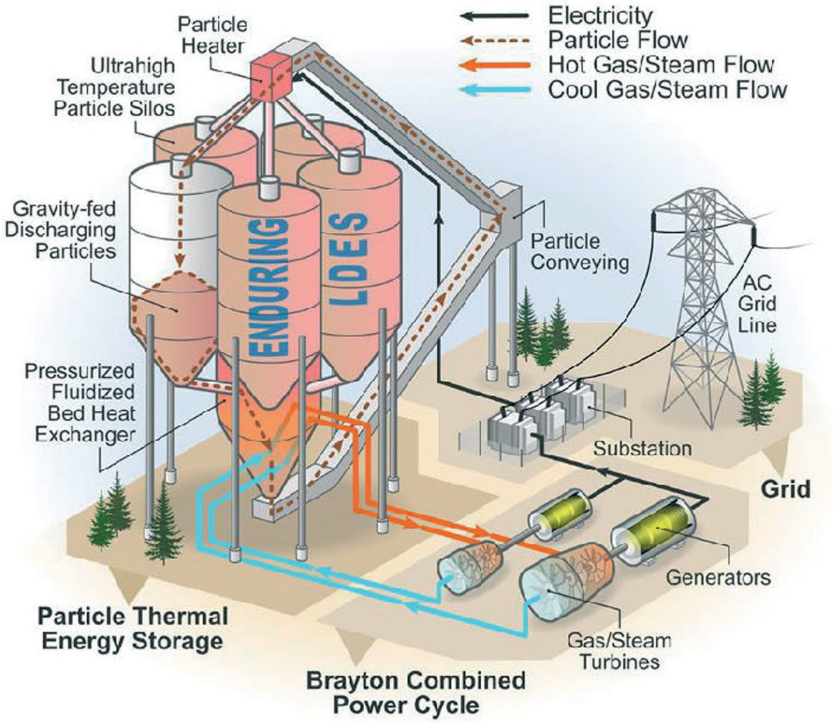


Figure 20. ENDURING energy system designed by NREL (NREL 2021)..

MGTES system by Magaldi Group also uses silica sand as storage medium. This system can use both electricity, through electrical resistors, and heat, through an integrated heat exchanger, to heat the fluidized sand bed to temperatures above 1,000°C. When energy is needed, the heat exchanger is reversed, and thermal energy is released through superheated steam or other high temperature fluids such as CO2 or hot air. When the system is in charging and discharging mode, air is blown through the sand, while the fluidization is switched off during storing phase. Same as Polar Night Energy system, MGTES can be adapted to work in combination with a power-block to generate electricity. (Magaldi Green Energy 2021.)

3.2.4 Rock-based energy storage

Rock-based energy storage system is a sensible thermal energy storage that uses rocks as its storage medium. Figure 21 shows a configuration of this type of sytem. Rocks have potential as thermal storage medium due to their high availability, low cost, non-toxicity and non-flammability. Furthermore, rock-based systems have the advantage of being able to withstand higher temperatures compared to water-based systems, and they experience lower heat losses. However, they have a lower energy density, which means they require larger volumes to store the same amount of heat. (Abdin & Khalilpour 2019.)

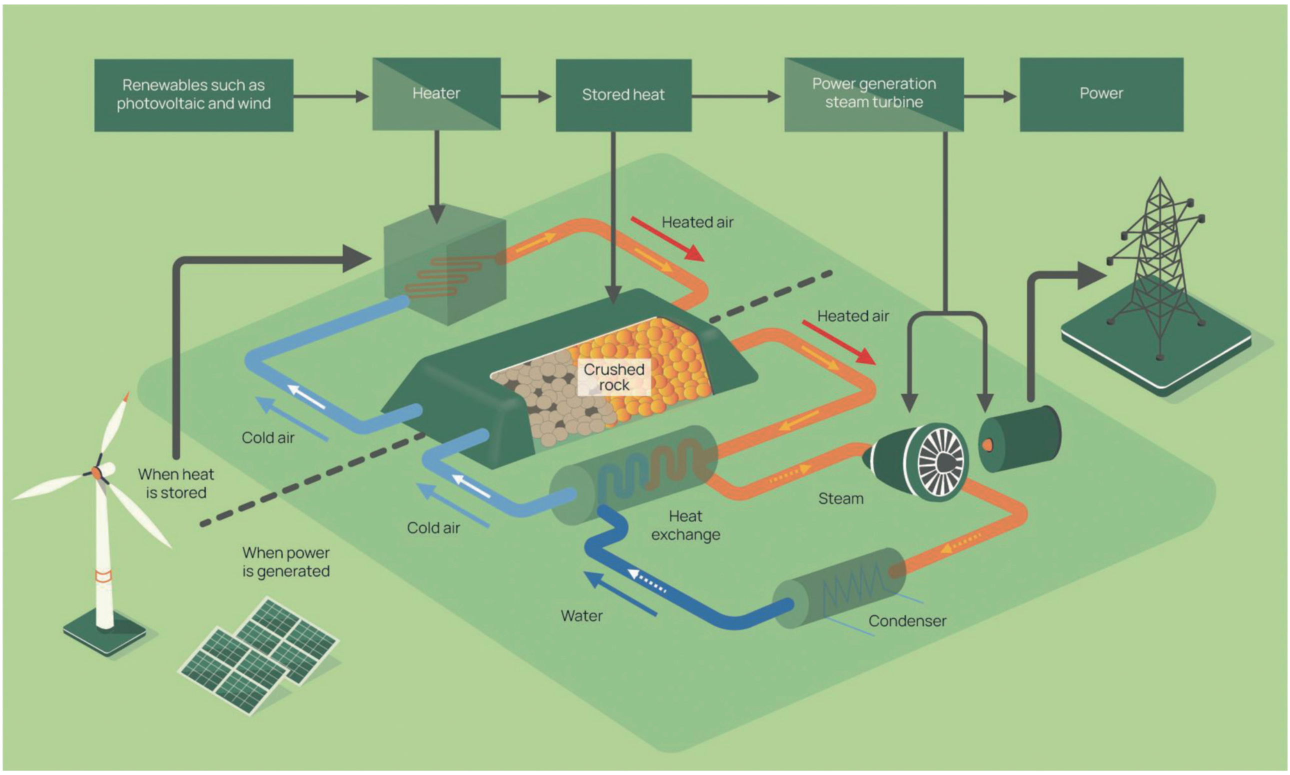


Figure 21. Rock-based energy storage system (Adapted from Inada 2021).

Examples

The SHS system designed by *Siemens Gamesa* uses the same working principle as the previously described sand-based energy storage systems. Low-price electricity is used to heat air via a resistive heater, although direct charge with heat is also possible. Then, heat is stored in the crushed volcanic rocks up to weeks and when needed, heat is converted to electricity through a steam turbine or alternatively, heat and process steam can be use directly. The pilot plant in Hamburg-Altenwerder (Germany) makes use of 1,000 tons of volcanic rocks heated up to 750°C. The system can store up to 130 MWh of thermal energy per week. (Siemens Gamesa 2019.)

Massachusetts Institute of Technology (MIT) is developing a 100 GWh heat storage system for use with concentrated solar power and nuclear reactor systems (Figure 22). An insulated container up to 20 m deep, 60 m wide and 1,000 m long, is filled with crushed rocks. During the charging phase, hot HTF is sprayed over the crushed rocks, and it cools down while it drains through the rocks to the collection pans at the bottom. During the discharging phase, cold HTF is sprayed over the rocks and the hot HTF collected at the bottom of the system is delivered to the power cycle. Heat transfer oils or nitrate salts are used for power systems to 400°C and 600°C, respectively. (Forsberg & Aljefri 2020.)

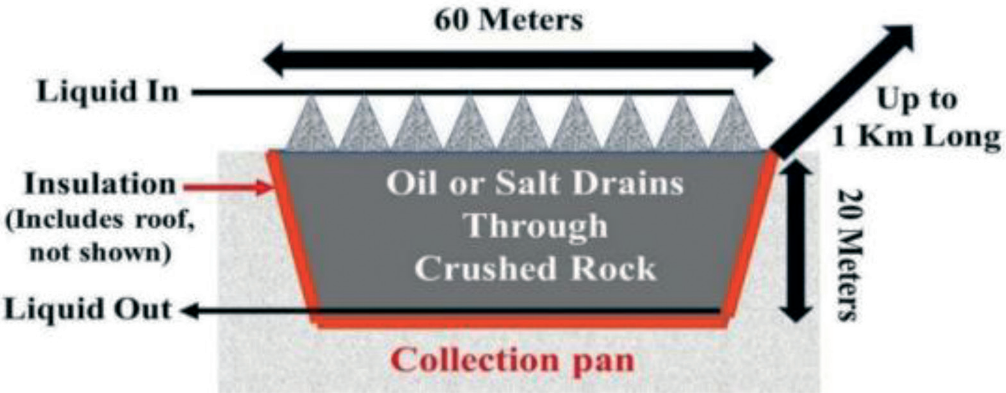


Figure 22. Scheme of rock-based heat storage system by MIT (Forsberg & Aljefri 2020).

Similarly, the Swiss company *Airlight Energy* has developed a thermal energy storage based on a packed bed of rocks with air as working fluid (Figure 23). The energy storage is being tested in Airlight Energy Ait-Baha CSP Pilot Plant (Morocco). In the charging phase, which takes 10 hours, hot air from the solar field flows through the packed bed. In the discharging phase, which lasts 4.5 hours, energy is extracted by pumping air at ambient temperature through the hot packed bed. The nominal charging and discharging temperatures are 570°C and 270°C, respectively. (Zavattoni, Zanganeh, Pedretti & Barbato 2018.)

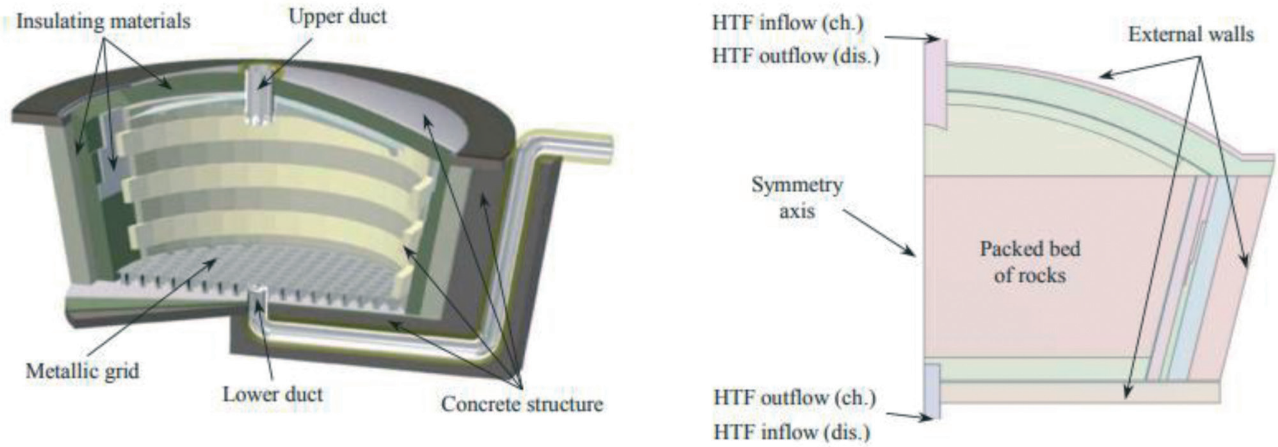


Figure 23. Scheme of Ait-Baha Pilot Plant's TES unit (Zavattoni et al. 2018).

Another example of this type of energy storage is the bGen unit designed by the Israeli company *Brenmiller Energy*. The system is charged electrically or thermally using electrical heaters or gas piping which runs through the storage modules, respectively. The heat is stored in crushed rocks, which are heated up to 750°C. In the discharge phase, water flows through a separated discharging piping cycle, and steam is delivered on demand. (Brenmiller Energy 2022.)

3.2.5 Graphite-based energy storage

Graphite has been recently studied and tested as sensible heat storage medium. The American company *Antora Energy* is developing a thermal energy storage that uses excess solar and wind electricity to heat blocks of graphite by direct resistive heating. The energy is stored in graphite blocks contained within an insulated shell. The system discharges on demand both electricity via thermophotovoltaic (TPV) modules and process heat up to 1,500°C. After the construction and successful operation of a 500-kWh prototype, the construction of a 100-MWh pilot plant will start in 2022. (Ponec 2021.)

3.2.6 Refractory bricks -based energy storage

Refractory bricks or firebricks are a well-known material, since they are indispensable in industrial processes where high temperatures are reached, such as the production of metals, cement, and ceramics. Firebricks present high thermal resistance while having low thermal conductivity. These properties make refractory bricks an interesting option as sensible heat storage medium.

Examples

The American company *Electrified Thermal Solutions* has designed The Joule Hive thermal battery, which generates high-temperature heat from intermittent renewable electricity. The energy storage system consists of a stack of electrically conductive firebricks in an insulated container. Electricity is run directly through the bricks to heat them up to 1,800°C. The bricks can store thermal energy with minimal thermal loss for hours or days. In the discharge phase, air or another gas is run through the stack of bricks providing high-temperature heat for industrial applications. (Electrified Thermal Solutions s.a.)

Another American company using refractory bricks as sensible heat storage medium is *Rondo*. Rondo's energy storage system uses renewable electricity to heat the refractory bricks via electric heaters. This ESS is able to store thermal energy at temperatures up to 1,500°C for hours or days at a time. When the system is discharged, air is blown over the bricks and heated up, and the heat is then delivered as superheated air and/or as superheated steam to industrial processes. (Rondo s.a.)

3.3 Latent heat storage (LHS)

Latent heat storage or phase change thermal energy storage implies the storage of heat in phase change materials (PCMs). PCMs are materials which release or absorb thermal energy when they undergo phase transition. This thermal energy is known as latent heat. The temperature of the PCMs remains almost constant during the phase transition process. Among the different phase transitions, solid-liquid transition is the most practical for heat storage because the volume change is within an accepTable range. Solid-liquid phase change materials can be divided into three categories according to their chemical nature: (Sarbu & Sebarchievici 2018.)

- organic: paraffin compounds and non-paraffin compounds,
- inorganic: salt hydrates and metallics,
- and eutectic: mixture of two or more PCM components, i.e., organic-organic, organic-inorganic, and inorganic-inorganic.

Table 9. Summary of properties of PCMs according to their chemical nature (adapted from Jouhara, ?abnie?ska-Góra, Khordehgah, Ahmad & Lipinski 2020).

Organic	Inorganic	Eutectics
+ No supercooling + Available in wide ranges of temperatures + Thermal and chemical stability + Congruent melting + Noncorrosive - Flammable - Low thermal conductivity - Low energy density - Lower heat of fusion	+ Higher heat of fusion + High thermal conductivity + Low volume change + Easily available + Non-flammable + High storage capacity - Supercooling - Corrosive - No congruent melting	+ Sharp melting point + High storage capacity - High cost - Limited data availability about properties

Jouhara et al. (2020) presented a comprehensive review on latent thermal energy storage technologies and applications. In this review, a few advantages and disadvantages of organic, inorganic, and eutectic phase change materials are listed (Table 9). As can be seen, each group has its own advantages and disadvantages to be considered when selecting a PCM so it meets the requirements of a specific application. Besides those properties, two important factors to take into account in the selection of a suiTable PCM are its melting point and its enthalpy of fusion or heat of fusion.

Figure 24 shows melting points and enthalpies of fusion for different groups of PCMs. The melting temperature defines the application for which the PCM is appropriate. For instance, for medical applications, the required melting temperature may be in the sub-zero temperature range, while for building applications may be in the range 20–30°C and for solar thermal power generation applications may be above 200°C. (Khan, Asfand & Al-Ghamdi 2022.)

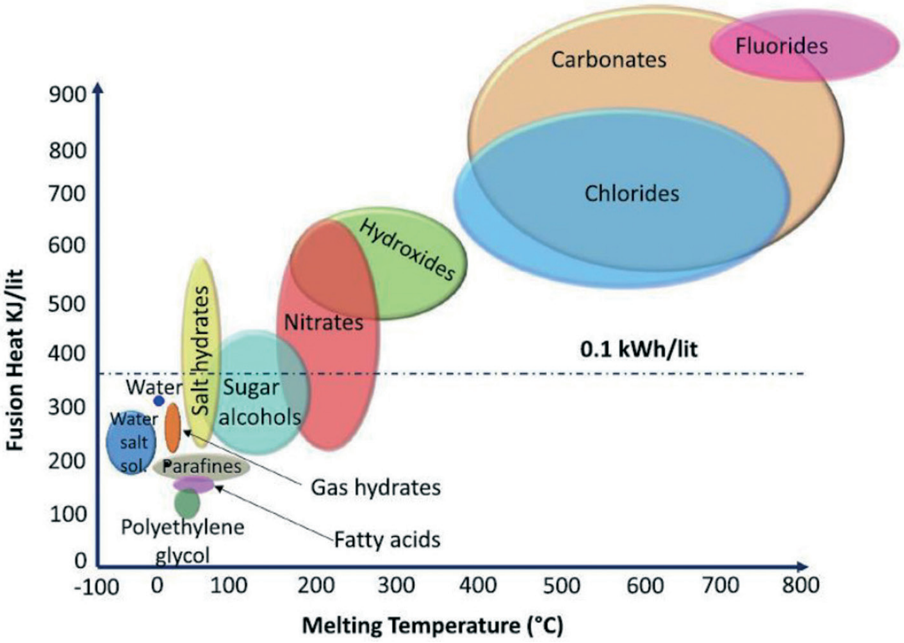


Figure 24. Melting points and heats of fusion for different groups of PCMs (Khan et al. 2022), used under CC BY 4.0.

PCMs have been extensively reviewed in the literature. Several PCMs have been commercially available for a few decades for different thermal applications, e.g., thermal regulation in buildings and cooling applications in different industries. In Table 10 are listed some recently investigated PCMs including water. Interest in PCMs for high-temperature applications such as waste heat recovery or solar thermal power generation has increased in the recent years. Inorganic salts, salt eutectic compounds, metal alloys and metallic eutectics have been studied for these high-temperature applications (Cárdenas & León 2013). Khan et al. (2022) gathered information about thermophysical properties of some inorganic PCMs with potential application in CSP plants in addition to solar salt (Table 11). For a more extensive review on phase change materials for high temperature latent heat thermal energy storage the work by Cárdenas and León (2013) is recommended.

Table 10. Some investigated phase change materials (adapted from Alnaimat & Rashid 2019).

Material	Heat Capacity (kJ/kg·K)	Heat of Fusion (kJ/kg)	Energy Density (MJ/m³)	Melting point (°C)
Water	4.187	335	NA	0
Organic fatty acid	NA	184.8	NA	94.9–99.2
D-mannitol	NA	297	NA	167
$NaNO_3$:KNO_3=60:40 (molar ratios) with 1% CuO	1.68–1.93	122.5–178.87	NA	216–218.21
$NaNO_3$:KNO_3=60:40 (molar ratios), (solar salt)	1.24–1.5	107.03	NA	219
Ternary carbonates	1.22–1.34	247	NA	405
Halotechnics salt stream SS60/40	1.53	120	64.61	565
Aluminium–silicon eutectic	1.04–1.74	470	NA	577
Halotechnics salt stream (SS700)	0.79	87	51.85	700
$MgCl_2$/graphite foam	1.06	374–404	240*	720

* Wh/m2.

Table 11. Thermophysical properties of some inorganic PCM with potential application in CSP plants (Khan et al. 2022).

Compound (wt.%)	Thermal conductivity (W/m·K)	Heat of Fusion (kJ/kg)	Energy density (kJ/m³)	Melting point (°C)	Density* (kg/m³)
KCl-$ZnCl_2$ (68.1:31.9)	0.8	198	491	235	2,480
$LiNO_3$	0.58	360	NA	254	2,380
LiCl-LiOH	1.1	485	752	262	1,550
$ZnCl_2$	0.5	75	218	280	2,907
$NaNO_3$	0.5	199	449	308	2,257
NaOH	0.92	165	346	318	2,100
KNO_3	0.5	116	245	336	2,110
NaCl-KCl (58:42)	0.48	119	248	360	2,084
KOH	0.5	149.7	305	380	2,044
$MgCl_2$-NaCl (38.5:61.5)	-	328	870	435	2,480
Na_2CO_3-Li_2CO_3 (56:44)	2.09	370	858	496	2,320
NaF-MgF_2 (75:25)	1.15	860	2,425	650	2,820
$MgCl_2$	NA	452	967	714	2,320
LiF-CaF_2 (80.5:19.5)	1.70 (liquid)	816	1,950	767	2,390
KCl	11	353	699	771	1,980
NaCl	5	492	1,062	800	2,160
Na_2CO_3	2	275.7	698	854	2,533
K_2CO_3	2	235.8	540	897	2,290

*Solid state.

Further research and development are needed before these materials can be commercially available as PCMs in high-temperature thermal energy storage systems. Jouhara et al. (2020) described different approaches that are under investigation to improve the performance of the PCMs. These include encapsulation and shape stabilization. Encapsulation implies covering limited amounts of PCM with capsules of different geometries that prevent contact of the PCM with its environment. Encapsulation techniques can be classified in macro-, micro- and nanoencapsulation. On the other hand, shape stabilization consists of integrating the PCM into a supporting material, generally porous, which allows the entire system to retain its shape and keep the PCM in place during the melting process. These approaches reduce the risk of leaks and increase the storage capacity and lifetime of the PCM. Another technique that has been studied to enhance the charging and discharging of PCMs is cascaded LHS systems, that use multiple PCM systems at different temperature ranges.

Latent heat storage is a promising technology for long-term energy storage since phase change materials achieve higher energy storage density and lower heat losses compared to sensible heat storage at moderate cost. Nevertheless, LHS technology needs further investigation to be successfully implemented. Table 1 shows a brief comparison between latent heat, sensible heat and thermochemical storage.

