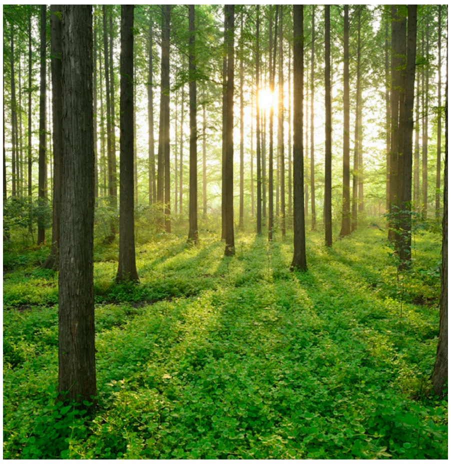
HIGH TEMPERATURE STORAGE FOR STEAM PRODUCTION

REPORT 2025:1149



ASHPROGRAMME

Energiforsk

High temperature storage for steam production

Ökad flexibilitet mot elmarknaden genom högtemperaturlager för ångproduktion

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ISBN 978-91-89918-56-6| © Energiforsk December 2025

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Foreword

This report explores how high-temperature thermal energy storage (TES) can improve operational flexibility and reduce electricity costs in industrial steam production.

The findings in this report provide valuable insights for industries seeking cost-effective and scalable energy storage solutions to optimize steam generation and respond to fluctuating electricity prices.

December 2025

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Responsible for the Ashprogramme at Energiforsk

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

Summary

This project investigates how high-temperature thermal energy storage (TES) can enhance flexibility in electricity consumption for industrial steam production, with focus on its application in a paper mill.

TES enables industries to optimize energy costs by storing heat during periods of low electricity prices and releasing it when needed. Technologies such as sensible heat storage (SHS), latent heat storage (LHS), and thermochemical storage (TCS) offer varying benefits in terms of efficiency, scalability, and cost.

In this study TES solutions in the range of 300–500 MWh and 80 MW for industrial steam production (3–12 bar), with a focus on integration into pulp and paper mills are evaluated. The Holmen Hallsta paper mill in Sweden, serves as a case study, where TES could enhance operational flexibility and reduce electricity costs by decoupling steam generation from real-time power consumption.

Solid-state SHS, using materials like concrete or ceramics, is identified as the most suitable technology for Hallsta paper mill due to its high efficiency (>90%), low investment cost (15–40 €/kWh), commercial maturity (Technology readiness level, TRL 8–9), and compatibility with existing infrastructure. It also offers temperature compatibility with required saturated steam generation 134-188 °C (3-12 bar) and is scalable to the required capacity.

Alternative technologies such as molten salt storage and battery systems are also considered. Molten salt offers slightly higher energy density but involves greater complexity and cost. Battery systems provide flexibility for electrical applications and may also be suitable in processes where heat is already generated electrically, as at Hallsta paper mill.

For Kraft pulp mills, battery energy storage provides significant flexibility for electricity management, while thermal energy storage does not contribute meaningfully to power-side flexibility and is therefore not economically viable.

Further work is recommended to refine cost estimates, to evaluate system integration challenges, and to explore the potential of combining TES and/or Battery Energy Storage System (BESS) with high-temperature heat pumps (HTHPs). A detailed analysis of levelized cost of storage (LCOS) and dynamic control strategies for demand-side response would support future implementation and optimization.

Keywords

Thermal energy storage, steam production, electricity cost, flexibility

Termisk energilagring, ångproduktion, elkostnad, flexibilitet

Sammanfattning

Detta projekt undersöker hur flexibiliteten i elanvändningen kan ökas genom termisk energilagring (TES) vid temperaturnivåer tillräckligt höga för ångproduktion inom pappersindustrin.

TES möjliggör optimering av energianvändningen genom att lagra värme under perioder med låg efterfrågan eller låga elpriser, och frigöra den när behovet är större. Tekniker såsom sensibel värmelagring (SHS), latent värmelagring (LHS) och termokemisk lagring (TCS) erbjuder olika fördelar vad gäller effektivitet, skalbarhet och kostnad.