Examples

The company *Elstor Oy*, located in Lappeenranta (Finland), has developed a new technology for energy storage that is based on the phase change of molten salt (Figure 25). Solid salt is heated up and melted, storing the energy as latent heat. The energy is discharged as heat or steam when the molten salt solidifies again. The ESS has a storage capacity of 5-15 MWh, charging power of 0.5-2.5 MW electricity and maximum discharge power of 2.0 MW, with an estimated round-trip efficiency of 95%. (Elstor 2022c.)

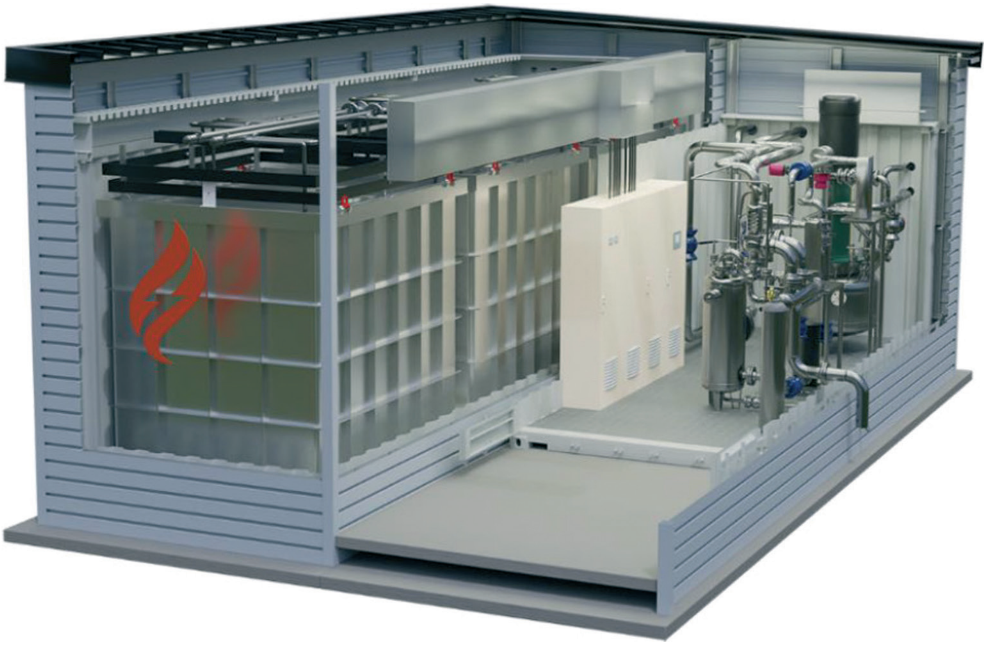


Figure 25. Elstor's thermal energy system (Elstor 2022c).

Elstor's first pilot salt battery was commissioned in 2021 to the district heating network of Mustola, Lappeenranta, and it is expected that it will decrease CO_2 emissions in 300–400 ton CO2e annually if operated continuously (HiilineutraaliSuomi 2022). The first industrial-scale 10 MWh salt battery was installed at the food manufacturer Herkkumaa, where it reduced the carbon footprint of Herkkumaa's production to zero. (Elstor 2022b.) The same technology is currently used at the food company Kaskein Marja, where it produces the industrial steam that the factory requires without the need for natural gas usage. (Elstor 2022a.)

The Swedish company *Azelio* has developed TES.POD, a latent heat storage system that uses an aluminium alloy as PCM. The aluminium alloy is heated up to phase change temperature (almost 600°C) using electricity from renewable sources. The molten alloy stores the thermal heat, which is transferred on demand to a Stirling engine through a heat transfer fluid. The Stirling engine delivers electricity via an electrical generator and heat between 55-65°C. The ESS has a nominal electrical output of 13 kW, a nominal thermal output of 23 kW and a storage capacity of 165 kWhe. (Azelio 2023b.)

Besides continually testing the heat storage in the test facility in Sweden, Azelio has two ongoing demonstration projects; one was inaugurated in 2020 at Ouarzazate Solar Power Station (Morocco) and the other one in 2022 at Khalifa University (Abu Dhabi). Moreover, Azelio has taken a TES.POD system into operation at Haneberg Farm (Sweden), where the system uses solar energy to provide both electricity and heat to dry grain. (Azelio 2023a.)

MGA Thermal company in Australia has invented a new material called Miscibility Gap Alloy (MGA), which is used to make MGA blocks (Figure 26). The blocks consist of tiny metal alloy particles dispersed through a matrix material. When the blocks are heated, the metal particles melt while the matrix material remains solid. The energy is stored as latent heat and it is released as the blocks cool and the particles become solid again, delivering high temperature heat or electricity. MGA Thermal is planning to construct a 5 MWh demonstration-scale thermal energy storage system for 2023. (MGA Thermal s.a.; MGA Thermal 2020.)

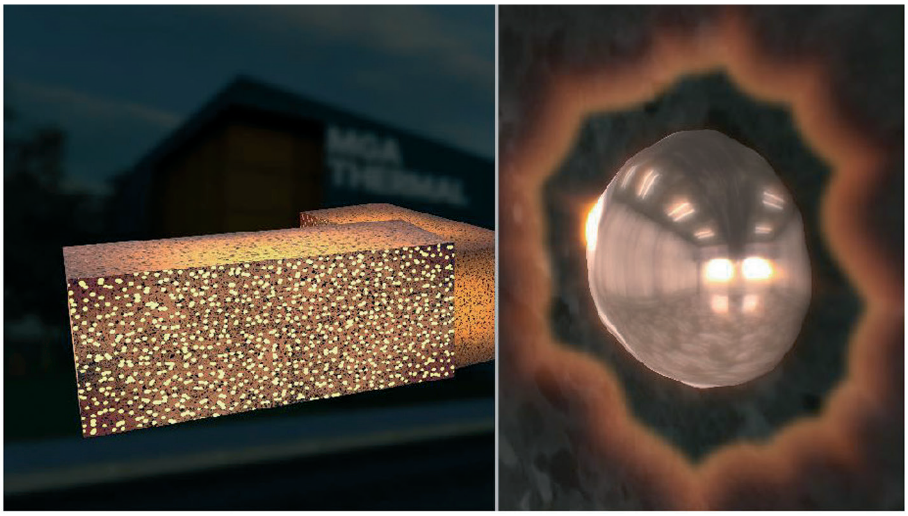


Figure 26. MGA Thermal's blocks (Picture courtesy of MGA Thermal).

The Australian company *1414 Degrees* has developed a silicon-based latent heat energy storage. The silicon alloy is heated via resistive heating until it melts, storing energy as latent heat at high temperatures above at 1,000°C. During the discharge phase, air is blown through the system and that hot air can be used directly in industrial processes or for power generation through turbines. 1414 Degrees has already built a 1 MWh thermal storage device to test its performance. At the same time, the company is doing engineering feasibility studies for alumina and cement industries as well as continual R&D for product improvement. (Venkataraman 2023.) Another example of silicon-based latent heat storage is the system being developed by the Spanish company *Silbat*. The ESS stores thermal energy and provides electricity on demand using thermophotovoltaics (TPV). (Silbat 2023.)

Several companies have been independently working on harnessing the phase change from liquid water to ice to store thermal energy and later use it, for example, for industrial cooling or air-conditioning. One of these companies is the German firm *BEKA* that has developed the sp.ICE technology. sp.ICE comprises specially arranged capillary tubes installed in a container or underground as a basin below the surface. Similarly, the American company *CALMAC* has designed IceBank, a seamless one-piece tank that contains the heat exchanger tubes. In both cases, a cooling medium is supplied to the thermal tanks where the water is contained. When electricity is cheap, it is used for freezing the water in the tanks and when there is need for cooling the ice is melted. (BEKA s.a; Trane 2020.)

Another example is the Israeli company *Nostromo Energy*, developer of IceBrick. In this case, the water is contained in plate-shaped or box-shaped capsules. Stacks of these capsules with water are arranged inside tubes like the one shown in Figure 27.

Ice is created during off-peak hours and later used to cool the building's circulating water while it passes through the IceBrick system. (Nostromo s.a.)

Figure 27. Nostromo's IceBrick (Nostromo s.a.).

3.4 Thermochemical energy storage (TCES)

Thermochemical energy storage is based on a reversible endothermic/exothermic reaction ($\mathrm{C+heat \leftrightarrows A+B}$ 1) (1) between reactants and products. In the charging process, energy is supplied to decompose the reactant C into the products A and B, which are then store separately with negligible thermal losses. When energy is needed, A and B react together forming the compound C and releasing the stored energy. (Sarbu & Sebarchievici 2018.)

$$\mathrm{C+heat \leftrightarrows A+B} \tag{1}$$

Thermochemical energy storage is commonly divided in the literature into two different groups based on the mechanism to store the energy: sorption processes (i.e., adsorption and absorption) and chemical reactions without sorption. Sorption is the phenomenon in which a substance, called sorbate, is sorbed (adsorbed or absorbed) on or in another substance, called sorbent. In adsorption the adsorbate adheres on the surface of the adsorbent, while in absorption the absorbate penetrates into the absorbent. On the other hand, chemical reactions without sorption imply a change in the molecular configuration of the compound involved. Sorption processes are commonly used for low- or medium-temperature applications, while chemical reactions are used for high temperature. (Abedin & Rosen 2011; IUPAC 2019.)

Table 1 shows a brief comparison between latent heat, sensible heat and thermochemical energy storage. The main advantages of using TCES systems compared to other TES systems are their high energy storage density as well as the possibility of long-term energy storage without significant losses. Additionally, TCES system are able to operate in a wide range of temperatures and pressures. On the other hand, TCES systems involve complex processes and high initial costs. (Abedin & Rosen 2011; Alnaimat & Rashid 2019.)

TCES systems are currently under research and development. One of the main targets of the R&D is to study the potential of TCES coupled with concentrated solar power for continuous production of the CSP plant. In the paper by Bayon et al. (2018) 17 thermochemical energy storage systems were studied, among which 8 were identified as competitive with molten salts systems in CSP. The properties of the materials studied in this work are presented in Table 12. In Table 13 some metal hydrides candidates for TCES systems in CSP plants are listed.

Table 12. Some materials and their properties for TCES systems in CSP plants (adapted from Bayon et al. 2018).

Thermochemical material	Operating temperatures (°C)		Volumetric energy storage density (MJ/m3)	Thermal efficiency (%)	Reaction enthalpy (kJ/mol)
	Charging	Discharging			
Alkaline Hydroxides					
$Ca(OH)_2/CaO$	700	505	101.97	98.51	109.2
$Sr(OH)_2/SrO$	600	525	97.09	97.56	NA
$Ba(OH)_2/BaO$	700	520	77.61	96.50	103.7
Alkaline Carbonates					
$CaCO_3/CaO$	989	650	39.01	51.30	178.2
$SrCO_3/SrO$	1,200	1,150	51.32	58.53	241.5
$BaCO_3/BaO$	1,400	1,300	47.76	57.47	272.5
$MgCO_3/MgO$	900	550	19.12	33.06	100.7
$La_2O_2CO_3/La_2O_3$	980	550	39.39	59.77	NA
$MgCO3\cdot CaCO_3$ (Dolomite)	930	600	8.05	17.52	306.2
Metal Oxides					
Co_3O_4/CoO	905	885	102.45	97.14	NA
Mn_2O_3/Mn_3O_4	989	650	32.69	91.76	NA
BaO_2/BaO	980	690	46.09	95.00	86.3
CuO/Cu_2O	1,100	900	113.43	97.88	404.7
Chemical Looping Combustion					
Fe_3O_4/FeO	1,100	900	175.54	98.48	NA
NiO/Ni	950	950	308.32	99.50	NA
CoO/Co	800	850	304.33	99.50	NA
Mn_3O_4/MnO	800	950	137.19	98.15	NA

Table 13. Some metal hydrides for TCES systems in CSP plants (Carrillo, González-Aguilar, Romero and Coronado 2019).

Reaction	Temperature (°C)	Energy storage density (kJ/kg)
$Mg_2NiH_4 \leftrightarrows Mg_2Ni_3 + 2H_2$	250-400	1,158
$MgH_2 \leftrightarrows Mg + H_2$	300-400	2,811
$Mg_2FeH_6 \leftrightarrows 2Mg + Fe + 3H_2$	350-550	2,096
$NaMgH_3 \leftrightarrows NaH + Mg + H_2$	430-585	1,721
$NaMgH_2F \leftrightarrows NaH + Mg + H_2$	510-605	1,416
$TiH_{1.7} \leftrightarrows Ti + 0.85H_2$	700-1,000	2,842
$CaH_2 \leftrightarrows Ca + H_2$	> 1,000	4,934
$LiH \leftrightarrows Li + 0.5H_2$	> 850	8,397

One of the most promising technologies for thermochemical energy storage in CSP plants is the number 4 in Table 12, i.e., Calcium-Looping (CaL) (Figure 28). In the last years several investigations have been published on this topic, for instance, the papers by Ortiz et al. (2019), Ortiz et al. (2020), and Medina-Carrasco and Valverde (2022). CaL is based on the reversible calcination–carbonation reaction of calcium carbonate ($CaCO_3$) and calcium oxide (CaO) (reaction 2). In CSP plants, direct solar radiation is used for the endothermic calcination of $CaCO_3$, that releases CO_2 and CaO as products. The products are stored separately and when energy is needed, they are brought together and the carbonation of CaO takes place. This process is exothermic; thus, the stored energy is released. (Medina-Carrasco & Valverde 2022.)

$$CaCO_3 \leftrightarrows CaO + CO_2 \qquad \Delta H = -178.2 \text{ kJ/mol} \tag{2}$$

Calcium-looping has been widely explored due to its high efficiency and low cost as a method of capturing and storing CO_2 (CCS) emitted by fossil fuel power plants. The key factors for the feasibility of CaL process are the low cost, wide availability, and nontoxicity of calcium oxide precursors such as limestone and dolomite. However, in order for CaL technology to be implemented as energy storage in CSP plants, further research is required in some areas such as solar calciner technology (nowadays only experimental solar calciners are available) and enhancement of the cyclic stability of calcium-based materials. (Ortiz et al. 2020; Medina-Carrasco & Valverde 2022.)

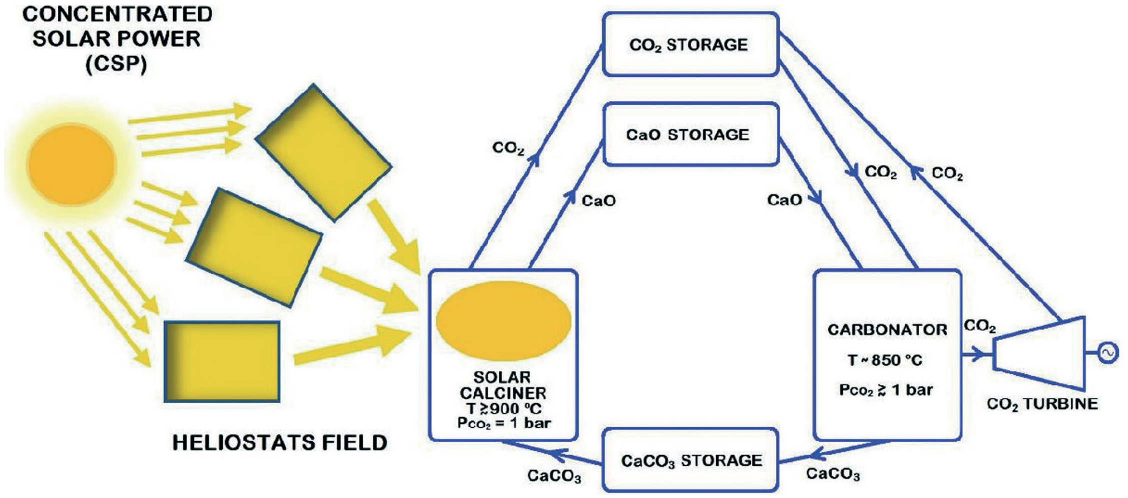


Figure 28. Calcium-Looping coupled with CSP (Medina-Carrasco & Valverde 2022), used under CC BY 4.0 .

Another technology included in the investigation by Bayon et al. and that has been investigated in several studies due to its potential for thermochemical energy storage is the dehydration of calcium hydroxide (reaction 3). Calcium hydroxide ($Ca(OH_2)$) decomposes to calcium oxide (CaO) and water vapour when heat is supplied. In the last decades, multiple studies have described different techniques to enhance the performance of $Ca(OH)_2/CaO$ materials for TCES. These techniques are focused on improving their thermodynamic, kinetic, and structural stability. These methods, which are reviewed in the publication by Feng et al. (2023), include doping modifications, composite powders, surface coating and supporting frames for powder materials, and composite granules, surface coatings, binder matrices and macro-encapsulation for granulated materials. (Feng, Li, Wu, Li, Zhang & Yang 2023.)

$$Ca(OH)_2 \leftrightarrows CaO + H_2O \qquad \Delta H = -109.2\ kJ/mol \tag{3}$$

In Table 14 are gathered other thermochemical materials that have received attention lately but are not included in the study by Bayon et al. because are meant for medium- or low-temperature applications. The most common chemistry investigated for low-temperature applications, such as space heating and domestic hot water, is the hydration/dehydration of salt hydrates (reaction 4). Other chemistries for medium- and low-temperature applications include, for instance, the deammoniation of ammoniate salts (reaction 5) and the dehydration of some metal hydroxides (reaction 6).

$$Salt{\cdot}(m+n)\ H_2O + heat \leftrightarrows Salt{\cdot}nH_2O + mH_2O \tag{4}$$

$$Salt{\cdot}(m+n)\ NH_2 + heat \leftrightarrows Salt{\cdot}nNH_2 + mNH_2 \tag{5}$$

$$Me_aOH)_b + heat \leftrightarrows Me_aO_{b/2} + H_2O \tag{6}$$

Despite the extensive research performed in the last decades regarding TCES materials, the design of the thermochemical energy storage system itself, and more specifically the reactor, has received less attention. The reactor is the most complex and important unit of the ESS, and it requires further research and development on its design before commercial implementation. In the recent years there has been an increasing interest and significant progress in this field, and several companies and research organizations are working on commercializing the technology.

In the literature, TCES reactions are categorized into solid–gas, liquid–gas, and gas–gas reactions, with regard to the nature of the reactants and products. Among the TCES reactors studied in the published investigations, a large majority are deployed for solid–gas reactions (reaction 7) due to their higher chemical reaction efficiencies. Solid–gas reactions can be classified depending on the composition of the solid reactant, including those based on hydrates, hydrides, hydroxides, carbonates, and oxides. (Kur, Darkwa, Calautit, Boukhanouf & Worall 2023.)

$$C_{(s)} + heat \leftrightarrows A_{(s)} + B_{(g)} \tag{7}$$

Table 14. Some TCES materials and their properties for low- and medium temperature applications (adapted from Abedin & Rosen (2011), Solé, Martorell and Cabeza (2015) and Liu et al. (2021)).

Thermochemical reaction	Theoretical energy storage density(GJ/m3)	Temperature (charging/ discharging) (°C)
$MgSO_4 \cdot 7H_2O \leftrightarrows MgSO_4 \cdot H_2O + 6H_2O$	2.3	150/105
$MgSO_4 \cdot 7H_2O \leftrightarrows MgSO_4 + 7H_2O$	1.5	122-150/122
$MgSO_4 \cdot 6H_2O \leftrightarrows MgSO_4 \cdot H_2O + 5H_2O$	2.37	72/NA
$MgCl_2 \cdot 6H_2O \leftrightarrows MgCl_2 \cdot H_2O + 5H_2O$	2.5	150/30-50
$MgCl_2 \cdot 4H_2O \leftrightarrows MgCl_2 \cdot 2H_2O + 2H_2O$	1.27	118/NA
$CaCl_2 \cdot 6H_2O \leftrightarrows CaCl_2 + 6H_2O$	2.82	80-100
$CaCl_2 \cdot 2H_2O \leftrightarrows CaCl_2 + 2H_2O$	1.1	95
$Al_2(SO_4)_3 \cdot 6H_2O \leftrightarrows Al_2(SO_4)_3 + 6H_2O$	1.9	150
$CaSO_4 \cdot 2H_2O \leftrightarrows CaSO_4 + 2H_2O$	1.4	NA/89
$Na_2S \cdot 5H_2O \leftrightarrows Na_2S + 5H_2O$	2.8	110
$Na_2S \cdot 5H_2O \leftrightarrows Na_2S \cdot 1/2H_2O + 9/2H_2O$	2.7	80/65
$SrBr_2 \cdot 6H_2O \leftrightarrows SrBr_2 \cdot H_2O + 5H_2O$	2.3	NA/23.5
$Li_2SO_4 \cdot H_2O \leftrightarrows Li_2SO_4 + H_2O$	0.92	103/NA
$CuSO_4 \cdot 5H_2O \leftrightarrows CuSO_4 \cdot H_2O + 4H_2O$	2.07	92/NA
$K_2CO_3 \cdot 1.5H_2O \leftrightarrows K_2CO_3 + 1.5H_2O$	1.29	<120
$Mg(OH)_2 \leftrightarrows MgO + H_2O$	1,333*	265
$Be(OH)_2 \leftrightarrows BeO + H_2O$	1,191*	70
$Mn(OH)_2 \leftrightarrows MnO + H_2O$	754*	190
$Fe(OH)_2 \leftrightarrows FeO + H_2O$	2.2	150
$FeCO_3 \leftrightarrows FeO + CO_2$	2.6	180
Salt·(m+n)NH3 ⇆ Salt·nNH3 + mNH3	253–2,900*	< 200

* kJ/kg

Table 15. Types of solid-gas TCES reactors (adapted from Solé et al. (2015), Carrillo et al. (2019) and Kur et al. (2023)).

	Fixed bed	Fluidized bed	Moving bed
Bed type	Solid particles are arranged into a fixed or packed bed	Fine solid particles are maintained in suspension in a fluidized bed	Solid particles are continuously moved through the reactor chamber
Particle size (mm)	> 2	< 1	Wide range
Types	- Direct contact - Indirect contact		- Shell and tubes - Rotary kiln - Screw extruder
Disadvantages	Low heat and mass transfer High-pressure drops	Complex hydrodynamics and modelling Internal component erosion	Complex hydrodynamics
Advantages	Easier modelling	Minimization of hotspots and thermal instability' High heat transfer coefficients	Direct solid–gas heat transfer

Generally, solid-gas TCES reactors can be divided into fixed-bed, fluidized bed and moving bed reactors. Table 15 shows the main advantages and disadvantages of these three types of reactors, which should be considered together with the specific requirements of the application when selecting a suiTable reactor. According to the literature, several prototypes are being designed and tested, with fixed bed being the most common (Solé et al. 2015).

Reactors can be working within a closed or an open system. In closed systems the reactant gas (i.e., working fluid) circulates in a closed loop and it is stored within the system, while in open systems, the working fluid is released into the ambient air. In closed systems heat exchangers and storage are needed.

In the design of a thermochemical storage reactor several important factors must be taken into consideration to ensure its efficiency, safety, and practicality. Some of these factors include:

- Thermochemical reaction: The reactor's design, reactor's configuration (fixed bed, fluidized bed, moving bed or other configuration) and reactor's material depends on the specific thermochemical reaction that will be taking place within it. The type of reactants and the products formed, as well as the reaction temperature and pressure, will all affect the reactor's design and material. The material should be able to withstand high temperatures and corrosive environments and should not react with the reactants or products.

- Heat transfer: The reactor design should allow efficient heat transfer between the reactants and the storage medium for both the charging and discharging phases. This could involve designing the reactor with a specific geometry, using mechanisms such as internal heat exchangers, fins, or other heat transfer enhancement techniques to improve heat exchange.

- Mass transfer: The design should also allow efficient mass transfer between the reactants and the storage medium. This could involve designing the reactor with a specific geometry, using a specific surface area or incorporating mixing devices to enhance mass transfer.

- Thermal insulation: The reactor should be designed to minimize heat losses and maintain the desired operating temperature. This could involve incorporating thermal insulation materials or designing the reactor with multiple layers.

- Safety considerations: The design should also take into account safety considerations, such as the potential for explosive reactions, the release of toxic gases, and the potential for thermal runaway reactions. Appropriate safety features like pressure relief systems, containment strategies, and emergency shutdown procedures should be incorporated.

- Environmental considerations: Additionally, the environmental impact of the reactor should be carefully assessed and minimized. This includes evaluating the emission of greenhouse gases, air pollutants, or any other potentially harmful byproducts.

- Scalability and costs: The reactor's design should consider scalability to meet the desired energy storage capacity. The cost of materials, fabrication, maintenance, and operation as well as energy efficiency should be evaluated to ensure the economic viability of the system.

- Integration with the energy system: The design should take into account the compatibility with the existing infrastructure and potential integration with other renewable energy sources, storage technologies, or power generation systems.

- Process control: Finally, the design should incorporate appropriate process control measures to ensure that the reactor operates safely and efficiently. This should involve incorporating sensors and controls to monitor and adjust key parameters such as temperature, pressure, and flow rates.

For more detailed information about TCES reactors and materials, there are available few articles on the topic including the papers by Solé et al. (2015), Carrillo et al. (2019), André and Abanades (2020), Gbenou, Fopah-Lele and Wang (2021), and Kur et al. (2023).

Examples

TCES systems are not commercially available but are undergoing investigation and pilot project tests. One example of this is the thermochemical storage system that is being developed by the Swedish energy-storage pioneer *SaltX Technology*. The ESS is based on the chemical reaction 3. To charge the system up nanocoated calcium hydroxide ($Ca(OH)_2$) is heated at about 500°C using electricity from renewable sources, solar heat, waste heat or gas. This causes the dehydration of $Ca(OH)_2$, and therefore the formation of quicklime or calcium oxide (CaO) and steam. The charged salt is stored at room temperature. When energy is needed, water is added to the calcium oxide which transforms back to calcium hydroxide releasing the stored chemical energy as heat up to 450°C. (SaltX Technology 2021.)

In 2022 a pilot plant was commissioned in Bollmora (Sweden), and it features a charging reactor from Calix (Australia) and a fluidized bed reactor from Sumitomo SHI FW (Finland) as the discharge reactor. Figure 29 shows the working principle of SaltX thermochemical energy storage. The patented nanocoating makes the material non-corrosive and makes possible to charge and discharge the energy many times, creating a system with a long lifetime.

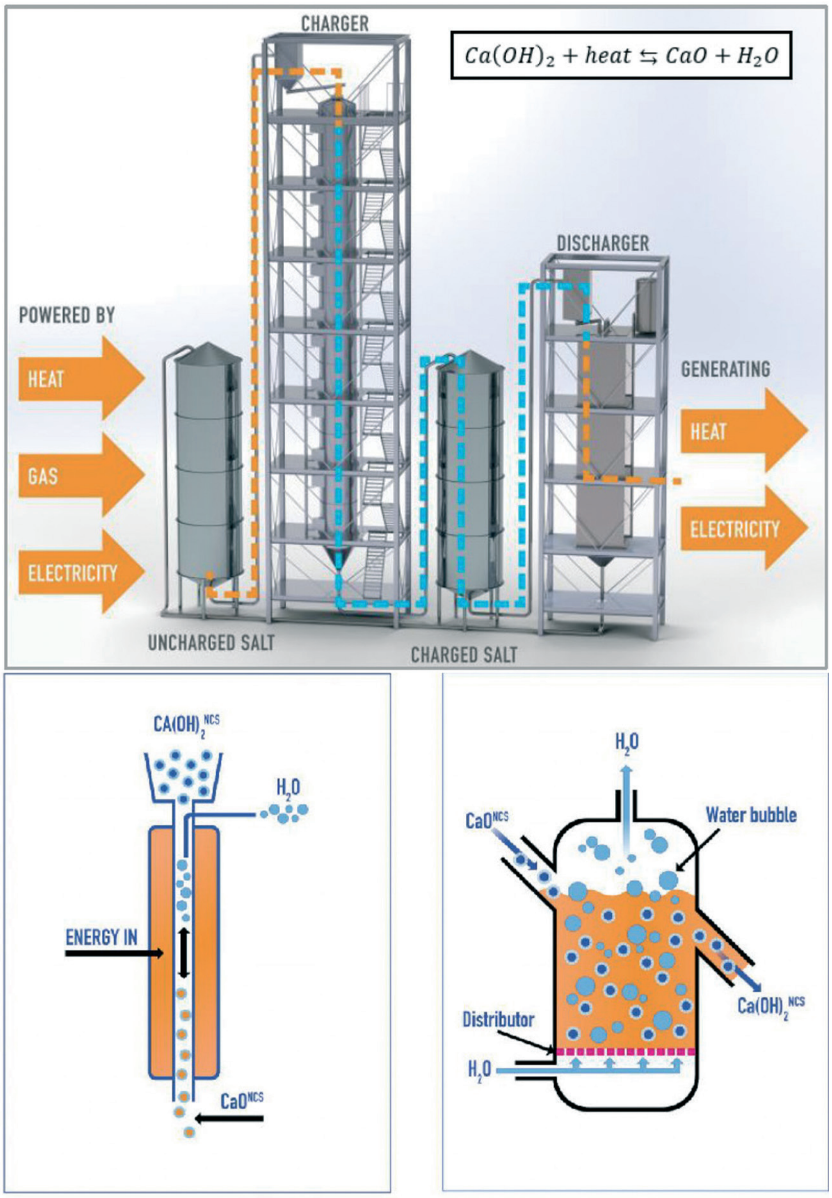


Figure 29. SaltX thermochemical energy storage (Picture courtesy of SaltX Technology).

The same chemical reaction (3) will be tested at the *Energy Research Centre of Savonia University of Applied Sciences* located in Varkaus. The Research Centre features industrial furnaces where the dehydration of $Ca(OH)_2$ will be carried out and will be investigated. In this same *Research Centre in Varkaus*, and within the project Heat Circulation Innovation Platform, a reactor has been designed and built to test the reaction (8) between sodium (Na) and chlorine (Cl_2) for thermochemical heat storage. The installation of the reactor will take place during the spring of 2023 and testing will start as soon as it is ready, and the health and safety plan is defined. The reactor (Figure 30) is air cooled and the released energy will be determined by measuring the temperature difference of cooling air.

$$2NaCl \leftrightarrows 2Na+?Cl_2 \qquad \Delta H= -410.9\ kJ/mol \tag{8}$$

Figure 30. Savonia's thermochemical energy storage reactor (Image: Markku Huhtinen).

Another example of TCES is the thermochemical battery based on metal hybrids developed by the Swedish company *TEXEL*. In the charging phase, the battery is charged with sustainable heat, and the hydrogen is released from the metal hydride. The hydrogen is then stored at ambient conditions. When energy is needed, the stored hydrogen is forced back to the side of the battery where the metal is, and thermal energy is released as the metal hydrides are reformed. The system combines the thermochemical battery itself with a Stirling converter that converts the thermal energy to electrical energy. The same company has started the development of another TCES based on metal carbonates. The working principle of this system is similar as the metal hydride system's, but it uses carbon dioxide as its working gas instead of hydrogen. (TEXEL 2022.)

The *Cellcius heat battery* is another example of TCES developed by TNO, a Dutch independent research organization. This energy storage system uses a salt composite, with potassium carbonate (K2CO3) as the base material, as the storage material. During charging, the salt is dehydrated using sustainable heat and is then stored until energy is needed. During discharging, the salt hydrate is rehydrated using water, releasing the stored thermal energy. This generated energy can be used for space heating or domestic water heating. This technology has been tested in several pilot projects in the Netherlands and other countries and has received international recognition for its innovative design and potential for commercialization. (TNO 2022.)

The *Redox heat battery* is another type of thermochemical energy storage system developed by TNO. In this case, the heat battery uses a redox pair (i.e., a pair of chemicals that can undergo oxidation and reduction reactions) as the storage material. The redox pair used in the battery consists of two metal solutions. During the discharge process, the metal core is oxidized using air and the heat released is used for domestic hot water and space heating. During the charge process, the core is regenerated by supplying hydrogen produced by renewable electricity. The Redox heat battery is still in the development phase and has not yet been tested in large-scale pilot projects. (SCORES s.a.)

4 MECHANICAL ENERGY STORAGE SYSTEMS

Mechanical energy storage systems store potential or kinetic energy for future use. At present, pumped hydro storage (PHS) stands as the prevailing technology for large-scale mechanical energy storage. Alternative well-known mechanical energy storage technologies include flywheels and compressed air energy storage (CAES). There are also novel mechanical energy storage systems that are at development stage, such as liquid air energy storage (LAES), pumped heat energy storage (PHES) and gravity-based energy storage (GES). (DOE 2021b.)

4.1 Pumped hydro storage (PHS)

Pumped hydro storage is the world's largest energy storage technology, accounting for over 94% of installed global energy storage capacity (Department Of Energy of USA 2022). A PHS facility features two reservoirs at different altitudes that are connected with a combination of aqueducts, pipes and tunnels. In the charging phase, water is pumped from the lower to the upper reservoir using surplus from renewable sources or the grid. In the discharging phase, water is released and flows from the upper to the lower reservoir through a turbine that is connected to a generator to produce electricity.

In conventional or open-loop PHS, the facility is continuously connected to a naturally flowing water source. Despite being a mature technology and being widely deployed, new versions of this established technology are emerging to overcome its disadvantages. Conventional PHS drawbacks include dependence on geographical conditions, environmental impacts, and high investment costs. The International Forum on Pumped Storage Hydropower (IFPSH) has gathered information about new approaches for PHS, dividing them into three categories: furthering PHS potential, retrofitting and upgrading PHS systems, and developing hybrid systems. (IFPSH 2021.)

According to Vuorenmaa, Mahmoodi, Lindblom, Värä and Sierakowski (2020), the use of pumped hydro storage in Finland faces difficulties due to geographical limitations. PHS relies on a sufficiently large difference in elevation between lower and higher reservoirs, which is challenging to find in Finland. However, experts from the design and engineering company AFRY believe that repurposing decommissioned mines for PHS plants holds potential. In section 4.1.2., the case of Pyhäsalmi mine is briefly discussed.

4.1.1 Furthering PHS potential

4.1.1.1 Off-river PHS

Off-river or closed-loop pumped hydro storage differs from the above-mentioned conventional PHS in that it does not require being near a river (Figure 31). Thus, off-river PHS requires lower amount of water and has minimal impacts on natural water flows. A comprehensive worldwide online atlas for off-river PSH has identified approximately 616,000 potential locations of storage, offering a combined storage capacity of 23,000 TWh. (IFPSH 2021.)

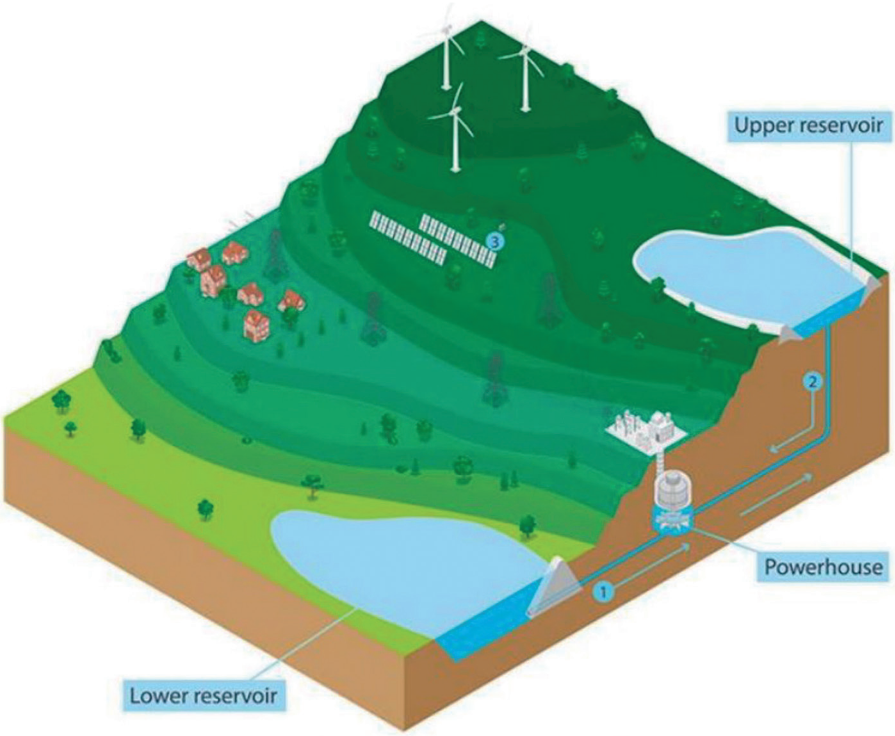


Figure 31. Off-river pumped hydro storage (IFPSH 2021) (Picture courtesy of The International Hydropower Association).

An example of this technology, which is also an example of retrofitting, is the *Snowy 2.0 project*, a 2 GW / 350 GWh system that is currently under construction in the Kosciuszko National Park in Australia. Two reservoirs will be connected with about 27 kilometres of tunnels and the power station complex will be located 800 metres underground and equipped with six Francis turbines. The project is expected to be completed by 2026. (Snowy Hydro 2020.)

4.1.1.2 Geomechanical PHS

Geomechanical PHS uses the same principles as aboveground PHS, but with subsurface water reservoirs. Water is pumped down the well into high-pressure storage lens during the charging phase, after which the well is closed. When electricity is needed, the well is opened, and high-pressure water flows up the well to drive a turbine and generate electricity. (IFPSH 2021.)

Geomechanical PHS is scalable, safe, and cost-effective, and it overcomes the siting constraints of conventional pumped hydro energy storage. However, geomechanical PHS needs a specific pressure profile to function effectively and impermeable rock layers both above and below the storage area to prevent any leakage.

Quidnet Energy pioneered this novel form of pumped hydro (Figure 32). The company promises a round-trip efficiency of 65-75% and a modularity of 1-10 MW per well for this ESS. (Quidnet Energy s.a.; IFPSH 2021.)

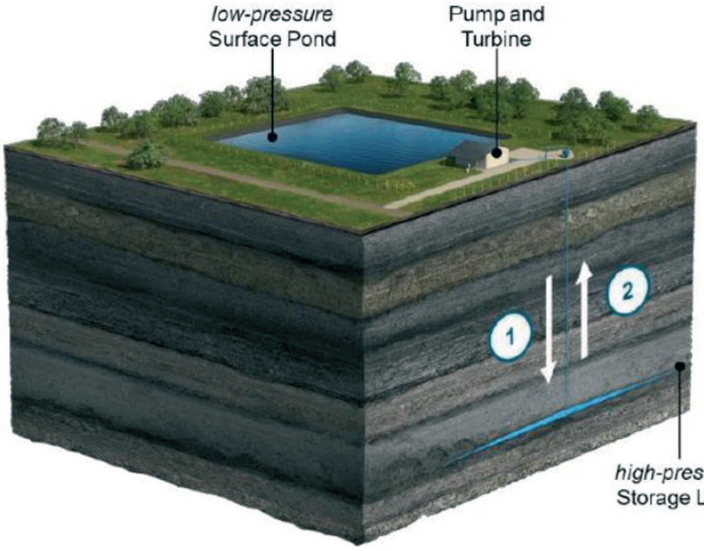


Figure 32. Geomechanical PHS by Quidnet Energy: 1. Charge, 2. Discharge (IFPSH 2021) (Picture courtesy of The International Hydropower Association).

4.1.1.3 Seawater PHS

Seawater pumped hydro storage (SPHS) is situated at sites near the cost using the sea as the lower reservoir. The setup and the characteristics of a SPHS plant are the same as in a conventional pumped hydro storage plant. However, saltwater might cause problems and challenges that have to be addressed and solved sustainably. (IFPSH 2021.)

Okinawa Yanbaru was the first PHS plant using seawater, with a maximum output of 31 MW. It was in operation from 1999 to 2016, when it was dismantled because it was not profiTable since the electrical power demand did not grow as expected. Another example of this technology is *Hidrocaleras*, a pilot project planned to be implemented in the region of Cantabria, Spain. The project involves the construction of a scalable pumped hydro storage facility that utilizes seawater. The PHS plant will be equipped with 49 MW turbines. The distance between the upper reservoir and the sea is 1,200 m and the gross head is 250 m. The system will provide 490 MWh of energy storage, which means a discharge time of 10 hours. (Rozas-Labrador 2021.)

4.1.1.4 Underground PHS

Underground pumped hydro energy storage (UPHS) is an adaptation of conventional PHS that uses an underground structure as a lower reservoir, so the upper reservoir may be located on flat land. Abandoned mines, underground caverns, and artificially created storage reservoirs are being considered as possible reservoir options, but no project has been constructed yet. The obstacles in development are due to concerns related to geotechnical and cost uncertainty. Compared to conventional PHS, underground PHS facilities require less land and can be located closer to the load centres, but it requires strong homogeneous bedrock close to the ground surface. (IFPSH 2021.)

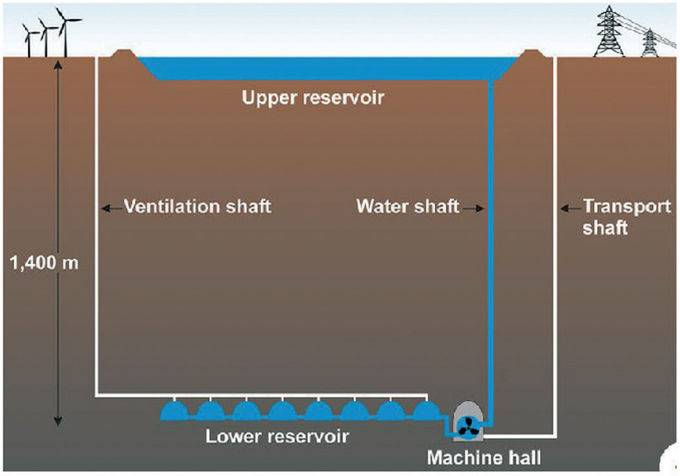


Figure 33. O-PAC storage system (O-PAC 2022).

An example of this technology is O-PAC (Figure 33), in Netherlands. O-PAC will construct a 1,400 MW system that will provide 8.4 GWh of energy storage capacity, which means 6 hours of discharge time at maximum output. The 400 m long, 400 m wide and 16 m deep upper reservoir will be connected to the lower reservoir located 1,400 m underground. (O-PAC 2022.)

4.1.1.5 High-density hydro

High-Density Hydro system designed by the British company *RheEnergise* is based on conventional PHS, but with the innovation of using a fluid that is 2.5 times denser than water. Therefore, RheEnergise's system requires smaller reservoirs and smaller height difference between lower and higher reservoirs compared to a system using water for the same power. Both storage tanks are buried and connected by underground penstocks. RheEnergise promises systems of 10 MW to 50 MW power and 2 to 16 hours of storage capacity. The company plans to deploy a demonstration plant by 2024. (RheEnergise 2021.)

4.1.2 Retrofitting and upgrading

Retrofitting refers to create a new pumped hydro storage facility using existing infrastructures instead of building new ones. Upgrading, on the other hand, refers to add energy generation capacity to existing hydropower plants through refurbishments and upgrades. Retrofitting and upgrading existing infrastructure could often be more cost-effective, environmentally friendly, and less risky compared to developing new projects. Examples of these are given in the IFPSH's report and include using existing open pit mines as reservoirs in PHS, retrofitting existing hydropower and dam facilities into PHS, and utilising abandoned underground mines as lower reservoirs in PHS, among others. (IFPSH 2021.)

According to Vuorenmaa et al. (2020), as Finland is one of the most developed countries in mining field of Europe, there is a potential to use decommissioned mines for different energy storage technologies, being pumped hydro one of them. In Pyhajärvi (Finland), the feasibility of a pumped hydro energy storage located in *Pyhäsalmi mine* will be studied. The system would use an old mine structure 1,445 m deep with a water volume reservoir of 162,000 m3 (Figure 34). The power of the plant would be 75 MW, and it would produce electricity for 7 hours at maximum output. After this, the system would be charged for 9 hours, pumping the water from the lower reservoir back to the upper one. (Pyhänjärven Callio 2018.)