I denna studie utvärderas TES-lösningar i storleksordningen 300–500 MWh och 80 MW för industriell ångproduktion (3–12 bar), med särskilt fokus på integration i massa- och pappersbruk. Holmen Hallsta pappersbruk i Sverige används som fallstudie, där TES kan bidra till ökad driftflexibilitet och minskade elkostnader genom att koppla loss ångproduktionen från realtidsförbrukningen av el.

SHS med fasta material (*solid state*), som betong eller keramik, identifieras som den mest lämpliga teknologin för Hallsta pappersbruk tack vare dess höga verkningsgrad (>90 %), låga investeringskostnad (15–40 €/kWh), kommersiella mognad (teknologisk mognadsgrad, TRL 8–9) samt kompatibilitet med befintlig infrastruktur. Tekniken erbjuder även temperaturkompatibilitet med den ångproduktion som krävs 134–188 °C (3–12 bar) och är skalbar till den efterfrågade kapaciteten.

Alternativa teknologier såsom smält salt-lagring och batterisystem har också beaktats. Smält salt erbjuder något högre energidensitet men medför större komplexitet och kostnader. Batterisystem ger flexibilitet för elektriska tillämpningar och kan vara lämpliga i sammanhang där värme redan genereras elektriskt, såsom vid Hallsta pappersbruk.

För sulfatmassabruk innebär batterilagring betydande flexibilitet i elanvändningen, medan termisk energilagring inte bidrar nämnvärt till effektflexibilitet och är därför inte ekonomiskt lönsam.

Som fortsatt arbete rekommenderas att göra mer detaljerade kostnadsuppskattningar, att utvärdera integrationsutmaningar och att undersöka potentialen i att kombinera TES och/eller batterilagring (BESS) med högtemperaturvärmepumpar (HTHPs). En detaljerad analys av utjämnad lagringskostnad (LCOS) samt dynamiska styrstrategier för efterfrågestyrning skulle stödja framtida implementering och optimering.

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List of Abbreviations

Abbreviation	Explanation
AC	Alternating current
BESS	Battery Energy Storage System
BMS	Battery management system
CAPEX	Capital expenditure
CESS	Chemical energy storage system
CSP	Concentrated solar power
DC	Direct current
DSR	Demand side response
ECESS	Electrochemical energy storage system
EESS	Electric energy storage system
EMS	Energy Management System
ESS	Energy Storage System
GWP	Global warming potential
HTHP	High-temperature heat pump
LCO	Lithium cobalt oxide
LCOS	Levelized Cost of Storage
LFP	Lithium iron phosphate
LHS	Latent heat storage
Li-ion	Lithium-ion
LTO	Lithium titanate
MESS	Mechanical energy storage systems
MVR	Mechanical vapor recompression
NaS	Sodium-sulphur
Ni-Cd	Nickel-cadmium
NMC	Nickel-manganese-cobalt
OPEX	Operational expenditure
PbA	Lead-acid
PCM	Phase Change Material
PCS	Power conversion system
PM	Paper Machine
SB	Steam Boiler
SHS	Sensible heat storage
TCM	Thermochemical Materials
TCS	Thermochemical storage
TES	Thermal energy storage
TESS	Thermal energy storage system
TMP	Thermomechanical pulp
TRL	Technology readiness level
UTES	Underground thermal energy storage

Abbreviation	Explanation
VRFB	Vanadium redox flow battery
WTTES	Water tank thermal energy storage

1 Introduction

1.1 INTRODUCTION TO ENERGY STORAGE

In the global transition toward sustainable and reliable energy systems, energy storage plays a critical role in bridging the gap between supply and demand. The growing integration of variable renewable sources, such as solar and wind, introduces fluctuations in power generation, challenging the stability of energy supply. Advanced storage technologies mitigate this issue by capturing excess energy during periods of oversupply and discharging it when demand increases or generation declines.

As shown in the Table 1, energy storage systems (ESS) can be broadly classified into five main categories based on the stored energy form:

- Mechanical energy storage systems MESS
- Electrochemical energy storage systems ECESS
- Electric energy storage systems EESS
- Chemical energy storage systems CESS
- Thermal energy storage systems TESS

Table 1. Classification of energy storage system [1].