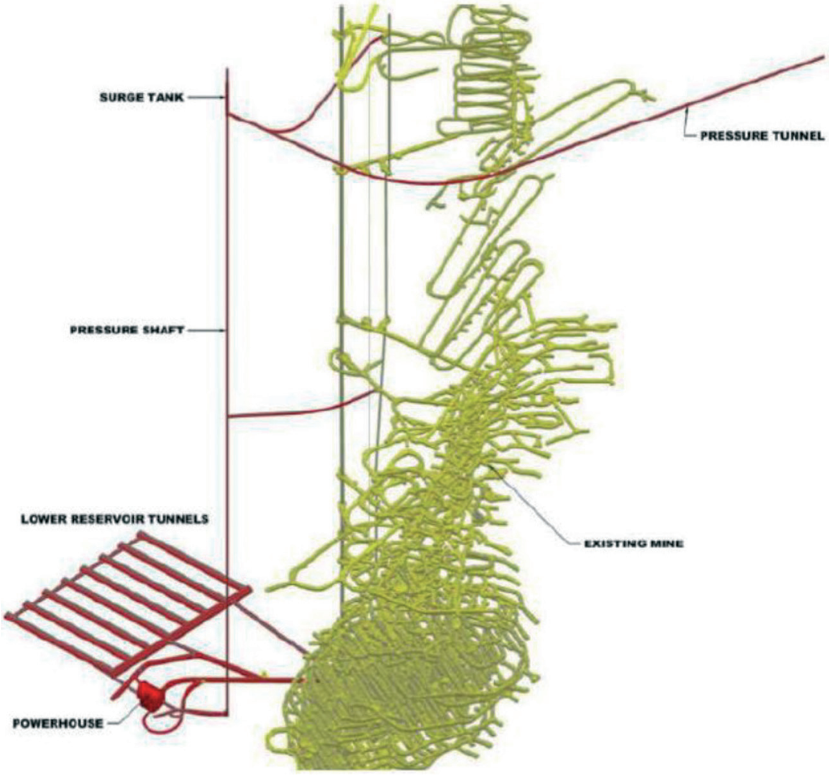


Figure 34. Layout of the PHS in Pyhäsalmi mine, Finland (IFPSH 2021) (Picture courtesy of The International Hydropower Association).

Another UPHS pilot facility will be constructed in Finland at the island of *Lilla Båtskär*, Åland. The UPHS system will be built in an abandoned mine in direct connection with an existing wind farm. The mine consists of a 290 m vertical shaft and the lower reservoir is a 1.6 km drift at a depth of 250 m. The pilot plant will have a maximum output of 2 MW and an energy storage capacity of 8 MWh. Currently, the mine is filled with water, so the first step is to empty and secure the mine, after which construction of the PHS pilot plant will start. It is expected to be commercially available by 2023. (IFPSH 2021.)

4.1.3 Hybrid systems

Hybrid systems integrate pumped hydro storage with other energy and water related technologies, such as batteries, solar photovoltaics (PV), desalination, and heat storage. This combination often leads to reduced costs and environmental impacts compared to using each technology separately. (IFPSH 2021.) Some examples of hybrid systems around the world are described in the following sections.

4.1.3.1 Hybrid pumped hydro storage - battery storage

The long-duration storage of pumped hydro storage can be combined with other short-duration energy storage system such as batteries, flywheels and supercapacitators. These short-duration energy storage technologies offer valuable complementary functions and services to enhance the capabilities of pumped hydro storage (IFPSH 2021).

There are a few examples of hybrid pumped hydro storage (PHS) and battery energy storage system (BESS). One of these examples is a 12.5 MW / 13 MWh BESS built by *Siemens* at a PSH plant in Trausnitz (Germany). Another example is a solar-battery-pumped hydro storage hybrid plant which is currently being developed by *AES* in Hawaii (United States) and could start operating in 2024. The system consists of a 35 MW photovoltaic solar array and a lithium-ion battery system with a storage capacity of 70 MWh. The pumped hydro facility has a capacity of 20 MW and a duration of 12 hours. (IFPSH 2021; KIUC & AES 2021.)

4.1.3.2 Integrated pumped hydro reverse osmosis clean energy system (IPHROCES)

Integrated pumped hydro reverse osmosis clean energy system simultaneously provides clean energy generation, energy storage, and freshwater (Figure 35). A PSH plant uses surplus from the grid or renewable energy sources to pump seawater into an upper reservoir using conventional hydropower technology. When required, water is released and flows from the upper to the lower reservoir through a turbine, that is connected to a generator to produce electricity. The seawater in the upper reservoir is also sent to a seawater reverse osmosis desalination plant, taking advantage of the pressure provided by the elevation. (IFPSH 2021.)

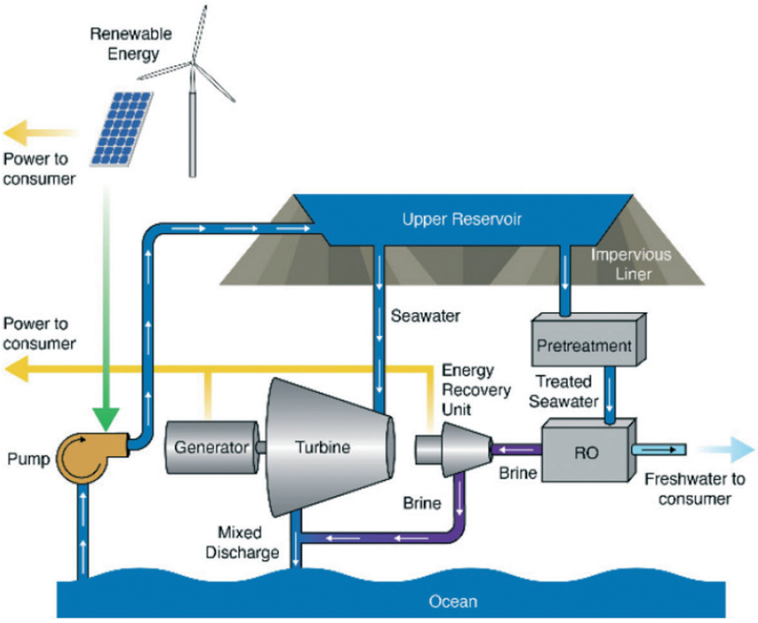


Figure 35. Integrated pumped hydro reverse osmosis clean energy system (Slocum & Gessel 2022), used under CC BY-NC-ND 4.0.

Oceanus is the infrastructure development company that has developed the IPHROCES concept. IPHROCES has the potential to provide low-cost, long-duration energy storage and offers several economic and environmental benefits in comparison to traditional, separate seawater reverse osmosis (SWRO) desalination and SPHS facilities. However, topography, local geology and marine conditions need to be studied and be favourable in order for the project to success. Oceanus has projects under development stage in Chile, USA and Mexico. (Oceanus s.a.)

4.1.3.3 Variable renewable energy (VRE) plant with PHS as storage

Variable renewable energy plant such a wind or solar power plant is installed in proximity to a PHS plant, which serves as on-site storage for the VRE plant, solving the problem of its intermittent supply. Solar photovoltaics systems can be either floating or land-based. Floating photovoltaic systems can be installed either in the upper or lower reservoirs of a PHS plant (Figure 36). The world's first hybrid floating PV and hydroelectric dam power plant system was installed in *Montalegre (Portugal)*. The PHS plant has capacity of 68 MW and the dam adds an additional 220 kW through the floating PV installation. Another example is located in *Kruonis (Lithuania)*, where a 60-kW pilot floating solar PV will be built in the upper reservoir of the existing 900 MW Kruonis PHS facility. The floating PV system could have a capacity of 200–250 MW at full size. (IRENA 2020.)

The *Valhalla project in Atacama Desert (Chile)* is a good example of PHS coupled with land-based solar PV. The Valhalla project will consist of a 600 MW solar PV farm and a 300 MW PHS plant. Another example is the *Hatta PHS facility* in United Arab Emirates. The Hatta PSH will have a storage capacity of 1,500 MWh with 250 MW of maximum output, and it will use surplus electricity from a 5 GW solar park, the world's largest planned solar PV installation. (IRENA 2020.)

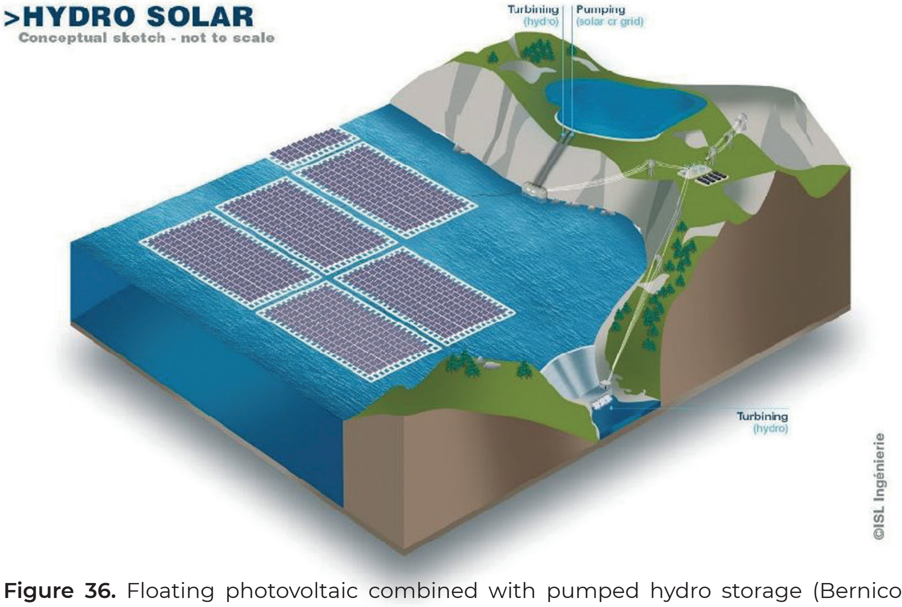


Figure 36. Floating photovoltaic combined with pumped hydro storage (Bernicot 2021).

In *El Hierro, Canary Islands (Spain)*, a 11 MW pumped hydro plant coupled with 11.5 MW wind power farm provides sustained renewable energy to the island, drastically reducing its need for diesel fuel (Figure 37). Aside from supplying electricity to both residential and commercial sectors, this hydrowind system also serves as the primary energy source for the island's desalination plants, which are connected to the lower reservoir. In *Kidston (Australia)*, a solar-hydro-wind project is being developed. When completed, the project will consist of a 320 MW solar plant, a 150 MW wind farm and a 250 MW pumped hydro storage. (IRENA 2020.).

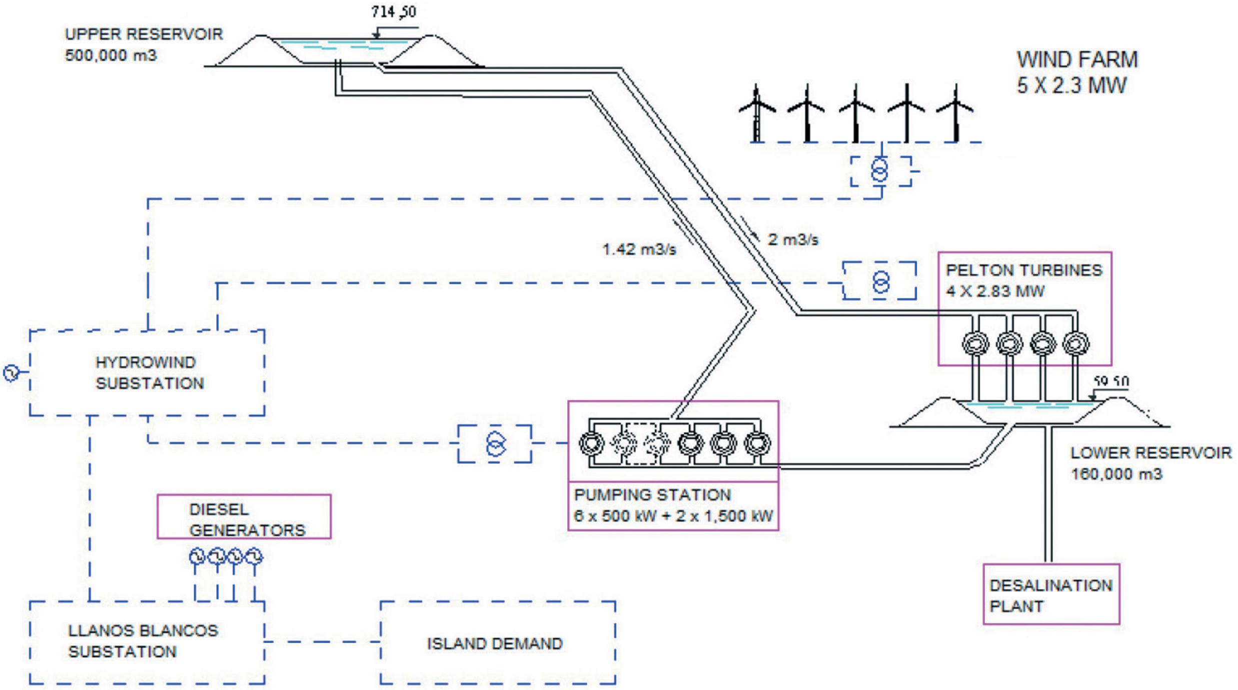


Figure 37. Scheme of closed-loop PHS coupled with wind power plant in El Hierro, Spain (Wikipedia Commons 2010), Author: Gorona del Viento – El Hierro, used under CC BY SA 3.0, translated from Spanish.

The above-mentioned UPHS pilot facility that will be constructed in Åland (Finland) as well as the solar-battery-hydro storage plant which is currently under development in Hawaii are also examples of VRE combined with pumped hydro.

4.1.3.4 Thermal underground pumped hydro (TUPH)

This technology combines underground pumped hydro energy storage with thermal energy storage as well as renewable energy sources. TUPH is a fully underground, closed-loop hot-water pumped hydro storage. The vertically separated water reservoirs are connected from the lower part via a pressure shaft to the powerhouse. The reservoirs are also connected from the upper part via an air pressure compensation shaft. The water is heated up to 90°C by means of heat exchangers, connected to waste heat suppliers, district heating systems and renewable heat sources. The system supplies electricity and thermal energy for district heating and cooling on demand. (IFPSH 2021.)

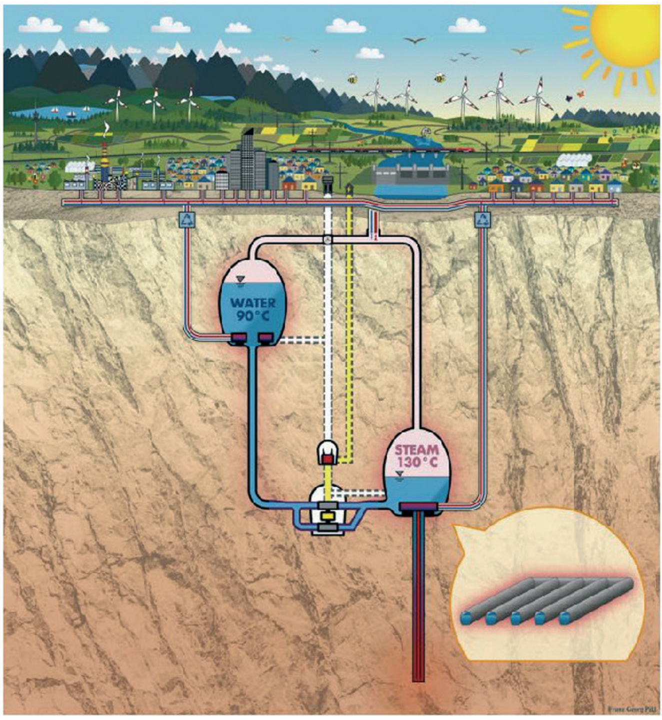


Figure 38. TUPH concept © Franz Georg Pikl (IFPSH 2021) (Picture courtesy of The International Hydropower Association).

The TUPH concept (Figure 38) has been developed by Franz Georg Pikl and is currently being further improved at Graz University of Technology (Austria). The modular, adapTable and flexible design of the system allows it to be installed close to cities and load centres, with minimum environmental impacts and no limitations of the topography. However, an appropriate geology with suiTable rock conditions is required, the complexity of deep excavations must be considered and the use of hot water for pumped hydro storage operation needs to be further investigated. (IFPSH 2021.)

4.2 Liquid air energy storage (LAES) or cryogenic energy storage (CES)

Cryogenic air separation units have been in the market for over 100 years. This technology has been used in a wide variety of fields (e.g., metallurgical industry, chemical applications, power plants, medical and aerospace sectors) for separating the different air components through air liquefaction. However, the liquefaction of air without the separation process is being recently studied for its energy storage capabilities. Studies have shown that liquid air energy storage (LAES) has the potential of being an effective and competitive clean energy storage solution for large scale, long-duration applications. (Cavadas 2019.)

The company *Sumitomo SHI-FW* provides the LAES technology developed by *Highview Power* (Figure 39). In the charging phase, electrical energy is used to drive an industrial air liquefier that extracts air from the surrounding environment. The air is first cleaned and then compressed and cooled to sub-zero temperatures until it liquifies, reducing its volume by a factor of 700. The liquified air is stored at low pressure in insulated tanks. When power is required, heat is applied to the liquid air, which produces the expansion of the liquid air into a high-pressure gas that drives a turbine and generates electricity. (Highview Power 2018; Cavadas 2019.)

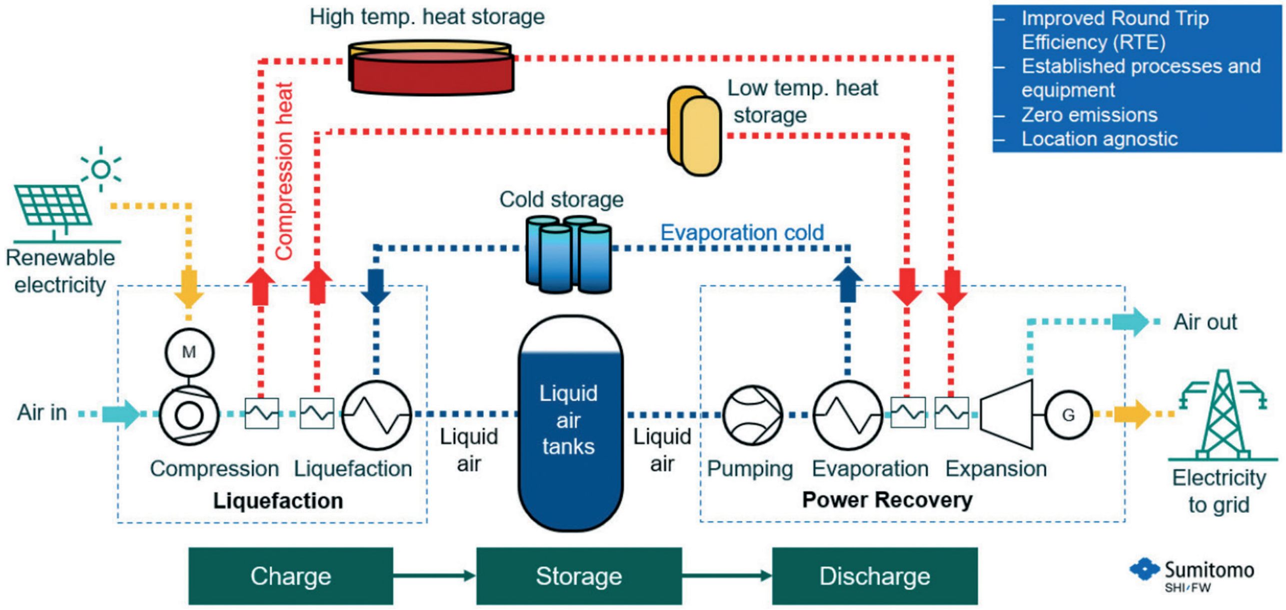


Figure 39. Liquid air energy storage (Picture courtesy of Sumitomo SHI-FW).

The efficiency of the system is enhanced by adding hot storage and a cold storage units, which store waste heat generated during the charging phase and waste cold produced during the discharging phase, respectively. The system can also integrate waste heat and waste cold from industrial processes. Highview Power claims that their system is scalable without size limitations nor geographic constraints, generates no emissions, and has a long lifespan. The system can provide from 4 hours to 4 weeks of energy. (Highview Power 2018.)

Two plants have been successfully built and demonstrated. A 350 kW / 2.5 MWh pilot plant was commissioned in 2011 in Heathrow (United Kingdom) and a 5 MW / 15 MWh commercial facility was commission in 2018 in Manchester (United Kingdom). Highview Power's second commercial plant in the UK is a 200 MW / 2.5 GWh facility in Yorkshire. The company also plans to build a 300 MWh system in Spain and several ones in Australia. (Highview Power 2022.)

4.3 Compressed air energy storage (CAES)

In compressed air energy storage systems (CAES), air is compressed usually into an underground cavern, and when energy is needed the air is heated and is allowed to expand in order to drive a turbine and generate electricity. In conventional diabatic CAES (D-CAES), the air is heated via combustion using natural gas or fuel during the air expansion stage (Figure 40). D-CAES is a mature technology, and it has the potential for large volumes of low-cost energy storage. However, there is a number of limitations of CAES such as low efficiencies when compared to other established energy storage technologies, low energy storage density, and geological restrictions. (European Association for Storage of Energy 2016.)

There are currently two plants of this type in operation. One is a 290 MW / 480 MWh plant in Huntorf (Germany), which was commissioned in 1978 and has an efficiency of 42% and a discharge time of 2 hours. The other one is a 110 MW / 2,000 MWh plant in McIntosch (USA), which was commissioned in 1991, and has an efficiency of 54% and a discharge time of 26 hours. (Vuorenmaa et al. 2020.)