Energy storage system ESS				
Mechanical MESS	**Electrochemical ECESS**	**Electric EESS**	**Chemical CESS**	**Thermal TESS**
Pumped hydro	Battery	Capacitors	Hydrogen	Sensible thermal
Compressed air	Flow Battery	Super capacitors	Ammonia	Latent thermal
Flywheel		Super conducting magnetic	Biofuels	Thermochemical

Among these, thermal energy storage (TES) is gaining prominence as a viable solution to address the intermittency of renewable energy. By storing heat or cold for later use, TES enables energy to be supplied precisely when and where it is needed. While widely implemented in sectors such as concentrated solar power (CSP) plants, district heating, and building heating, these systems also offer valuable benefits for industrial applications.

In general, thermal energy storage (TES) can be used to store solar or wind power when in excess to be stored and thus reduce the need for fossil energy in a mixed (bio and fossil) energy system whether it is an industrial application or national electric grid. But in this project applied to the Holmen Hallsta paper mill in Sweden TES will have insignificant impact on fossil CO_2 emissions since the fossil CO_2 emission of the Swedish power grid is very low. Furthermore, Hallsta paper mill does not use any fossil fuels for steam production anyhow. For the definition of this project the motive for TES is primarily to reduce electric energy costs.

1.2 BACKGROUND

Holmen AB, a large Swedish forest industry company, is considering the implementation of a thermal energy storage (TES) at its pulp and paper mill in Hallstavik, Sweden. Today there are no other primary energy resources than electricity. The plant has already been designed to operate with a high level of energy efficiency. However, this has come at the expense of operational flexibility. For instance, the pulp and paper sections must operate simultaneously, as the excess heat from the pulp process is used to generate steam for the paper machines. To the authors' knowledge, there is no comparable facility in operation globally, and therefore no prior research specifically addressing this type of case in combination with high-temperature thermal energy storage.

The goal of introducing a thermal storage system is to enhance the plant´s demand side response (DSR) capabilities, thereby improving flexibility in electricity consumption in response to volatile electricity prices. In addition, the overall operational flexibility of the mill can be increased.

1.2.1 The thermomechanical pulping process

This project primarily deals with the integration of thermal energy storage for steam production in integrated paper mills that utilize thermomechanical pulp (TMP) to manufacture graphical paper, such as magazine and book paper (see Figure 1).

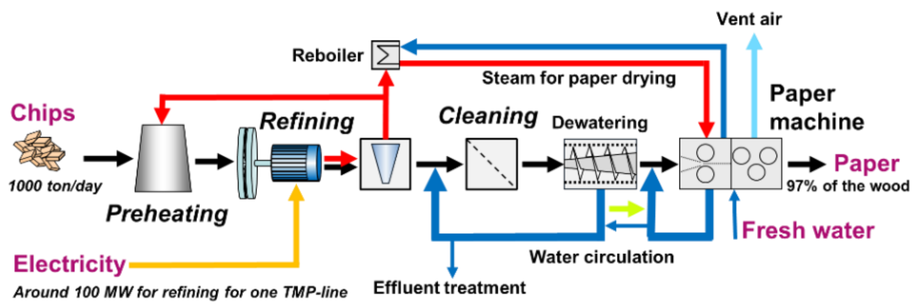

Figure 1. Simplified overview of a TMP line and paper machine showing fibre, steam and water flows. Source: Holmen.

TMP is an efficient method for converting wood chips into individual fibres used in papermaking. These fibres are diluted with water and formed into a thin sheet on the paper machine. The water is removed by pressing and drying with steam-heated cylinders, resulting in paper that has high opacity and bulk. TMP offers a high wood yield, approximately 97% of the original wood chips are converted into usable fibres, significantly reducing wood raw material costs compared to chemical pulp.

At the core of the TMP process is the refiner, Figure 2. Before refining, wood chips are transported from storage silos, washed with water, and then softened using steam. This steam treatment loosens the lignin, the natural glue binding wood fibres together. Once softened, the chips are fed into the refiner via a high-pressure screw system together with water which is necessary for cooling of the grinding.

The refiner contains grind discs which grind the wood chips into pulp. A magnification of a disc is shown in Figure 2. In the grinding process the mechanical energy is converted to heat through friction which evaporates the added water to steam. The steam blows the separated fibres out of the refiner to a steam separator whereafter the fibres are diluted with water and transported via a cleaning process and finally to the paper machine. The steam from the refiners is partly used for wood chip preheating, but the main flow goes to a reboiler where the dirty refiner steam is used to produce clean steam from boiler water.

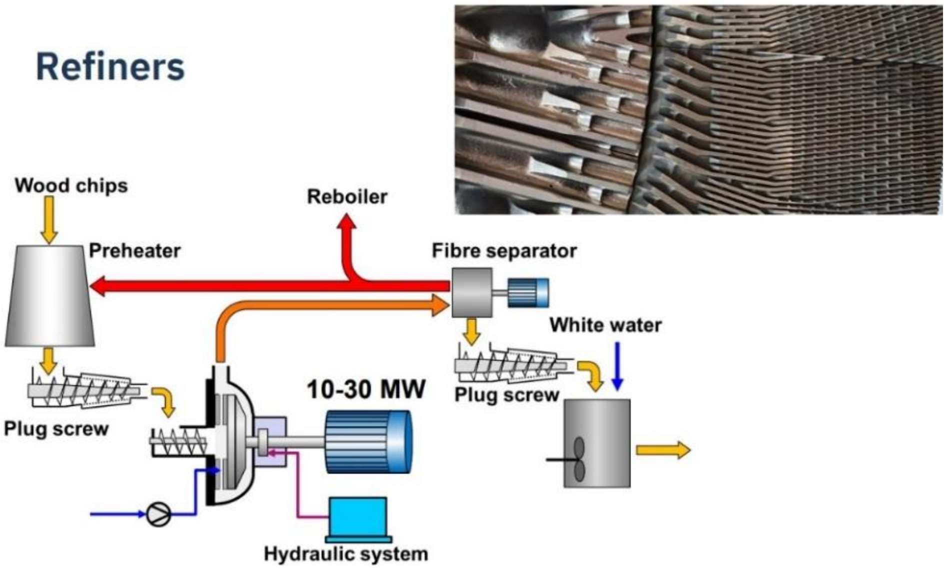

Figure 2. The refiner process. Source: Holmen.

1.2.2 Steam Recovery and Reboiler integration

The TMP refining process requires a high input of electric energy, typically 150-200 MW for one papermill. The electric power of a typical refiner motor is 10-30 MW of which almost all end up as latent and sensible heat in the pulp and steam leaving the refiner.

In the reboiler the dirty TMP steam is used to produce low pressure steam (typically 2-4 bar(g)) from water of boiler feed water quality, Figure 3. Dirty TMP steam (red) is condensed in tubes, and the energy is used to produce saturated steam on the outside of the tubes from boiler feed water. The produced steam is mainly used to dry the paper in the paper machine.

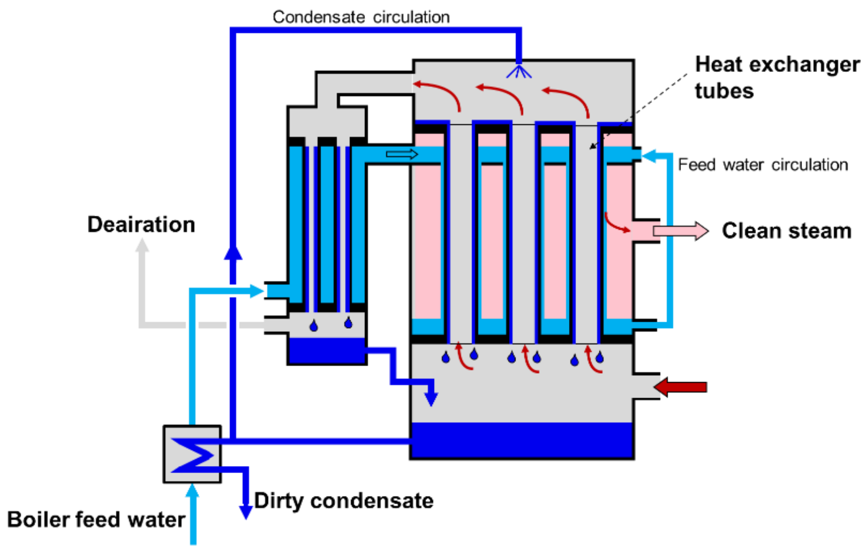

Figure 3. Reboiler principles. Source: Holmen.