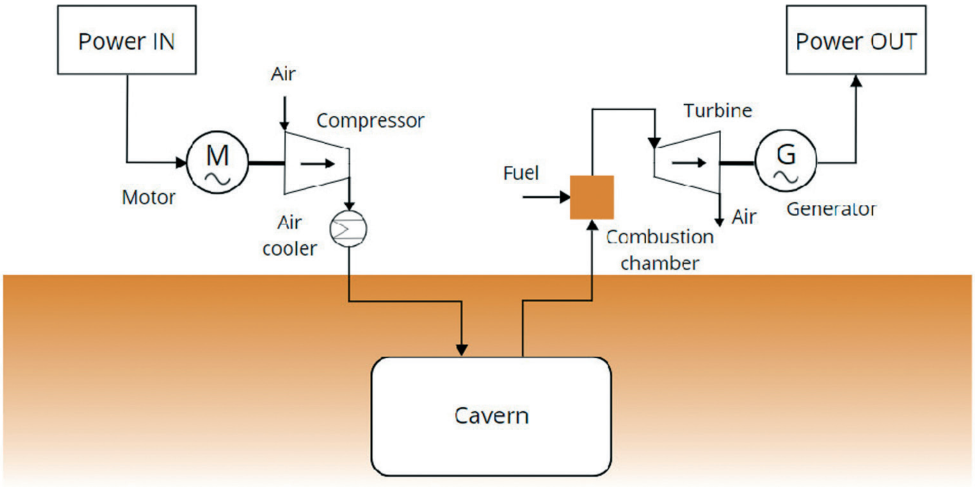


Figure 40. Schematic diagram of D-CAES (adapted from EASE 2016a).

An advanced form of this technology is adiabatic compressed air energy storage (A-CAES). In these systems, the heat produced during compression is captured and stored for using it later during air expansion stage (Figure 41). This adiabatic process eliminates the need for fossil fuels during operation and is expected to increase overall efficiency to 50%-75%.

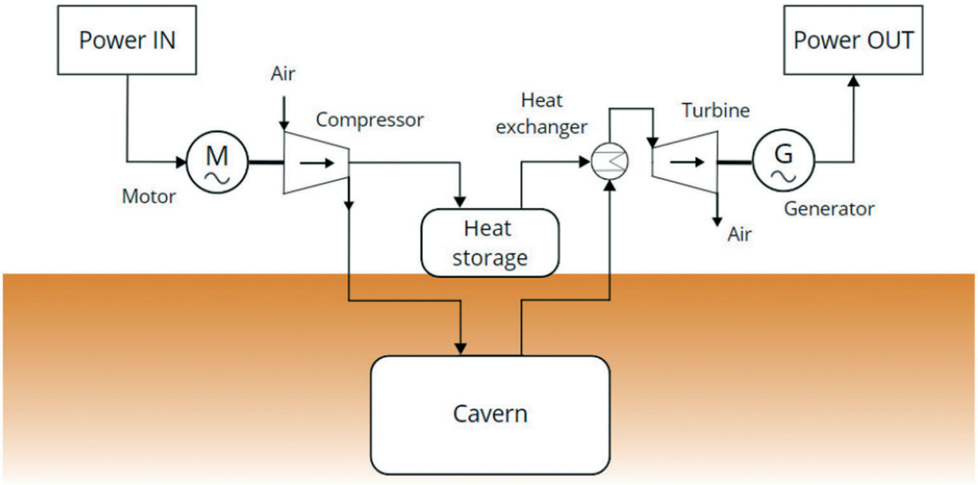


Figure 41. Schematic diagram of A-CAES (adapted from EASE 2016b).

There have been numerous major CAES projects in the recent years. For example, the 10 MW A-CAES power station in Feicheng (China), in operation since 2019. It utilises underground salt and coal mine caverns to store the compressed air, and ultimately it will provide 1,250 MW of power and 7,500 MWh of energy storage. (King, Jain, Bhakar, Mathur & Wang 2021.)

Hydrostor is the developer of the world's first commercial A-CAES facility in Ontario (Canada), which has been in service since 2019. A particular characteristic of this system is that the compressed air is stored in a purpose-built cavern where hydrostatic compensation is used to maintain the system at a constant pressure during operation. The facility has a charge rating of 2.2 MW, a peak power output of 1.75 MW and a storage capacity of over 10 MWh. (King et al. 2021.)

Another new approach to improve round-trip efficiencies of conventional CAES facilities is the development of isothermal CAES (I-CAES). I-CAES aims to achieve slow compression and expansion of the air so that the temperature remains constant during these processes, which would eliminate the need for heat storage. The only commercial plant of I-CAES in recent years was the 1.5 MW pilot plant in Seabrook (USA) from *SustainX*. The system was based on the utilization of an innovative foam, formed as a mixture of air and water, to facilitate fast heat transfer and maintain constant temperature throughout. The system achieved round-trip efficiencies of 54%. However, specially constructed above-ground air vessels were used, which could limit the scalability of the prototype. (King et al. 2021.)

Additionally, there have been other ideas about how to store compressed air. Some studies have focused on underwater compressed air energy storage (UW-CAES). Air storage reservoirs for UW-CAES can be flexible or rigid, and anchored to the seabed with fixed or variable buoyancy depth. (Tiano, F. A. & Rizzo, G. 2021.) Some other companies have targeted above-ground CAES, like the above-mentioned SustainX. However, the future of these technologies is unclear.

There are no CAES systems in Finland. In order to build up the required pressure, CAES requires a closed, tight space, which is usually found deep in mines, in caverns and smaller spaces. According to a study by Vuorenmaa et al. Finland has a sTable bedrock and abandoned mines, resulting in good possibilities for CAES. There have been feasibility studies regarding the construction of a CAES in Pyhäsalmi mine, the same mine as discussed in section 4.1.2, but finally pumped hydro storage was selected. (Vuorenmaa et al. 2020.)

4.4 Pumped heat energy storage (PHES) or pumped thermal electricity storage (PTES)

Pumped thermal electricity storage or pumped heat energy storage is a novel ESS technology that is based on the use of surplus electricity to run a heat pump and create a temperature differential that is stored in cold and hot reservoirs as sensible or latent heat (Figure 42). When power is needed, the system works as a heat engine, and thermal energy is converted back into electrical energy. Different working fluids (e.g., argon, air, sCO2) and storage media (e.g., water, molten salts, rocks, concrete) can be used, as well as different storage temperature levels. (Benato & Stoppato 2018; Allison 2020.)

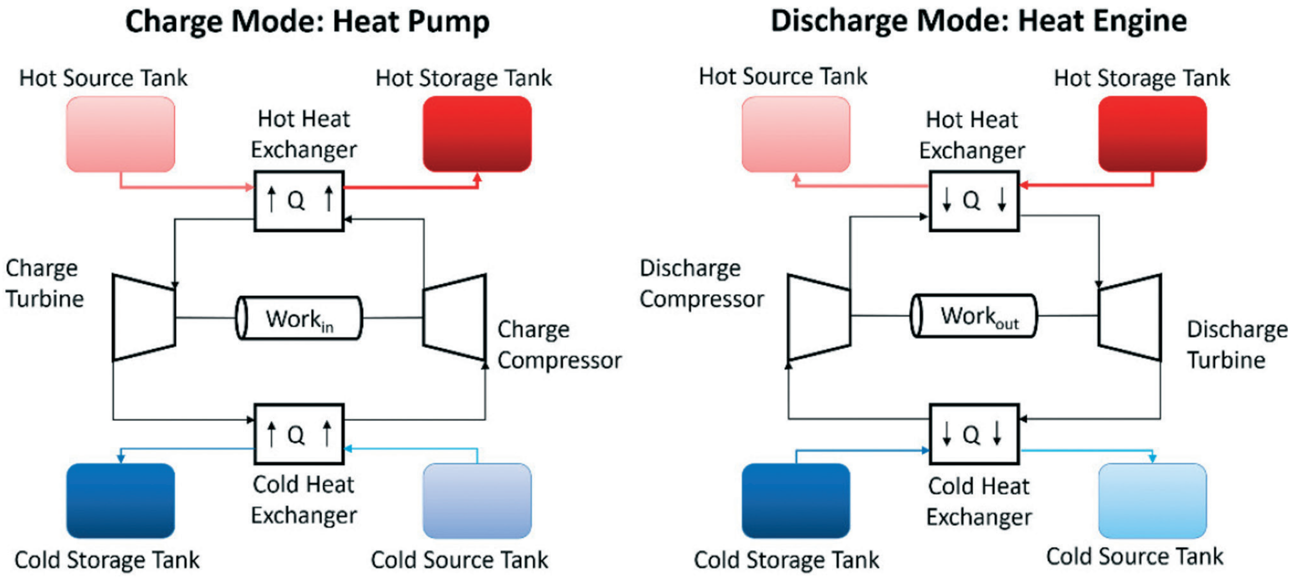


Figure 42. Example of PHES configuration (Allison 2020).

In Table 16, a comparison between PHES and other energy storage technologies is presented. As can be seen, PHES is characterised by high energy density (110–170 Wh/l or 50–140 Wh/kg), low capital costs, and relatively good performance (expected round-trip efficiency of 70–80% and lifetime of 25–30 year). In addition, PHES systems present low self-discharge rate, no geographical limitations, and small installation footprint. Despite the great potential of PHES, this technology is still in the early stages of development and only few investigations are available on the topic. (Benato & Stoppato 2018.)

Table 16. Comparison between PHES and other energy storage technologies (Benato & Stoppato 2018.).

Energy storage technology	Energy density (Wh/l)	Price per energy unit stored ($/kWh)	Round trip efficiency (%)	Lifetime (years)
PHS	0.5-1.5	5-100	65-87	30-60
GES	0.5-1.5	NA	70-86	30-40
CAES	3-12	2-200	40-95	20-60
LAES	50	260-530	40-85	20-40
Hydrogen	500-3,000	1-10	20-50	5-30
PHES	*110-170*	*60*	*70-80*	*25-30*

Based on the thermodynamic cycle, the proposed and studied PHES are grouped into Rankine cycles and Brayton cycles, and more specifically into reversible Brayton cycles, reversible transcritical organic Rankine cycles and conventional steam Rankine cycles. Reversible Brayton cycle uses a single-phase gas like air or argon, and it is equipped with a low and a high pressure and temperature reservoirs. Transcritical Organic Rankine Cycle (ORC) uses CO2 as working fluid and is equipped with ice and pressurised water storages. Conventional Rankine cycle uses water as the working fluid. (Benato & Stoppato 2018.) For a more detailed information about PHES systems, the review by Benato and Stoppato (2018) is recommended.

Examples

The company *Stiesdal Storage Technologies* in Denmark has developed GridScale (Figure 43). The GridScale system converts excess electricity into heat and stores the heat in crushed rock, usually basalt, using air as its working fluid. Before charging, the storage tank filled with cool stones and cool air is at 75°C and the storage tank filled with hot stones and hot air at 385°C. During charging, the system is conFigured as a heat pump, and thermal energy is pumped from the cold storage to the hot one. Once the system is fully charged, the hot tank is storing thermal energy at 600°C while the cold tank is sitting at -30°C. During discharging, the system is conFigured as a heat engine, releasing the thermal energy from the hot tank to the cold tank and producing electricity. GridScale systems has a minimum charging/discharging power rating of 4 MW / 2 MW and a minimum storage capacity of 10 hours. (Stiesdal 2021.)

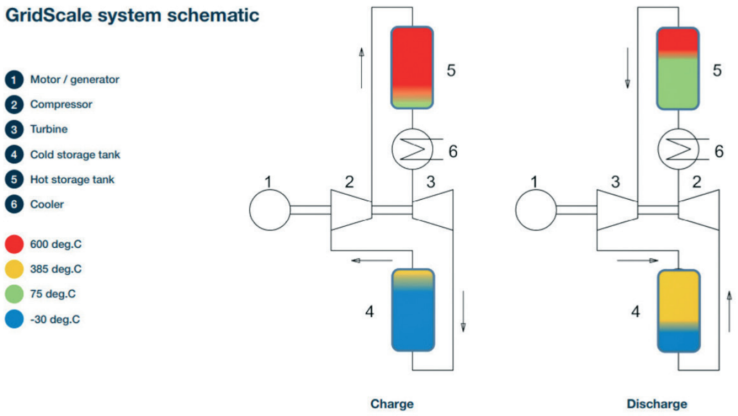


Figure 43. GridScale pumped heat energy storage system (Stiesdal 2021).

The American company *Echogen* has developed a PHES system that uses electricity to power a heat pump that transfers heat from a cold tank that contains ice/water to a warm tank that contains grains of sand (Figure 44). The heat is then stored in the sand and, when energy is required, a heat engine converts the thermal energy into electrical energy. Echogen's technology uses supercritical carbon dioxide (sCO2) as its working fluid. Echogen has already built and tested a small-scale 200-kW PHES system in Akron (USA) and is expected to build a 25 MW / 250 MWh commercial project in the coming years. (Echogen s.a.)

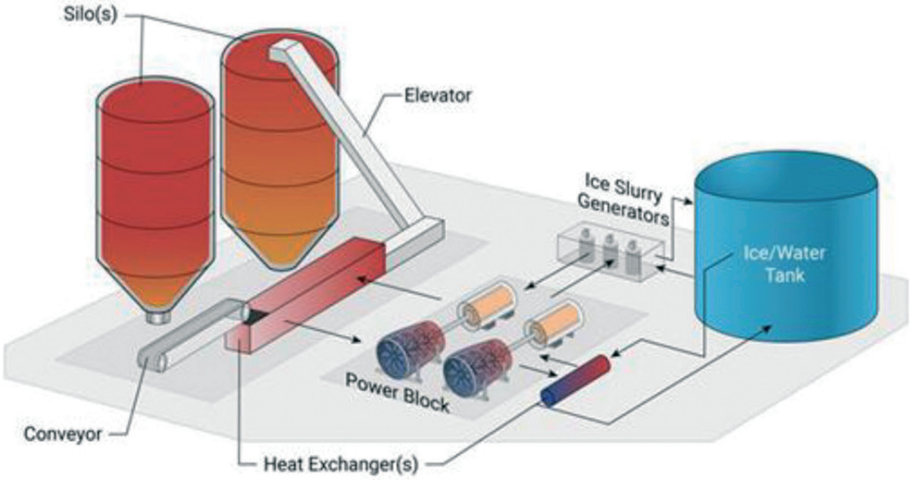


Figure 44. Echogen's PHES (Echogen s.a.).

The *American Southwest Research Institute (SwRI) and Malta, Inc.* have developed a PHES system based on Brayton cycle with air as working fluid. The PHES stores the heat in molten salt at 565°C, and the cold in an antifreeze-like solution at -60°C. The thermal energy is converted back to electrical energy with a heat engine when needed. The assembly and commissioning of the first pumped heat energy storage demonstration facility was completed in 2022 (Figure 45). Malta is now collaborating with Siemens to develop a 100 MW storage system for 10-200 hours of storage with an expected round-trip efficiency up to 60%. (SwRI 2022.)

Figure 45. PHES demonstration facility by SwRI and Malta (SwRI 2022).

Newcastle University's Sir Joseph Swan Centre for Energy Research developed a Brayton cycle -based PHES with argon as the working fluid. A 150-kW demonstration facility was installed and tested in Hampshire, United Kingdom. The PHES system was designed to offer a storage capacity of 600 kWh with a storage cycle of 8 hours. In the charging phase, argon gas is compressed using excess electricity from the grid until it reaches 500°C while in the discharging phase, argon gas is allowed to expand until its temperature is -160°C. In both cases, argon flows through the storage tanks, respectively heating and cooling the storage medium (i.e., magnetite pebbles), and it leaves the tanks at ambient temperature. The results of the study by Ameen et al. (2023) showed that about 71% electricity-to-electricity round-trip-efficiency can be achieved by this system. (The Engineer 2017; Ameen, Ma, Smallbone, Norman & Roskilly 2023.)

MAN Energy Solutions and ABB have partnered to develop a new energy storage system called ETES (Figure 46). A turbo compressor compresses the working fluid, i.e., carbon dioxide, to its super-critical state at typically 140 bar and 120°C. First, the CO2 heats water by means of a heat exchanger and then it is forced to expand, and it liquefies and cools. The liquified CO2 is used to cool down water by means of another heat exchanger. The hot water and ice generated in the previous step are stored in insulated reservoirs. The stored thermal energy can be used directly as heat and cold, for example, for district heating and data centre cooling, respectively, or it can be converted back into electricity and fed to the grid. (MAN Energy Solutions 2018.)

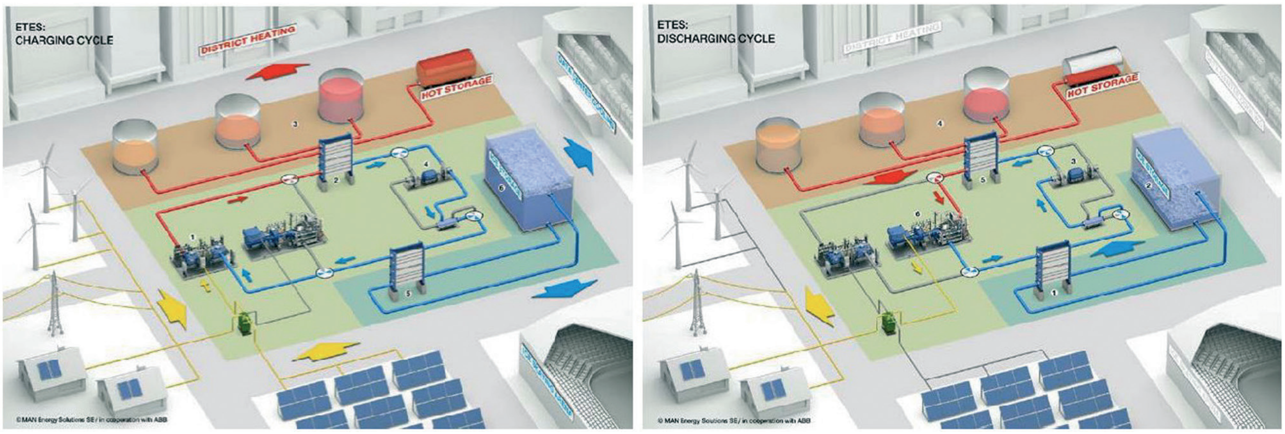


Figure 46. MAN and ABB's ETES. Charging phase (left) and discharging phase (right) (MAN Energy Solutions 2018).

Energy Dome has developed the world's first CO2 battery (Figure 47). Carbon dioxide is stored in a dome in gas form. In the charging phase, CO2 is pulled from the dome and compressed into liquid using surplus electricity. The heat released in this process is stored in the TES unit and the CO2 is stored in liquid form under pressure at ambient temperature. When electricity is needed, the liquid CO2 is heated up with the thermal energy stored in the TES and is turned back into gas. As the CO2 expands from liquid to gas, it drives a turbine to generate electricity. Energy Dome, together with its partner Ørsted, is planning to run a feasibility study on a 20 MW storage facility that is expected to dispatch energy for at least 10 hours at a time. (The Verge 2022; Energy Dome 2023.)

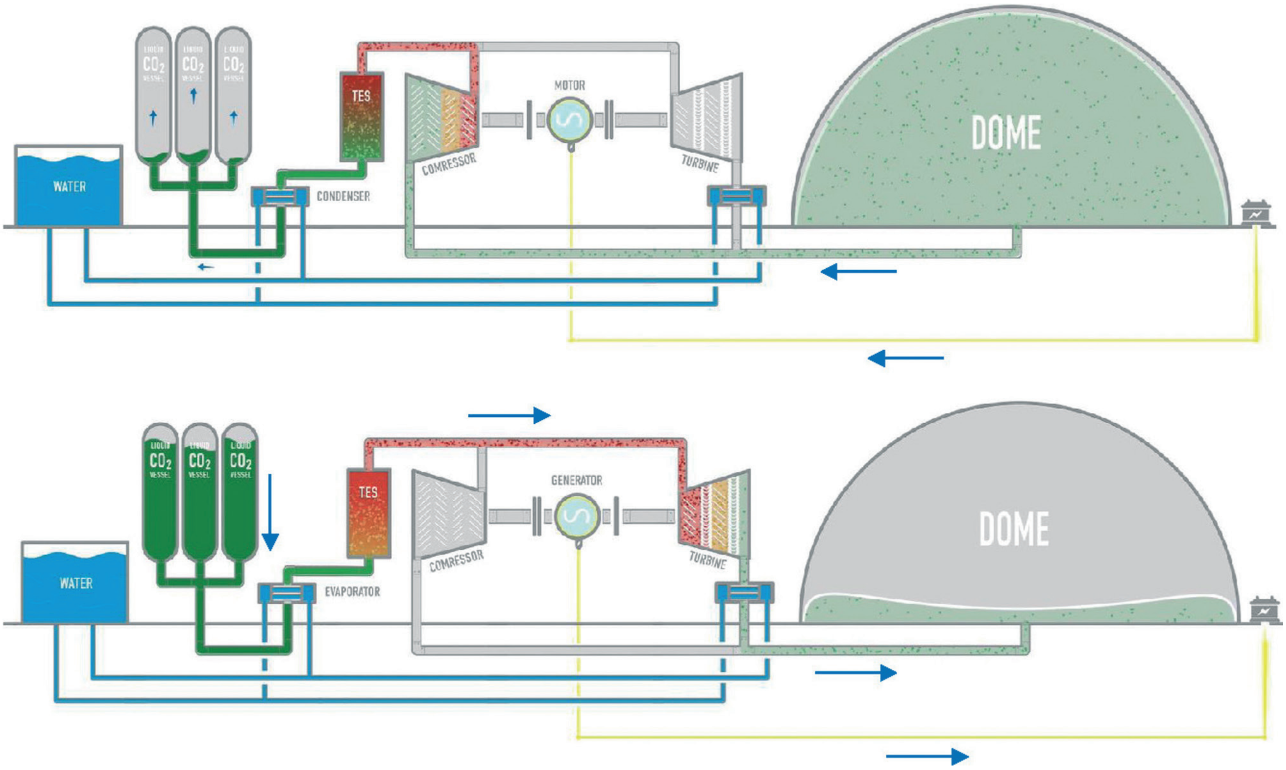


Figure 47. Energy Dome CO2 battery's charging phase (up) and discharging phase (down) (Energy Dome 2023).