1.2.3 Water and steam system integration

In modern TMP-based paper mills, large quantities of water are used in the pulp and paper production processes, but most of it is recirculated in closed loops to minimize overall water consumption. Fresh water is preheated with effluent streams and added to the paper machine and reused as "white water" in counter-current washing before being sent to effluent treatment, Figure 1.

Most mills require more steam than what can be produced from the refiner steam in the reboilers. This can be due to highly efficient refiners or that the paper contains a high share of mineral fillers and thereby the produced steam from refining is not enough. Typically, the auxiliary steam is produced in bark or gas boilers or in electrical boilers. Generally, a steam accumulator is also used in pulp and paper mills to help stabilize steam pressure during short periods, typically 15-30 minutes.

1.2.4 Paper machine operation

On the paper machine, the diluted fibre suspension is dewatered between wires (from 1% consistency to around 15% consistency). After the wire section the pulp web is pressed to a dry content of around 50% and finally the paper is dried to around 93% dry content with steam heated cylinders.

1.2.5 Energy flexibility

In many parts of the world the TMP mills have, for many years, been facing the large variations in the electricity price that we now have in the Nordic countries. The variations have contributed to investments in refiner over capacity and large pulp storage towers which were filled during periods with low prices and then the refiners were stopped during peak periods. During the time with high electricity prices, steam is produced in boilers using cheaper fuels, such as natural gas or bark. Nowadays, the electricity prices vary from day to day and from hour to hour also in the Nordic region, Figure 4. Within a day there can even be hours with negative electricity prices whilst the electricity prices surpass several hundreds of euros/MWh a couple of hours later.

Since these large variations are more common in Europe nowadays, many mills (and other industries) might benefit from heat storage, which is charged with electric energy during low-cost periods, and used to reduce electric power consumption during peak price hours.

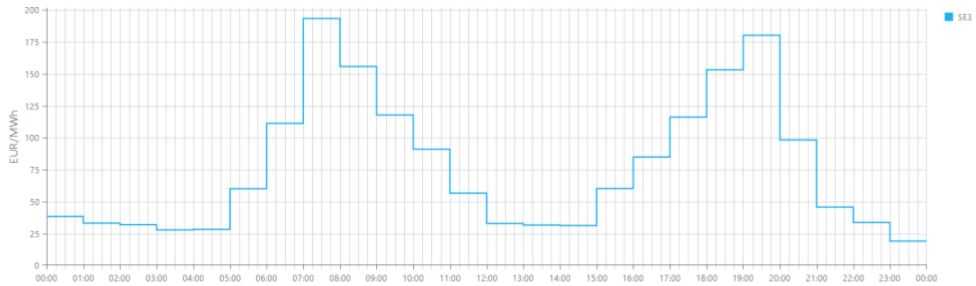

Figure 4. Hourly grid electricity SE3 prices 2025-09-10. Source: Nord Pool.

1.3 THE HALLSTA MILL CASE

1.3.1 Hallsta mill configuration

Hallsta has two paper machines (PM) which mainly produce book and magazine papers. Each PM is supplied with pulp from a TMP line using a mixture of spruce round wood and sawmill chips as raw material, Figure 5.

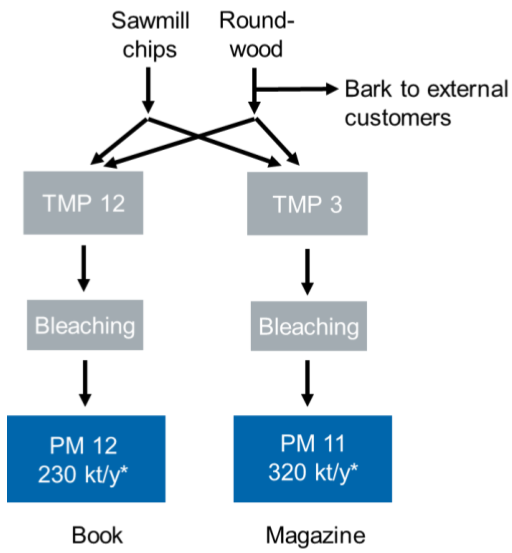

Figure 5. The Holmen Hallsta mill configuration with two TMP lines supplying the paper machines. Source: Holmen.