Researchers from the Spanish *Polytechnic University of Madrid* (UPM) have proposed to store renewable electricity with a pumped heat energy storage system based on supercritical carbon dioxide (sCO2) as the working fluid and molten salts as the thermal storage fluid. The network generated by the proposal was 12.46 MW in the load and 10 MW in the discharge, reaching an efficiency of 80.26%. (Tafur-Escanta, Valencia-Chapi, López-Guillem, Fierros-Peraza and Muñoz-Antón 2022.)

In the article by McTigue et al. (2019), a PHES variant that uses supercritical carbon dioxide (sCO_2) as the working fluid was introduced. It was concluded that sCO_2-PHES systems present higher work ratios and higher round-trip efficiencies than ideal gas cycles at comparable temperatures. McTigue et al. also introduced the concept of sCO2-PHES coupled with CSP. (McTigue, Farres-Antunez, Ellingwood, Neises & White 2019.)

4.5 Gravity-based energy storage (GES)

Gravity-based or solid mass energy storage systems are a type of mechanical storage systems that make use of gravity to store electrical energy, e.g., raising a weight with surplus energy and then lowering it when energy is needed. This concept is not new, pumped storage hydropower has been using it for over 100 years. The gravity-based technologies described in this section rely on gravity in the same way as PSH, but instead of using water, they are using other materials. Furthermore, these novel gravity-based energy storage systems are designed to overcome PHS drawbacks including high investment costs, geographical restrictions, and environmental impacts.

As commented before and according to Vuorenmaa et al. (2020), in Finland there is a potential to use decommissioned mines for various energy storage methods, including gravity-based energy storage. Thus, the potential of implementation of this energy storage technology in Finland has to be investigated.

4.5.1 Heindl energy storage

The energy storage solution developed by the German company Heindl, also known as *Gravity Storage or Hydraulic Rock Storage*, consists of a massive rock piston with a diameter of at least 100 m, placed in a shaft drilled into the bedrock (Figure 48). Electrical pumps, driven by excess electricity from renewable sources, pump water under the piston, lifting it. Energy can be stored for long periods of 6-14 hours and when electricity is needed, the pressurized water is directed through a turbine to generate electricity, allowing the piston to lower. (Heindl Energy 2017.)

Gravity Storage systems do not require elevation difference like PHS, so they are suiTable for flat terrains. However, they should be located in areas with solid bedrock. The most favourable sites have sTable, little-faulted rock such as granite or compact layers of otherwise solid rock material. The energy storage achieves a round-trip efficiency of over 80% and its capacity can be chosen between 1 and 10 GWh, considering that a diameter of 250 meters would already result in a storage capacity of 8 GWh. The company is planning to construct a pilot plan of about 200 MWh capacity to verify the concept in the coming years. (Heindl Energy 2017.)

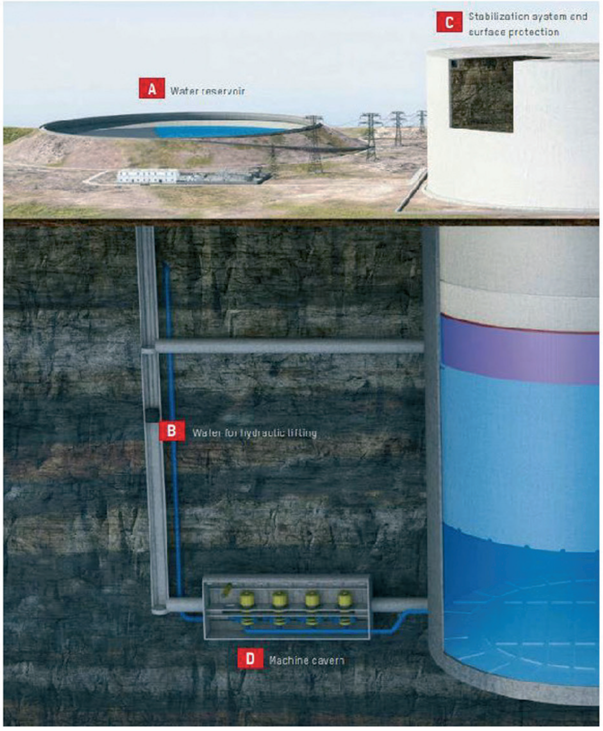


Figure 48. Gravity Storage by Heindl: (A) water reservoir, (B) water for hydraulic lifting, (C) stabilization system and surface protection, (D) machine cavern (Illustration with permission of Gravity Storage GmbH, www.gravity-storage.com)

4.5.2 Gravity Power energy storage

The American company *Gravity Power's energy storage idea* (Figure 49) consists of a piston of reinforced rock that slides inside a shaft dig into the bedrock. Water is added to fill the shaft, which is later capped, creating a closed loop system. A conventional pump and turbine system pushes water down the penstock into the shaft, raising the piston and charging the system. When the piston lowers, it pushes water back up through the penstock, causing a turbine to spin. This spinning motion drives a generator, creating electricity. (Gravity Power 2021.)

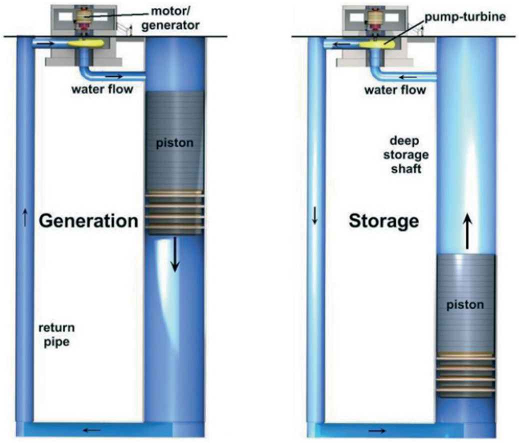


Figure 49. Gravity Power solution (Gravity Power 2021).

4.5.3 Energy Vault energy storage

The Swiss-based company Energy Vault has developed a *6-arm crane system* (Figure 50), which utilizes the excess electricity from the grid to drive motors and generators that lift and stack bricks in a very specific sequence. The tower stores energy in the form of potential energy and when power is needed, the system will lower the bricks and discharge the electricity. According to Energy Vault, a 120 m tower can store 35 MWh and achieve a round trip efficiency of 80-90%. (Energy Vault s.a.)

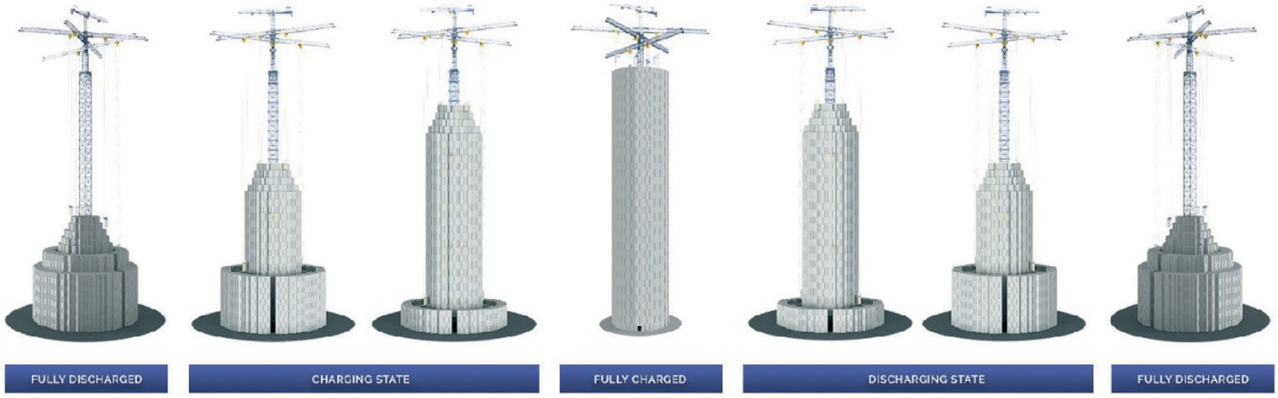


Figure 50. Crane system by Energy Vault (Energy Vault s.a.).

After the original crane system concept, Energy Vault is developing a new idea (Figure 52), called *Energy Vault Resiliency Centre* (EVRC). During the charging phase, 30-ton bricks made of locally sourced soil, sand or waste materials are elevated, assembled and stacked by the crane system. During discharging phase, bricks are lowered down, and kinetic energy is released back to the grid making use of gravitational force. According to Energy Vault, the system has a round-trip efficiency of 80-85% and it can be built to scale in increments of 10 MWh units. (Energy Vault s.a.)

Figure 51. EVRC by Energy Vault (Energy Vault s.a.).

4.5.4 Gravitricity energy storage

The company *Gravitricity* from Scotland is developing a new form of energy storage (Figure 52). The energy system uses weight configurations up to 12,000 tons in a shaft up to 1,500 m deep, suspended by a number of cables to distribute the load evenly between several electric winches. Excess electricity from the grid is used to pull the weight to the top of the shaft. When electricity is required, the weight is lowered, turning a generator. According to Gravitricity, the system has a round-trip efficiency of 80% and it can store energy from 15 mins to 8 hours. (Gravitricity 2022a.)

During 2021, Gravitricity successfully constructed, commissioned, and operated a 250 kW, grid-connected demonstration project using a 15 m high rig in Edinburgh. Currently, the company is studying the suitability of different sites for its first full-scale project, that will consist of a 4-8 MW single weight which will deliver up to 2 MWh of energy storage. Future multi-weight systems could have a capacity of 25 MWh or more. (Gravitricity 2022b.)

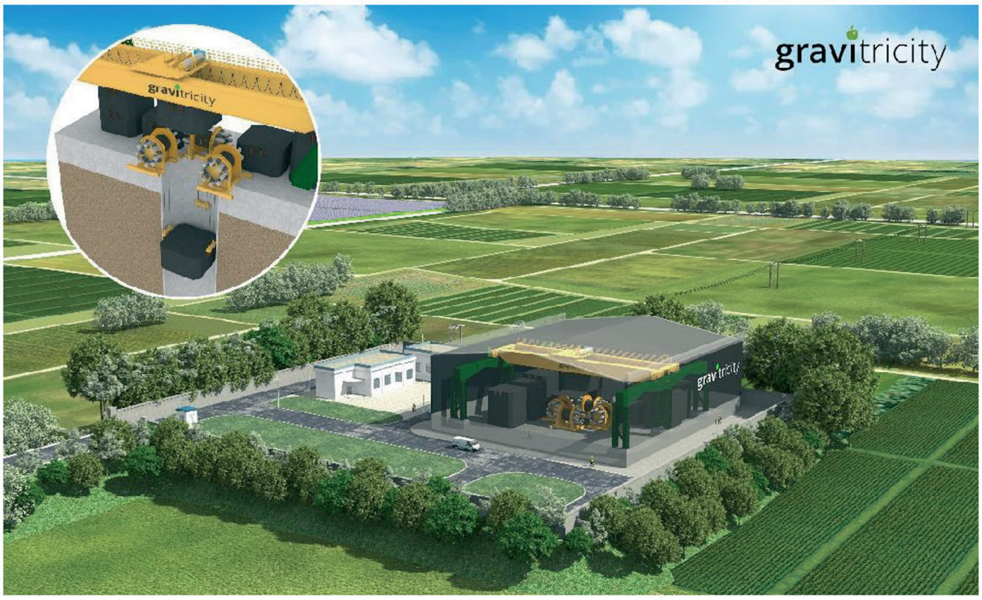


Figure 52. Gravitricity energy storage (Picture courtesy of Gravitricity Ltd).

4.5.5 Advanced rail energy storage (ARES)

The American company ARES has developed *GravityLine*, a rail-based gravity-powered energy storage system. Surplus electricity from the grid or renewable sources is used to drive electric motors that lift heavy mass cars uphill. These cars remain at the highest point, storing a maximum amount of potential energy, until electricity is required. Then, the cars are lowered, and the reversible motor operates in reverse, acting as a power generator. (ARES 2020.)

The GravityLine storage system is made up of multiple 5-MW tracks and can vary in size from 5 MW to 1 GW of power depending on weight and number of mass cars, slope and distance. According to the developers, ARES system is expected to have a round-trip efficiency of over 90% and it can store energy from 15 mins to 10 hours. The first of this type will be ARES Nevada Project, a 50-MW system that, once operational, will provide 12.5 MWh of energy storage. (ARES 2020.)

4.5.6 Mountain gravity energy storage (MGES)

Mountain gravity energy storage has been studied as a potential solution for storing energy in small-scale power grids or isolated locations like micro-grids or small islands. This approach is particularly suiTable for situations where the required storage capacity is below 20 MW. MGES involves using two cranes positioned on a steep mountain (Figure 53). These cranes transport sand or gravel between a lower storage area and an upper storage area. The energy is stored as potential energy when the sand or gravel is lifted to the top storage. When electricity is needed, the sand or gravel is lowered from the upper storage to the lower storage, and this process generates electricity. An underground filling station is used to load the sand or gravel into the storage areas, and valves release the stored materials as needed. (Hunt, Zakeri, Falchetta, Nascimento, Wada & Riahi 2020.)

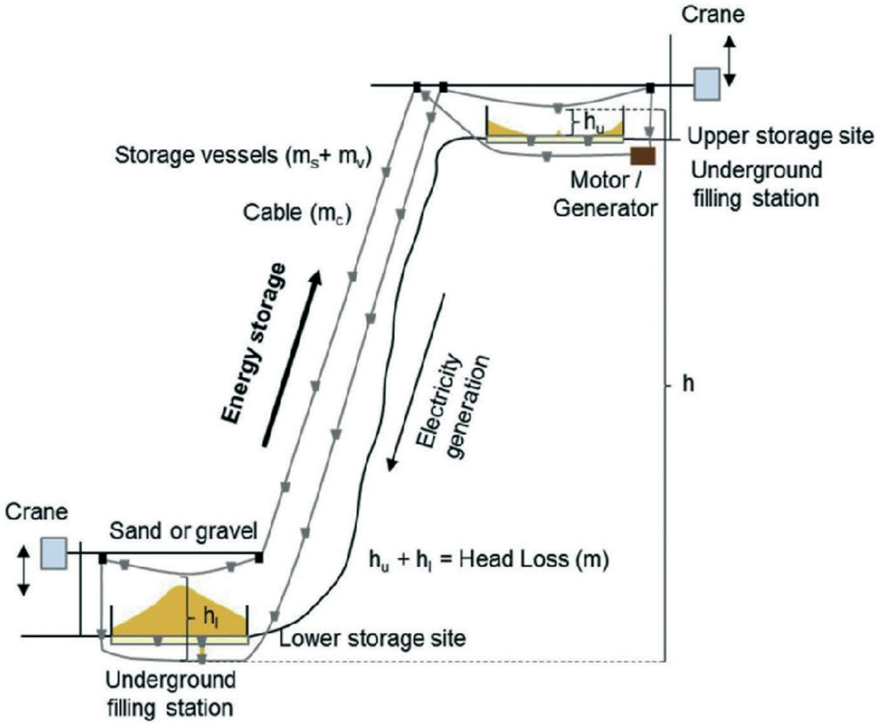


Figure 53. Schematic example of mountain gravitational energy storage (Hunt et al. 2020).

5 CHEMICAL ENERGY STORAGE SYSTEMS

Chemical energy storage refers to the production of hydrogen and other energy carriers from renewable energy sources or other energy sources. Thus, energy is stored in the bonds of chemical compounds, and when needed, these energy carriers can be used to produce electricity or for a variety of other applications (Figure 54). Chemical energy storage systems will play a key role in decarbonizing the power sector while also having the potential to decarbonize other sectors including transport and industry.

Chemical energy storage can provide large storage capacities with long discharge durations up to months. Moreover, it presents many pathways for production, storage and end use, and has the advantage that an extensive infrastructure for transportation and handling some chemicals already exists. On the other hand, the main limitations are that it has lower round-trip efficiency compared to other storage technologies and that the volumetric energy densities of some chemicals are low, which causes storage complications. Other drawbacks of this technology include the safety hazards associated with chemical physical properties, and that some storage methods are dependent on regional geology aspects and may have large land requirements. (DOE 2021a.)

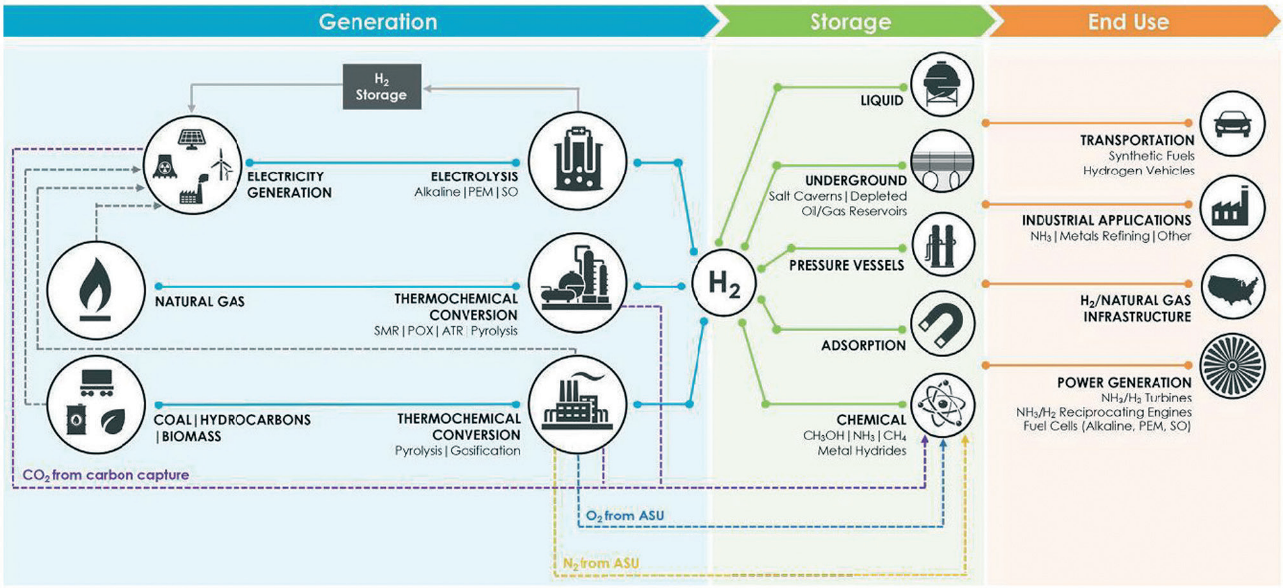


Figure 54. Chemical energy storage: pathways for production, storage and end use (DOE 2021a) (Picture courtesy of U.S. Department of Energy's National Energy Technology Laboratory).

5.1 Power-to-Hydrogen (P2H2)

There are three main types of hydrogen based on its origin: blue, grey, and green hydrogen. Green hydrogen is produced by using excess electricity from renewable energy sources to split water into hydrogen and oxygen, i.e., water electrolysis. This technology is known as Power-to-Hydrogen (P2H2). The hydrogen can be then stored as compressed gas, in liquid form or in chemical compounds. The stored hydrogen can be converted back into electricity, e.g., via hydrogen fuel cells, gas turbines or engines. Alternatively, the stored hydrogen can be used in other sectors besides power sector such as transport, industry, and residential heat. (EASE 2016c; DOE 2021a.)

Hydrogen in gaseous form can be stored in pressurized vessels in salt caverns, depleted gas fields, and rock caverns, while hydrogen in liquid form is stored at high pressure in cryogenic vessels (U.S. Department of Energy 2020). As commented above, hydrogen can also be converted into other energy carriers such as ammonia, methanol, and methane. These chemicals present higher volumetric energy densities in comparison to hydrogen, which makes storage and delivery easier. The process of converting power into gaseous energy carrier is known as Power-to-Gas (P2G).

Hydrogen is the most abundant and simplest element in the universe. In addition, it can be produced through various low-carbon methods and used in a wide range of applications. Hydrogen energy storage provides a clean and flexible solution for storing large amounts of energy over extended periods, making it a key player in the transition to green energy. While hydrogen has a high gravimetric energy density, its low volumetric energy density makes storage challenging. To overcome this, hydrogen is often compressed at high pressures, which helps address the concerns regarding storage volume and weight. (Vuorenmaa et al. 2020; DOE 2021a.)

Several P2H2 projects are currently ongoing in Europe. However, most of these projects are pilot projects and not commercial plants. Regensburg Technical University of Applied Sciences (OTH) together with POWER magazine have created an *interactive map* showing the existing Power-to-Gas projects worldwide as of September 2019 (Patel 2019). Hydrogen Cluster Finland (2022) has created a similar tool, an interactive map that shows selected clean hydrogen projects in Finland. Some of these projects are shown in Table 17.

Table 17. Selected hydrogen projects in Finland (Hydrogen Cluster Finland 2022).

Company	Location	Project	Power (MW)	Project phase	Start-up year
P2X Solutions	Harjavalta	Green hydrogen production	20	Under construction	2024
Green NortH2 Energy	Naantali	Green hydrogen production and P2X	100	Feasibility study	2026
Nordic Ren-Gas Oy	Tampere	Green hydrogen production and P2G	60	Feasibility study	2028
Nordic Ren-Gas Oy	Mikkeli	Green hydrogen production and P2G (methane)	40	Feasibility study	2026
Nordic Ren-Gas Oy	Lahti	Green hydrogen production and P2X fuels	120	Feasibility study	2025
EPV Energia Oy (EPV)	Vaasa	Green hydrogen production and P2X2P	-	Planning	2024
Vantaan Energia Oy	Vantaa	Power to Materials/Chemicals	100-500	Planning	2029
Vantaan Energia Oy	Vantaa	Power-to-Gas (P2G) plant	22	Basic engineering	2025
Convion Ltd	Espoo	Green hydrogen production and e-fuel production	0,125	Demonstration	2023
Neste Oyj	Porvoo	Green hydrogen production and CCUS	50	Feasibility study	-

The first green hydrogen production plant in Finland will be built by the Finnish pioneer in green hydrogen, P2X Solutions. The 20 MW electrolyser plant will start producing green hydrogen in 2024 using electricity produced by wind, solar, biomass or hydropower. The company is seeking for investment support to make this project commercially feasible. (P2X Solutions s.a.)

Another green hydrogen production project is in the planning stage in Vaasa (Finland). The companies Wärtsilä, EPV Energy and Vaasan Sähkö plan to build a Power-to-X-to-Power (P2X2P) system that will produce hydrogen from renewable energy sources. The produced hydrogen will be stored and later used for electricity generation. The project is expected to be finished by 2024. The use of hydrogen as a fuel for the engine power plant will be gradually increased and by the end of 2026 the plant will run 100% with renewable hydrogen. (EPV 2021.)

5.2 Power-to-Methane (P2M)

Power-to-Methane technology involves the conversion of electrical energy into methane gas (CH_4) through a series of chemical reactions. Hydrogen is produced by water electrolysis and carbon dioxide is captured from a flue gas via post-combustion capture. Both gases are then converted to methane using a catalytic or bio-catalytic reactor. Methane has a larger volumetric energy density compared to hydrogen, and there is already a significant infrastructure in place for transportation and handling this gas. (EASE 2018b; DOE 2021a.)

Most operational Power-to-Methane projects are primarily found in Germany. For instance, Audi has a 6.3 MW Power-to-Methane plant in Werlte (Germany) since 2013. Wind energy is used to provide power and CO_2 from nearby biogas plant is used to generate hydrogen. The generated hydrogen is converted into methane and injected into the gas network. (Vuorenmaa et al. 2020.)

In Finland, Vantaa Energy and the technology company Wärtsilä are researching the possibility to build a 10 MW Power-to-Gas plant to produce synthetic methane in Vantaa Energy's municipal waste CHP-plant. The generated gas can be used as a substitute for natural gas their natural gas hobs or straight as a fuel for transportation. (Vuorenmaa et al. 2020.) When completed in 2025, this P2G plant will be the largest in Finland and the first to produce carbon-neutral synthetic methane on a commercial level. (Vantaan Energia 2022)

Etelä-Savon Energia Oy and Nordic Ren-Gas Oy will study the feasibility of a Power-to-Gas facility producing both renewable methane and green hydrogen. When completed in 2030, the Power-to-Gas plant would reach a capacity of 40 MW. Almost 40% of Etelä-Savon Energia' district heat could be produced cost-effectively with waste heat and 36,000 tons of biobased carbon dioxide from the Pursiala power plant could be recovered per year. (Nordic Ren-Gas Oy 2022.)

5.3 Power-to-Ammonia (P2A)

Ammonia is another potential energy carrier. Power-to-Ammonia technology involves the conversion of electrical energy into ammonia (NH_3) through a series of chemical reactions. Hydrogen is produced by water electrolysis and nitrogen is separated from air via an Air Separation Unit. Both gases are converted to ammonia by using the Haber Bosch reaction with an efficiency up to 50-55%. Like methane, there is existing infrastructure for the transportation of ammonia due to its widespread use as fertilizer. The use of ammonia directly as a fuel for power generation systems is a current area of research. (EASE 2018a; DOE 2021a.)

The Institute for Sustainable Process Technology (ISPT) has recently studied together with its partners the feasibility of the storage of renewable energy in ammonia for three business cases. In the first case ammonia would be used to store and/or import CO2, in the second case an island's power storage could be handled by ammonia, and in the third case renewable energy would be used for ammonia production to reduce gas usage. The study showed that the electrochemical production of ammonia from renewable energy is a likely option and offers a very promising solution for large-scale seasonal storage and import of renewable energy. (ISPT 2017; Vuorenmaa et al. 2020.)

5.4 Power-to-Methanol

Power-to-Methanol technology involves the conversion of electrical energy into methanol (CH_3OH) through a series of chemical reactions. Hydrogen is produced by water electrolysis while carbon dioxide is captured from a flue gas via post-combustion capture. Both gases are converted to methanol by using a catalytic reactor with an efficiency up to 50-55%. Methanol, as a liquid chemical, can be easily stored and transported compared to other fuels. Methanol can be converted into a variety of other chemicals and may also have potential as a transportation fuel. (EASE 2018c; DOE 2021a.)

The production of green methanol has been studied in different projects in the recent years. For example, the industrial-scale demonstration plant built by the INOVYN consortium in Antwerp (Belgium) aims to produce methanol combining hydrogen from renewable energy and CO2 captured by means of CCU. Tests in Germany by BSE Engineering have also proven conversion of wind power to renewable methanol with alkaline electrolysis. (Vuorenmaa et al. 2020.) Also the Danish company European Energy is developing a large-scale commercial green methanol production facility with the hydrogen being provided by a 50 MW electrolyser plant by Siemens Energy and the electricity by a nearby 300 MW solar park (Habibic 2022). In Finland, the company St1 is planning to build the first synthetic methanol plant in the country, in Lappeenranta. The plant will use CO_2 emissions from the cement factory Finnsementti. (St1 2022.)

6 CONCLUSIONS

A high-level penetration of renewable energy sources such as wind and solar into the grid is necessary to achieve zero-carbon power sector. The variable and intermittent nature of these energy sources will require energy storage systems to control the temporal mismatch between supply and demand. The energy storage technologies that are currently available commercially entail different drawbacks. For instance, lithium-ion batteries, traditional pumped hydro and conventional compressed air energy storage present disadvantages such as high costs, geographical constraints and use of fossil fuels, respectively. For this reason, ongoing research, development and innovation activities aim to improve the performance, cost-effectiveness, and sustainability of existing energy storage technologies as well as to develop new ones.

The present study has reviewed different technologies used for long-duration energy storage including thermal, mechanical, and chemical energy storage systems. Regarding thermal energy storage, sensible heat storage is a relatively mature technology that has been applied in a wide range of applications. In Finland, several borehole thermal energy storage systems, energy piles and cavern thermal energy storage systems has already been installed and numerous above ground tank thermal energy systems are currently connected to district heating networks. However, research on SHS is still needed, especially on materials and system design. On the other hand, latent heat storage and thermochemical storage systems are in the early stages of development with several ongoing demonstration projects worldwide, including in Finland.

With respect to mechanical energy storage, pumped hydro storage is the most widely deployed energy storage technology. Nevertheless, new versions of this well-established technology as well as other types of mechanical energy storage systems are being developed to overcome the disadvantages of PHS. For instance, liquid air energy storage has emerged in the recent years as a promising technology for providing large-scale, long-duration energy storage solutions. In Finland there is a potential to use decommissioned mines for various mechanical energy storage methods, including novel pumped hydro energy storage, compressed air energy storage and gravity-based energy storage (Vuorenmaa et al. 2020).

Additionally, chemical energy storage systems will play a key role in decarbonizing the power sector while also having the potential to decarbonize other sectors including transport and industry. Hydrogen is considered a promising emerging technology that can contribute to the green energy transition and provide seasonal storage of renewable energy. In Finland, there are currently several ongoing clean hydrogen projects in various phases. Hydrogen Cluster Finland believes that hydrogen could become a new export industry and pillar of the Finnish economy. (Hydrogen Cluster Finland 2023.)

REFERENCES

Aalto, P. 2021. Electrification: Accelerating the Energy Transition. Academic Press. https://doi.org/10.1016/C2019-0-03794-6.

Abdin, Z. & Khalilpour, K. R. 2019. Single and Polystorage Technologies for Renewable-Based Hybrid Energy Systems. https://doi.org/10.1016/B978-0-12-813306-4.00004-5.

Abedin, A. H. & Rosen, M. A. 2011. A Critical Review of Thermochemical Energy Storage Systems. http://dx.doi.org/10.2174/1876387101004010042.

Allison, T. C. 2020. Thermal Mechanical Chemical Energy Storage Technology Overview. PDF file. Southwest Research Institute. Published 4.2.2020.

Alnaimat, F. & Rashid, Y. 2019. Thermal Energy Storage in Solar Power Plants: A Review of the Materials, Associated Limitations, and Proposed Solutions. https://doi.org/10.3390/en12214164.

Ameen, M.T.; Ma, Z.; Smallbone, A.; Norman, R. & Roskilly, A. P. 2023. Demonstration system of pumped heat energy storage (PHES) and its round-trip efficiency. https://doi.org/10.1016/j.apenergy.2022.120580.

André, L. & Abanades, S. 2020. Recent Advances in Thermochemical Energy Storage via Solid–Gas Reversible Reactions at High Temperature. https://doi.org/10.3390/en13225859.

ARES 2015. Challenges of Storage Development - Advanced Rail Energy Storage (ARES) for Bulk Storage Conference in Sacramento. PowerPoint file. Published 20.11.2015. https://efiling.energy.ca.gov/GetDocument.aspx?tn=206697&DocumentContentId=22236.

ARES 2020. GravityLine. Internet publication. Published September 2020. https://aresnorthamerica.com/gravityline/. Accessed 29.9.2021.

Azelio 2023a. Demonstration projects. Internet publication. Updated: 10.3.2023. https://www.azelio.com/the-solution/demonstration-projects. Accessed 4.4.2023.

Azelio 2023b. The solution: Technology. Internet publication. Updated: 10.3.2023. https://www.azelio.com/the-solution/technology/. Accessed 4.4.2023.

Bauer, T.; Odenthal, C. & Bonk, A. 2021. Molten Salt Storage for Power Generation. https://doi.org/10.1002/cite.202000137.

Bayon, A.; Bader, R.; Jafarian, M.; Fedunik-Hofman, L.; Sun, Y.; Hinkley, J.; Miller, S. & Lipi?ski, W. 2018. Techno-economic assessment of solid–gas thermochemical energy storage systems for solar thermal power applications. https://doi.org/10.1016/j.energy.2017.11.084.

BEKA s.a. Thermal Ice Storage with Capillary Tube Technology. Internet publication. https://www.beka-klima.de/en/ice-storage/sp-ice-storage-cooling-technology/. Accessed 29.3.2023.

Benato, A. & Stoppato, A. 2018. Pumped Thermal Electricity Storage: A technology overview. https://doi.org/10.1016/j.tsep.2018.01.017.

Bernicot, M. 2021. An overview of the floating solar industry. PDF-file. Published 21.7.2022.

Biencinto, M.; Bayón, R.; Rojas, E. & González, L. 2014. Simulation and assessment of operation strategies for solar thermal power plants with a thermocline storage tank. https://doi.org/10.1016/j.solener.2014.02.037.

Bloemendal, M.; Olsthoorn, T. & van de Ven, F. 2015. Combining climatic and geo-hydrological preconditions as a method to determine world potential for aquifer thermal energy storage. https://doi.org/10.1016/j.scitotenv.2015.07.084.

Bowen, T.; Chernyakhovskiy, I. & Denholm, P. 2019. Grid-Scale Battery Storage. PDF file. National Renewable Energy Laboratory. Published September 2019. https://www.nrel.gov/docs/fy19osti/74426.pdf.

Brenmiller Energy 2022. Technology. Internet publication. Updated: 18.1.2022. https://bren-energy.com/technology/. Accessed 30.3.2023.

Cabeza, L. 2015. Advances in Thermal Energy Storage Systems: Methods and Applications. https://doi.org/10.1016/C2013-0-16453-7.

Caraballo, A.; Galán-Casado, S.; Caballero, A. & Serena, S. 2021. Molten Salts for Sensible Thermal Energy Storage: A Review and an Energy Performance Analysis. https://doi.org/10.3390/en14041197.

Cárdenas, B. & León, N. 2013. High temperature latent heat thermal energy storage: Phase change materials, design considerations and performance enhancement techniques. https://doi.org/10.1016/j.rser.2013.07.028.

Carrillo, A. J.; González-Aguilar, J.; Romero, M. & Coronado, J. M. 2019. Solar Energy on Demand: A Review on High Temperature Thermochemical Heat Storage Systems and Materials. https://doi.org/10.1021/acs.chemrev.8b00315.

Cavadas, J. 2019. CRYOBattery Storage? | Highview Power Interview. Video. YouTube video service, published 20.7.2020. https://www.youtube.com/watch?v=H6Ql9J3cUy8. Accessed 13.9.2022.

Climate Action Tracker 2022. Net zero targets. Internet publication. https://climateactiontracker.org/methodology/net-zero-targets/. Accessed 3.9.2021.

Cruickshank, C. A. & Baldwin, C. 2016. Storing Energy. Chapter 15 - Sensible Thermal Energy Storage: Diurnal and Seasonal. https://doi.org/10.1016/B978-0-12-803440-8.00015-4.

Das, C. K.; Bass, O.; Kothapalli, G.; Mahmoud, T. S. & Habibi, D. 2018. Overview of energy storage systems in distribution networks: Placement, sizing, operation, and power quality. Published 1.6.2018. https://doi.org/10.1016/j.rser.2018.03.068.

Department Of Energy of USA 2021a. Chemical energy storage. PDF file. Published February 2021. https://netl.doe.gov/sites/default/files/2021-02/Chemical_Storage.pdf.

Department Of Energy of USA 2021b. Mechanical energy storage. PDF file. Published February 2021. https://netl.doe.gov/sites/default/files/2021-02/Mechanical_Storage.pdf.

Diago, M.; Crespo-Iniesta, A.; Delclos, T. & Soum-Glaude, A. 2016. Characterization of desert sand as a sensible thermal energy storage medium. https://doi.org/10.1063/1.4949109.

Doczekal, C. 2019. Fact Sheet: Heat Storages. PDF file. Published September 2019. TRACER. https://tracer-h2020.eu/wp-content/uploads/2019/10/TRACER_D2.1-Heat-Storages.pdf.

Echogen s.a. Supercritical CO2-Based Long-Duration Electrical Energy Storage Technical Overview. PDF file. https://www.echogen.com/_CE/pagecontent/Documents/Echogen-Technical%20Overview%207.18.19-3.pdf.

Electrified Thermal Solutions s.a. Decarbonizing industry with renewable heat. Internet publication. https://www.electrifiedthermal.com/. Accessed 29.3.2023.

Elstor 2022a. Elstor industrial steam generation pilot plant reached the 12-month usage mark – steam without CO2 emissions and for smaller costs than fossil fuels. Internet publication. Published 22.6.2022. https://elstor.fi/en/elstor-industrial-steam-generation-pilot-plant-reached-the-12-month-usage-mark-steam-without-co2-emissions-and-for-smaller-costs-than-fossil-fuels/. Accessed 27.3.2023.

Elstor 2022b. Food manufacturer Herkkumaa is the first to switch to emission-free production with the help of new technology. Internet publication. Published 11.7.2022. https://elstor.fi/en/food-manufacturer-herkkumaa-is-the-first-to-switch-to-emission-free-production-with-the-help-of-new-technology/. Accessed 27.3.2023.

Elstor 2022c. Our technology and services. Internet publication. Updated 21.9.2022. https://elstor.fi/en/technology-and-services/. Accessed 30.3.2023.

Energy Dome 2023. CO2 battery. Internet publication. Updated 26.4.2023. https://energydome.com/co2-battery/. Accessed 17.5.2023.

Energy Vault s.a. Grid resiliency at scale - EVRC. Internet publication. Published https://www.energyvault.com/evrc. Accessed 13.9.2022.

Energy Vault s.a. Harnessing the power of gravity. Internet publication. Published https://www.energyvault.com/ev1. Accessed 13.9.2022.

EPV 2021. The hydrogen solution for electricity generation and storage planned for Vaasa has been granted EUR 14 million in investment aid. Internet publication. Published 23.12.2021. https://www.epv.fi/en/2021/12/23/finlands-first-power-to-x-to-power-hydrogen-system-to-be-built-in-vaasa/. Accessed 22.9.2022.

EPV Energia Oy 2020. Tulevaisuuden lämpöenergiavarasto otettiin käyttöön Vaasassa. Internet publication. Published 29.9.2020. https://www.epv.fi/2020/09/29/tulevaisuuden-lampoenergia-varasto-otettiin-kayttoon-vaasassa. Accessed 21.3.2022.

European Association for Storage of Energy (EASE) 2016a. Energy Storage Technology Descriptions - Diabatic Compressed Air Energy Storage. PDF-file. https://ease-storage.eu/wp-content/uploads/2016/07/EASE_TD_Mechanical_DCAES.pdf.

European Association for Storage of Energy (EASE) 2016b. Energy Storage Technology Descriptions - Adiabatic Compressed Air Energy Storage. PDF-file. https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_ACAES.pdf.

European Association for Storage of Energy (EASE) 2016c. Energy Storage Technology Descriptions - Hydrogen. PDF-file. https://ease-storage.eu/wp-content/uploads/2016/03/EASE_TD_Hydrogen.pdf.

European Association for Storage of Energy (EASE) 2018a. Energy Storage Technology Descriptions - Power to Ammonia - Gasoline synthesis from H2 and N2 by using water electrolysis and Air Separation. PDF-file. https://ease-storage.eu/wp-content/uploads/2018/09/2018.08_TVAC_WG1_TD-Power-to-Ammonia.pdf.

European Association for Storage of Energy (EASE) 2018b. Energy Storage Technology Descriptions - Power to Methane - Methane Synthesis from H2 and CO2 by Using Water Electrolysis and Post-Combustion Capture. PDF-file. https://ease-storage.eu/wp-content/uploads/2018/09/2018.08_TVAC_WG1_TD-Power-to-Methane.pdf.

European Association for Storage of Energy (EASE) 2018c. Energy Storage Technology Descriptions - Power to Methanol/Power to Gasoline – Methanol/Gasoline Synthesis from H2 and CO2 by Using Water Electrolysis and Post-Combustion Capture. PDF-file. https://ease-storage.eu/wp-content/uploads/2021/03/2018.08_TVAC_WG1_TD-Power-to-Methanol-Gasoline-b.pdf.

European Commission 2020. EDGAR - Emissions Database for Global Atmospheric Research. Internet publication. https://edgar.jrc.ec.europa.eu/climate_change. Accessed 3.9.2021.

Feng, Y.; Li, X.; Wu, H.; Li, C.; Zhang, M. & Yang, H. 2023. Critical Review of Ca(OH)2/CaO Thermochemical Energy Storage Materials. https://doi.org/10.3390/en16073019.

Finnish Government 2019. Ministry of Economic Affairs and Employment. Finland's Integrated Energy and Climate Plan. PDF file. Published 20.12.2019. https://ec.europa.eu/energy/sites/ener/files/documents/fi_final_necp_main_en.pdf.

Finnish Government s.a. Ministry of the Environment. Internet publication. https://ym.fi/en/finland-s-national-climate-change-policy. Accessed 8.3.2022.

Forsberg, C. & Aljefri, A. S. 2020. 100-Gigawatt-hour crushed-rock heat storage for CSP and nuclear. PDF file. Published 29.10.2020. https://www.solarpaces.org/wp-content/uploads/100-Gigawatt-Hour-Crushed-Rock-Heat-Storage-for-CSP-and-Nuclear.pdf.

Fortum 2015. Fortum rakentaa Suomen suurimman kaukolämpöakun Espoon Suomenojalle. Internet publication. Published 24.3.2015. https://www.fortum.fi/media/2015/03/fortum-rakentaa-suomen-suurimman-kaukolampoakun-espoon-suomenojalle. Accessed 19.4.2022.

Gbenou, S.; Fopah-Lele, A. & Wang, K. 2021. Recent Status and Prospects on Thermochemical Heat Storage Processes and Applications. https://doi.org/10.3390/e23080953.

Gehlin, S. 2016. Advances in Ground-Source Heat Pump Systems. Chapter 11: Borehole thermal energy storage. http://dx.doi.org/10.1016/B978-0-08-100311-4.00011-X.

Gehlin, S.; Andersson, O. & Rosberg, J-E. 2021. Country Update for Sweden 2020. PDF file. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2020/01040.pdf.

González-Roubaud, E.; Pérez-Osorio, D. & Prieto, C. 2017. Review of commercial thermal energy storage in concentrated solar powerplants: Steam vs. molten salts. https://doi.org/10.1016/j.rser.2017.05.084.

Gravitricity 2022a. Fast, long-life energy storage. Internet publication. Updated 20.6.2022. https://gravitricity.com/technology/. Accessed 13.9.2022.

Gravitricity 2022b. Projects. Internet publication. Updated 15.6.2022. https://gravitricity.com/projects/. Accessed 13.9.2022.

Gravity Power 2021. Low-cost energy storage with minimal environmental impact. Internet publication. Updated 12.8.2021. https://www.gravitypower.net/. Accessed 13.9.2022.

Habibic, A. 2022. Internet publication. Published 2.3.2022. https://www.offshore-energy.biz/worlds-1st-large-scale-e-methanol-project-to-fuel-maersks-boxships/. Accessed 22.9.2022.

Heindl Energy 2017. Gravity Storage: A new solution for large scale energy storage. PDF file. Published July 2017. https://www.heindl-energy.com/wp-content/uploads/2017/10/Brochure_Gravity_Storage_2017.pdf.

Helen Oy 2014a. Salmisaaren voimalaitos. Internet publication. Published 5.2.2014. https://www.helen.fi/helen-oy/energia/energiantuotanto/voimalaitokset/salmisaari. Accessed 19.4.2022.

Helen Oy 2014b. Vuosaaren voimalaitokset. Internet publication. Published 5.2.2014. https://www.helen.fi/helen-oy/energia/energiantuotanto/voimalaitokset/vuosaari. Accessed 19.4.2022.

Heliostorage 2020. Heliostorage technology in use. PDF file. Published November 2020. https://projekti.centria.fi/data/liitteet/197fa901aba64a8885b1ea529fc8fcf2.pdf.

Highview Power 2018. Technology. Internet publication. Published 14.2.2018. https://highviewpower.com/technology/. Accessed 13.9.2022.

Highview Power 2022. Plants. Internet publication. Updated 27.7.2022. https://highviewpower.com/plants/. Accessed 13.9.2022.

HiilineutraaliSuomi. Lappeenranta replaces fossil fuels with a new kind of thermal battery. Internet publication. Published 3.8.2022. https://hiilineutraalisuomi.fi/en-US/Current/Lappeenranta_replaces_fossil_fuels_with_(63564). Accessed 30.3.2023.

Hirvonen, J. 2020. Seasonal thermal energy storage in Finland. PDF file. Published 9.3.2020. https://www.aalto.fi/sites/g/files/flghsv161/files/2020-03/Janne%20-%20Seasonal_storage_in_Finland_2020_03_09%20Distrib.pdf.