At the Hallsta paper mill the only primary energy source is electricity, but waste heat is used efficiently for many applications. A simplified flow diagram for the mill is shown in Figure 6 and a Sankey diagram with the energy flows is illustrated in Figure 7.

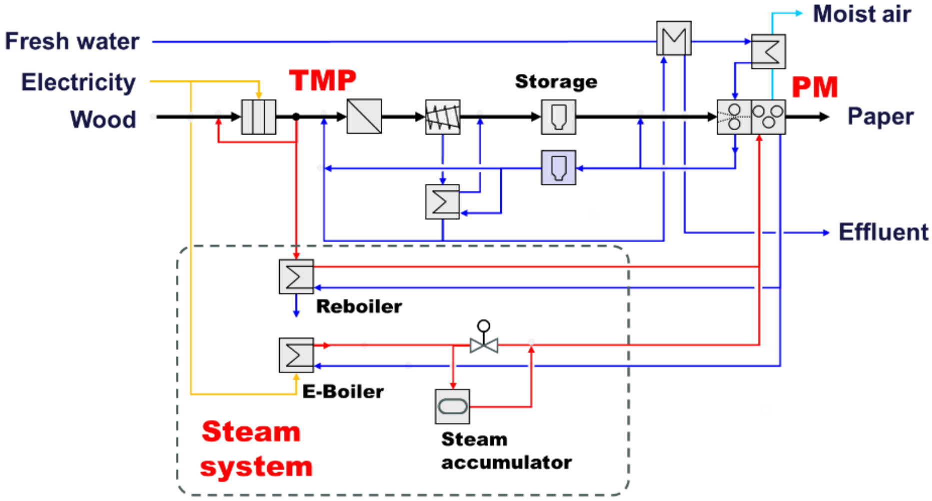

Figure 6. Simplified flow diagram for Holmen Hallsta paper mill. Source: Holmen.

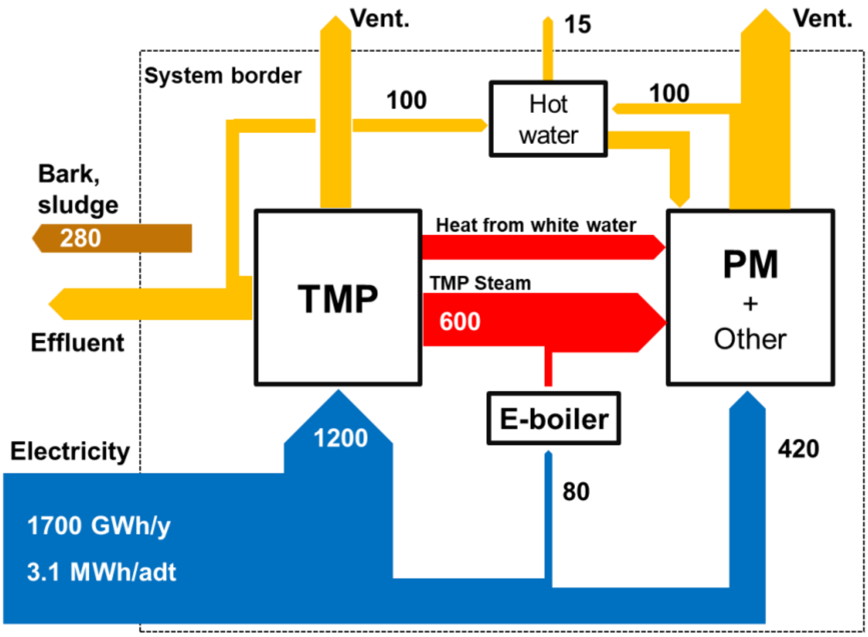

Figure 7. Sankey diagram with energy flows at Holmen Hallsta paper mill. Source: Holmen.

The main electric energy consumer in the mill is the TMP refining process. Temporarily stopping refiners, drastically reduces power demand but also stops reboiler steam production. With large storage towers with finished pulp, paper machines can still produce paper but the drawback with intermittent refiner operation is the lost reboiler steam production. Shorter periods of lost refiner, steam production is replaced with steam from steam accumulators and electric boilers, see Figure 6. In Hallsta paper mill, the TMP steam generation and PM steam consumption is balanced, which means that most of the time no additional steam generation is needed beyond the reboiler. The electric boilers are therefore primarily used for start, shut down and unstable mill conditions.

1.3.2 Existing flexibility and future development

Hallsta paper mill already has some operational flexibility through an existing pulp storage (up to 6-8 hours, 3000 m^3, approximately 380 tons) and a steam accumulator (10 MWh, up to 18 bar).

These systems allow partial decoupling between TMP and paper machine operations but are insufficient for managing longer electricity price fluctuations.

To enhance operational flexibility and reduce energy costs, Holmen is now exploring the implementation of a high-temperature thermal energy storage system, Figure 8. This system would replace TMP-generated steam during periods of high electricity prices, enabling more dynamic and cost-efficient operation, Figure 9.

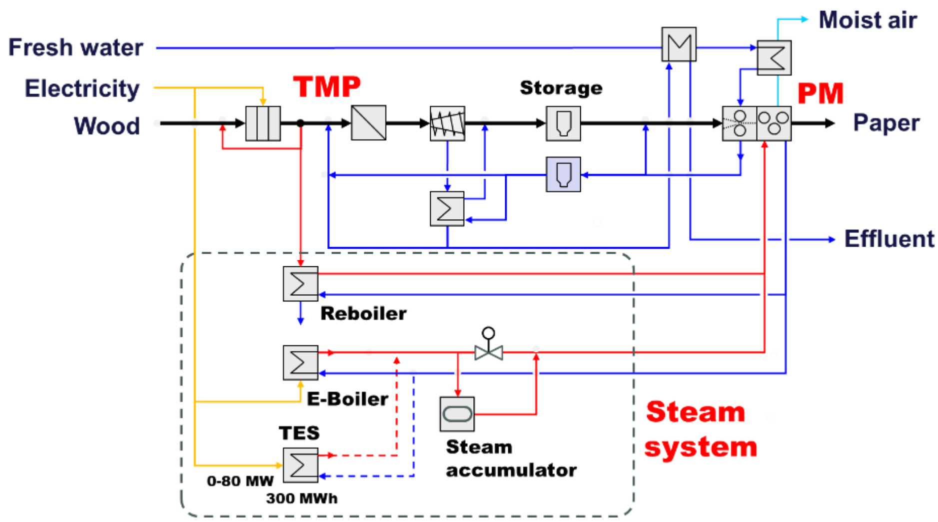

Figure 8. Holmen Hallsta paper mill overview with TES (Thermal heat storage). Source: Holmen.

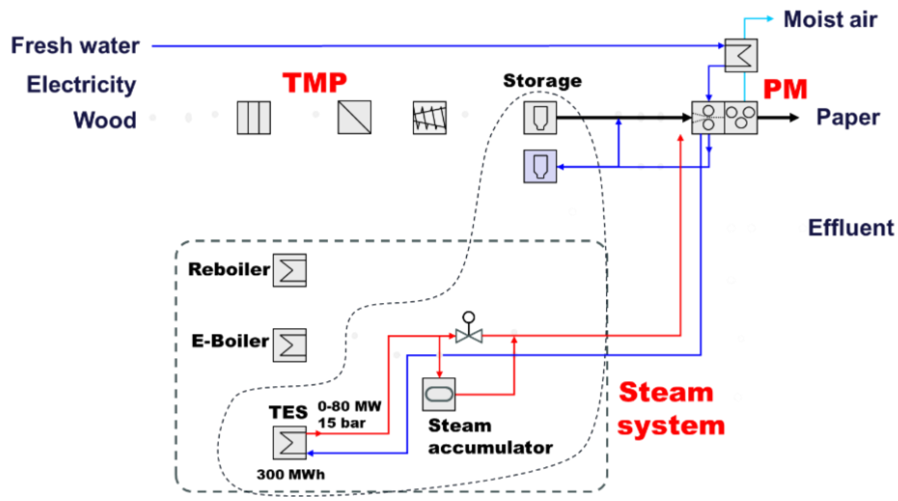

Figure 9. Paper machines at Holmen Hallsta running on pulp and heat storage. Source: Holmen.