Huhtinen, M. 2021. Heat Circulation Innovation Platform North Savo

HCIP-NS-project. PowerPoint file. Savonia University of Applied Sciences. Published 30.8.2021.

Hunt, J. D.; Zakeri, B.; Falchetta, G.; Nascimento, A.; Wada, Y. & Riahi, K. 2020. Mountain Gravity Energy Storage: A new solution for closing the gap between existing short- and long-term storage technologies. https://doi.org/10.1016/j.energy.2019.116419.

Hydrogen Cluster Finland 2022. Projects. Internet publication. Updated 18.8.2022. https://h2cluster.fi/projects/. Accessed 22.9.2022.

Hydrogen Cluster Finland 2023. A set of hydrogen projects is opening up the market in Finland. Internet publication. Published 5.1.2023. https://h2cluster.fi/hydrogen-projects-opening-up-the-market-in-finland/. Accessed 23.5.2023.

Inada, Y. 2021. Thermal energy storage developing for a decarbonized society. PDF file. Published February 2021. Mitsui & Co. Global Strategic Studies Institute. https://www.mitsui.com/mgssi/en/report/detail/___icsFiles/afieldfile/2021/04/27/2102m_inada_e.pdf.

Institute for Sustainable Process Technology (ISPT) 2017. Power to Ammonia: From renewable energy to CO_2-free ammonia as chemical feedstock and fuel. Internet publication. Published 16.3.2017. https://ispt.eu/news/power-ammonia-renewable-energy-co2-free-ammonia-chemical-feedstock-fuel/. Accessed 22.9.2022.

International Forum on Pumped Storage Hydropower (IFPSH) 2021. Innovative Pumped Storage Hydropower Configurations And Uses Capabilities, Costs & Innovation Working Group. PDF file. Published September 2021.

IRENA 2020. Innovative operation of pumped hydropower storage. Abu Dhabi: International Renewable Energy Agency.

IUPAC 2019. Compendium of Chemical Terminology, 2nd ed. (the ”Gold Book”). Online version created by S. J. Chalk. https://doi.org/10.1351/goldbook.

Janiszewski, M. 2019. Techno-economic aspects of seasonal underground storage of solar thermal energy in hard crystalline rocks. Doctoral dissertation. Civil Engineering. Aalto University. http://urn.fi/URN:ISBN:978-952-60-8724-5.

Janiszewski, M.; Shen, B. & Rinne, M. 2018. Hydraulically fractured hard rock aquifer for seasonal storage of solar thermal energy. In V. Litvinenko (Ed.), Geomechanics and Geodynamics of Rock Masses: Proceedings of the 2018 European Rock Mechanics Symposium (Vol. 1, pp. 821-826). CRC PRESS.

Jouhara, H.; Żabnieńska-Góra, A.; Khordehgah, N.; Ahmad, D. & Lipinski, T. 2020. Latent thermal energy storage technologies and applications: A review. https://doi.org/10.1016/j.ijft.2020.100039.

Kaua’i Island Utility Cooperative & AES West Kauai Energy Project, LLC. 2021. West Kaua’i Energy Project: Draft Environmental Assessment. PDF file. XXXX. Published July 2021. https://files.hawaii.gov/dbedt/erp/Doc_Library/2021-08-23-KA-DEA-West-Kauai-Energy-Project-Vol-1.pdf.

Khan, M. I.; Asfand, F. & Al-Ghamdi, S. G. 2022. Progress in research and development of phase change materials for thermal energy storage in concentrated solar power. https://doi.org/10.1016/j.applthermaleng.2022.119546.

King, M.; Jain, A.; Bhakar, R.; Mathur, J.; Wang, J. 2021. Overview of current compressed air energy storage projects and analysis of the potential underground storage capacity in India and the UK. 2021. https://doi.org/10.1016/j.rser.2021.110705.

Kur, A.; Darkwa, J.; Calautit, J.; Boukhanouf, R. & Worall, M. 2023. Solid–Gas Thermochemical Energy Storage Materials and Reactors for Low to High-Temperature Applications: A Concise Review. https://doi.org/10.3390/en16020756.

LDES Council 2022. The journey to net-zero: An action plan to unlock a secure, net-zero power system. PDF file. Published June 2022. https://www.ldescouncil.com/assets/pdf/journey-to-net-zero-june2022.pdf.

Liu, H.; Wang, W. & Zhang, Y. 2021. Performance gap between thermochemical energy storage systems based on salt hydrates and materials. https://doi.org/10.1016/j.jclepro.2021.127908.

Lizana, J.; Chacartegui, R.; Barrios-Padura, Á. & Valverde, J. M. 2017. Proceedings of the 3rd International Congress on Sustainable Construction and Eco-Efficient Solutions. Chapter 30: Characterization of thermal energy storage materials for building applications. https://idus.us.es/bitstream/handle/11441/59094/Jesus%20lizana%20%28eng%29.pdf?sequence=1&isAllowed=y.

Magaldi Green Energy 2021. Thermal Energy Storage. Internet publication. Published October 2021. https://www.magaldigreenenergy.com/en/mgtes-magaldi-green-thermal-energy-storage. Accessed 9.8.2022.

MAN Energy Solutions 2018. MAN and ABB introduce unique Energy Storage Solution. PDF file.

MAN Energy Solutions SE. Published 26.06.2018. https://www.man-es.com/docs/default-source/press-releases-new/180626-man-press-release_etes_en.pdf.

McTigue, J.; Farres-Antunez, P.; Ellingwood, K.; Neises, T. & White, A. 2019. Pumped Thermal Electricity Storage with Supercritical CO2 Cycles and Solar Heat Input: Preprint. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-74753. https://www.nrel.gov/docs/fy20osti/74753.pdf.

Medina-Carrasco, S. & Valverde, J. M. 2022. The Calcium Looping process for energy storage: Insights from in situ XRD analysis. https://doi.org/10.1016/j.cej.2021.132244.

MGA Thermal 2022. Introducing the MGA Block. Long Duration Energy Storage 101: All About Thermal Energy Storage Technologies Part 2. Video. YouTube video service, published 15.11.2022. https://www.youtube.com/watch?v=4Y-y4P1VAcM. Accessed 15.3.2023.

MGA Thermal s.a. Introducing the MGA Block. Internet publication. https://www.mgathermal.com/pilot. Accessed 29.3.2023.

Murray, C. 2022. Vattenfall starts filling up 200MW thermal storage tower in Berlin. Internet publication. Energy Storage News. Published 4.7.2022. https://www.energy-storage.news/vattenfall-starts-filling-up-200mw-thermal-storage-tower-in-berlin/. Accessed 9.8.2022.

Nilsson, E. & Rohdin, P. 2019. Performance evaluation of an industrial borehole thermal energy storage (BTES) project – Experiences from the first seven years of operation. https://doi.org/10.1016/j.renene.2019.05.020.

NollaE 2023. Turun toriparkki. Internet publication. Updated 28.06.2023. https://www.nollae.fi/en/turun-toriparkki-2/. Accessed 28.6.2023.

Nordic Ren-Gas Oy 2022. Etelä-Savon Energia and Nordic Ren-Gas have signed a cooperation agreement to develop 100 MEUR hydrogen investment in Mikkeli. Internet publication. Published 2.2.2022. https://ren-gas.com/en/news/etela-savon-energia-and-nordic-ren-gas-have-signed-a-cooperation-agreement-to-develop-100-meur-hydrogen-investment-in-mikkeli/. Accessed 22.9.2022.

Nostromo s.a. Technology. Internet publication. https://www.nostromo.energy/technology/. Accessed 29.3.2023.

NREL 2021. NREL Options a Modular, Cost-Effective, Build-Anywhere Particle Thermal Energy Storage Technology. Internet publication. Published 30.8.2021. https://www.nrel.gov/news/program/2021/nrel-options-a-modular-cost-effective-build-anywhere-particle-thermal-energy-storage-technology.html. Accessed 2.8.2022.

NREL 2022. Concentrating Solar Power Projects. Excel file. Published 1.7.2022. https://solarpaces.nrel.gov/. Accessed 19.4.2023.

Oceanus s.a. Resilient and Affordable Sources of Water and Energy Storage. Internet publication. https://www.oceanus.pw/. Accessed 19.9.2022.

Official Statistics of Finland 2020. Energy supply and consumption. Internet publication. http://www.stat.fi/til/ehk/2020/ehk_2020_2021-12-16_tie_001_en.html. Accessed 8.3.2022.

O-PAC 2022. O-PAC, the sustainable solution. Updated 25.8.2022. https://o-pac.nl/. Accessed 20.9.2022.

Ortiz, C.; Valverde, J. M.; Chacartegui, R.; Pérez-Maqueda, L. A. & Gimenez-Gavarrell, P. 2020. Scaling-up the Calcium-Looping Process for CO2 Capture and Energy Storage. https://doi.org/10.14356/kona.2021005.

Ortiz, C.; Valverde, J. M.; Chacartegui, R.; Pérez-Maqueda, L. A. & Gimenez-Gavarrell, P. 2019. The Calcium-Looping (CaCO3/CaO) process for thermochemical energy storage in Concentrating Solar Power plants. http://dx.doi.org/10.1016/j.rser.2019.109252.

P2X Solutions s.a. Project. Internet publication. https://p2x.fi/en/project/. Accessed 22.9.2022.

Patel, S. 2019. A Review of Global Power-to-Gas Projects To Date. Internet publication. Published 2.12.2019. https://www.powermag.com/a-review-of-global-power-to-gas-projects-to-date-interactive/. Accessed 22.9.2022.

PlanEnergi 2018. Long term storage and solar district heating. PDF file. Published May 2018. http://planenergi.dk/wp-content/uploads/2018/05/24-sol-til-fjernvarme_brochure_oplag-2_til-web.pdf.

Polar Night Energy 2022. Technology. Internet publication. https://polarnightenergy.fi/technology. Accessed 16.8.2022.

Ponec, A. 2021. Long-duration Energy Storage for Energy Seminar at Standford University. Video. YouTube video service, published 28.10.2021. https://www.youtube.com/watch?v=XYd3GGV07UE. Accessed 18.8.2022.

Pyhänjärven Callio 2018. Callio Pyhäjärvi PPHES in Mine. Video. YouTube video service, published 20.3.2018. https://www.youtube.com/watch?v=0Fcr1nAsYUg. Accessed 18.8.2022.

Quidnet Energy s.a. Geomechanical Pumped Storage. Internet publication. https://www.quidnetenergy.com/solution/. Accessed 16.8.2022.

Raos, S.; Ilak, P.; Rajšl, I.; Bilic, T. & Trullenque, G. 2019. Multiple-Criteria Decision-Making for Assessing the Enhanced Geothermal Systems. https://doi.org/10.3390/en12091597.

RheEnergise 2021. Introducing High-Density Hydro (V3.3). PDF file. Published 2021.

Rondo s.a. The Rondo Heat Battery. Internet publication. https://rondo.com/how-it-works. Accessed 30.3.2023.

Rozas-Labrador, C. R. 2021. Proyecto Hidrocaleras: Almacenamiento Hidroeléctrico de Energía con agua de mar. PDF file. Published 29.4.2021. http://www.clubderoma.net/jornadas/2021-CECoRGr-Ara-20210429/Presentacion-CarlosRozas-GrArag-20210429-AlmacenamientoEnergetico.pdf.

SaltX Technology 2021. The Technology Behind SaltX Energy Storage. Internet publication. Updated 10.3.2021. https://investor.saltxtechnology.com/technology/. Accessed 18.4.2023.

Sandia National Laboratories 2022. Global Energy Storage Database. Internet publication. Updated January 2022. https://sandia.gov/ess-ssl/gesdb/public/statistics.html. Accessed 4.7.2022.

Sarbu, I. & Sebarchievici, C. 2018. A Comprehensive Review of Thermochemical Energy Storage Systems. https://doi.org/10.3390/su10010191.

SCORES s.a. Redox heat battery - energy storage solution. Internet publication. http://www.scores-project.eu/redox-heat-battery. Accessed 10.5.2023.

Siemens Gamesa 2019. World first: Siemens Gamesa begins operation of its innovative electrothermal energy storage system. Internet publication. Published 12.6.2019. https://www.siemensgamesa.com/newsroom/2019/06/190612-siemens-gamesa-inauguration-energy-system-thermal. Accessed 18.10.2022.

Silbat 2023. The Art Of Canning A Red Dwarf. Internet publication. Updated: 2.4.2023. https://silbat.com/. Accessed 5.4.2023.

Slocum, A. H. & Gessel, D. J. 2022. Evolving from a hydrocarbon-based to a sustainable economy: Starting with a case study for Iran. https://doi.org/10.1016/j.rser.2021.111750.

Snowy Hydro 2020. Snowy 2.0 Project Update. Booklet file. Published August 2020. https://issuu.com/snowyhydro/docs/sh1715_snow_2.0_booklet_v10_coord/14.

Solé, A.; Martorell, I. & Cabeza, L. F. 2015. State of the art on gas–solid thermochemical energy storage systems and reactors for building applications. https://doi.org/10.1016/j.rser.2015.03.077.

St1 2022. St1 is planning a synthetic methanol pilot plant in Lappeenranta, Finland. Internet publication. Published 4.10.22. https://www.st1.com/st1-is-planning-a-synthetic-methanol-pilot-plant-in-lappeenranta-finland. Accessed 22.5.2023.

Stiesdal 2021. GridScale Energy storage system. PDF file. Published November 2021. https://www.stiesdal.com/wp-content/uploads/2021/11/30883-Stiesdal-Storage-Technologies-brochure.pdf.

SwRI 2022. SwRI demonstrates small-scale pumped heat energy storage system. Internet publication. Published 22.8.2022. https://www.swri.org/press-release/swri-demonstrates-small-scale-pumped-heat-energy-storage-system. Accessed 17.5.2023.

Sähköviesti 2021. Kaukolämpöakku tuottanut miljoonan jo ensimmäisenä vuonna. Internet publication. Published 25.05.2021. https://www.sahkoviesti.fi/paikalliset/kaukolampoakku-tuottanut-miljoonan-jo-ensimmaisena-vuonna.html. Accessed 18.10.2022.

Tafur-Escanta, P.; Valencia-Chapi, R.; López-Guillem, M.; Fierros-Peraza O. & Muñoz-Antón, J. 2022. Electrical energy storage using a supercritical CO2 heat pump. https://doi.org/10.1016/j.egyr.2022.01.073.

Tahvanainen, A. 2018. Thermal energy storing in the Skanssin torni. Bachelor's thesis. Energy and environmental engineering. Turku University of Applied Sciences. https://urn.fi/URN:NBN:fi:amk-2018092215315.

TEXEL Energy Storage 2022. The Battery Technology. Published 2022. Internet publication. https://www.texeles.com/technology/. Accessed 12.5.2023.

The Engineer 2017. Hot rocks offer solution to grid-scale energy storage. Internet publication. Published 3.11.2017. https://www.theengineer.co.uk/content/news/hot-rocks-offer-solution-to-grid-scale-energy-storage. Accessed 17.5.2023.

The European Association for Storage of Energy 2021. Description of different energy storage systems. Internet publication. Updated 5.3.2021. https://ease-storage.eu/energy-storage/technologies/. Accessed 2.9.2021.

The Verge 2022. Meet the CO2 battery cozying up with a wind energy giant. Published 12.10.2022. https://www.theverge.com/2022/10/12/23399567/co2-battery-wind-solar-renewable-energy-storage. Accessed 17.5.2023.

Tiano, F. A. & Rizzo, G. 2021. Use of an Under-Water Compressed Air Energy Storage (UWCAES) to Fully Power the Sicily Region (Italy) With Renewable Energy: A Case Study. https://doi.org/10.3389/fmech.2021.641995.

TNO 2022. Cellcius: the compact heat battery for at-home energy storage. Updated 23.6.2022. Internet publication. https://www.tno.nl/en/sustainable/safe-sustainable-living-environment/energy-built-environment/energy-storage/cellcius-compact-heat-battery-home/. Accessed 10.5.2023.

Todorov, O.; Alanne, K.; Virtanen, M. & Kosonen, R. 2020. A method and analysis of aquifer thermal energy storage (ATES) system for district heating and cooling: A case study in Finland. https://doi.org/10.1016/j.scs.2019.101977.

Todorov, O.; Alanne, K.; Virtanen, M. & Kosonen, R. 2020. Aquifer Thermal Energy Storage (ATES) for District Heating and Cooling: A Novel Modeling Approach Applied in a Case Study of a Finnish Urban District. https://doi.org/10.3390/en13102478.

Trane 2020. CALMAC® Ice Bank® Energy Storage Tank Model C. Internet publication. https://www.trane.com/commercial/latin-america/pr/en/products-systems/energy-storage-solutions/Energy-storage-tank-c.html. Accessed 5.4.2023.

U.S. Department of Energy 2020. Energy Storage Grand Challenge: Energy Storage Market Report. PDF file. Published December 2020. https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Market%20Report%202020_0.pdf.

U.S. Energy Information Administration (EIA) 2020. Battery Storage in the United States: An Update on Market Trends. PDF file. Published July 2020. https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage.pdf.

Underground Energy 2017a. ATES – Aquifer Thermal Energy Storage. Internet publication. https://underground-energy.com/our-technology/ates/. Accessed 15.3.2023.

Underground Energy 2017b. BTES – Borehole Thermal Energy Storage. Internet publication. https://underground-energy.com/our-technology/btes/. Accessed 15.3.2023.

ur Rehman, H. 2020. Introduction - Thermal energy storage. PDF file. Published 11.3.2020. https://mycourses.aalto.fi/pluginfile.php/1206570/mod_folder/content/0/TES_L3_Introduction%20%20overview%20to%20TES_Hassam%20ur%20Rehman.pdf.

van den Heuvel, M. 2020. Peak Buffering by the Ecovat Thermal Energy Storage System. Master's thesis. Eindhoven University of Technology. https://www.ecovat.eu/wp-content/uploads/2020/10/0950302-Peak-Buffering-by-the-Ecovat-Thermal-Energy-Storage-System-Master-Thesis-Marijn-van-den-Heuvel-gecomprimeerd.pdf.

Vantaan Energia 2022. Finland’s first industrial-scale Power-to-Gas plant – Vantaa Energy and Wärtsilä take Finland towards carbon neutrality. Internet publication. Published 8.12.2021. https://www.vantaanenergia.fi/en/finlands-first-industrial-scale-power-to-gas-plant-vantaa-energy-and-wartsila-take-finland-towards-carbon-neutrality/. Accessed 22.9.2022.

Vatajankoski 2020. SYKEn webinaari. Case Kankaanpää: Lämpöä ilman tulta. PDF file. Published 3.11.2020. https://www.hiilineutraalisuomi.fi/download/noname/%7B1C67932C-7D0E-48BA-B58A-49FB627817DE%7D/163090.

Venkataraman, M. 2023. Long Duration Energy Storage 101: All About Thermal Energy Storage Technologies Part 2. Video. YouTube video service, published 15.3.2023. https://www.youtube.com/watch?v=tAX-PHeLhaM. Accessed 5.4.2023.

Vuorenmaa, M.; Mahmoodi, K.; Lindblom, O.; Värä, A.; Sierakowski, M. 2020. Technologies for storing electricity in medium- and long term – potential in Finland. https://energia.fi/files/5519/ET_Energy_storages_report_final_20201211.pdf.

Wikipedia Commons 2010. Esquema altimetrico. Published 2.6.2010. https://commons.wikimedia.org/wiki/File:Esquema_altimetrico.jpg. Accessed 29.9.2023.

World Health Organization 2021. Climate change and health. Internet publication. Published 30.10.2021. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health. Accessed 25.1.2022.

Wyrwa, A.; Raczynski, M.; Kulik, M.; Oluwapelumi, O.; Mateusiak, L.; Zhang, H. & Kempka, M. 2022. Greening of the District Heating Systems—Case Study of Local Systems. https://doi.org/10.3390/en15093165.

Yliluoto, P. 2022. Bachelor’s thesis. Survey and technical comparison of rock cavern thermal energy storages built and under construction in Finland. Energy and environmental engineering. Turku University of Applied Sciences. https://urn.fi/URN:NBN:fi:amk-202201131260.

Zavattoni, S. A.; Zanganeh, G.; Pedretti, A. & Barbato, M. C. 2018. Numerical Analysis of the Packed Bed TES System Integrated into the First Parabolic Trough CSP Pilot-plant Using Air as Heat Transfer Fluid. Published 8.11.2018. https://aip.scitation.org/doi/pdf/10.1063/1.5067121.

SAVONIA
University of Applied Sciences

HEAT CIRCULATION INNOVATION PLATFORM NORTH SAVO HCIP-NS-PROJECT

ENERGY STORAGE SYSTEMS: A STATE-OF-THE-ART STUDY

This state-of-the-art study on energy storage systems has been written within the project Heat Circulation Innovation Platform North-Savo (HCIP-NS) realized from 1.8.2021 to 30.10.2023. The project was realized by Savonia UAS Energy Research Centre organisation at Varkaus Campus.

This study describes the principles of several long duration energy storage (LDES) technologies. LDES is a promising solution to control the temporal mismatch between supply and demand caused by a high-level penetration of intermittent renewable energy sources such as wind and solar into the grid. Sensible heat storage technologies, including aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), tank thermal energy storage (TTES), pit thermal energy storage (PTES), cavern thermal energy storage (CTES) and fractured thermal energy storage (FTES) methods, are reviewed. Additionally, latent heat storage (LHS) systems as well as thermochemical storage (TCES) are discussed.

The review also describes mechanical storage systems such as novel pumped hydro storage (PHS), compressed air energy storage (CAES), liquid air energy storage (LAES), pumped heat energy storage (PHES) and gravity-based energy storage technologies. Finally, Power-to-X technologies such as Power-to-Hydrogen are briefly reviewed.

European Union
European Regional
Development Fund

Leverage from
the EU
2014–2020

Pohjois-Savon liitto
Regional Council of Pohjois-Savo

Energy Cluster
POHJOIS-SAVO • NORTH SAVO

ISBN: 978-952-203-323-9 (PDF)
ISSN: 2343-5496
SAVONIA AMMATTIKORKEAKOULUN JULKAISUSARJA: 12/2023