1.4 OBJECTIVE

The objective of this project is to review and compare different high temperature energy storage techniques suitable for steam supply to paper machines (3-12 bar), i.e. typically 300-500 MWh steam energy and a thermal power of up to 80 MW (corresponding to a yearly production of 500 000 ton of paper fibres. Comparison is primarily based on the capital expenditure (CAPEX) even called investment cost, efficiency, energy density, operating temperature range, storage capacity, and technology readiness level (TRL).

Energy storage technologies outside this definition are not included.

Furthermore, the project shall provide a cost estimate for an energy storage system designed for the Holmen Hallsta paper, with a steam demand lasting 5-10 hours. The estimate will be compared with the cost of storing electricity in a battery and using conventional steam boilers. The desired capacity and discharge time of the energy storage system are indicated by the red ellipse in Figure 10 below.

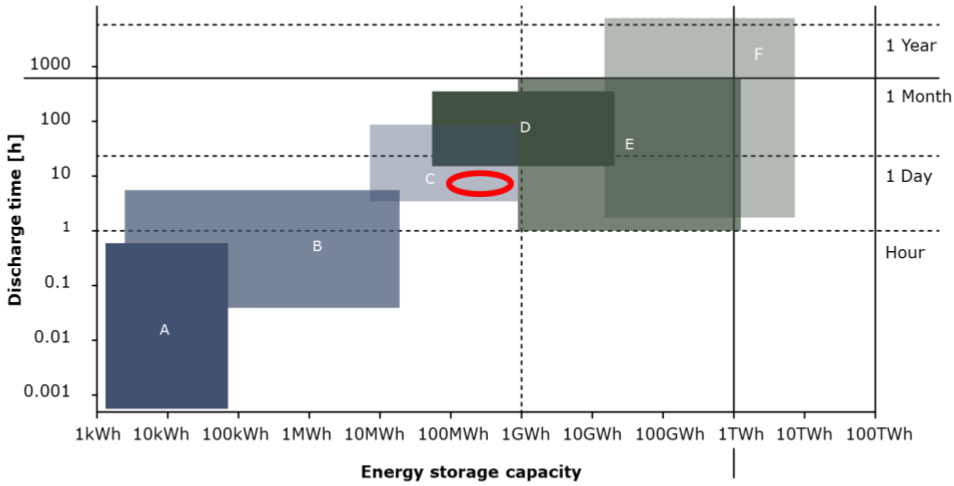

Figure 10. Desired capacity and discharge time of the investigated high-temperature energy storage at the Holmen Hallsta paper mill.

1.5 METHOD

This study was conducted through a combination of literature review, technical analysis, and case-based evaluation, supported by the author´s own expertise and industry experience.

1.5.1 Literature Review and Technology Mapping

The project began with a comprehensive review and compilation of scientific publications, technical reports, and market surveys to map available technologies within thermal energy storage (TES) and battery energy storage systems (BESS). The focus was on technologies with sufficient maturity and relevance for industrial steam production.

1.5.2 Case Study: Hallsta Paper Mill

The Hallsta paper mill was selected as a case study due to its electricity-intensive operation and existing flexibility solutions. A detailed analysis of the mill's energy flows, steam demand, and operational conditions was carried out. This included mapping of existing systems such as TMP lines, reboilers, steam accumulators, and electric boilers.

1.5.3 Technical and Economic Comparison

Each storage technology was evaluated based on technical parameters such as efficiency, energy density, operating temperature range, storage capacity, and TRL. Economic indicators, such as Capital expenditure (CAPEX), were analyzed using public sources and articles. For the Hallsta case, cost estimates were developed for both TES and BESS, including auxiliary systems such as steam generators.

In addition to the main case study, a brief analysis was also conducted for energy storage applications at a Kraft pulp mill. This included a comparative assessment of TES and BESS, focusing on their potential to provide electricity-side flexibility and economic viability in different mill configurations.

2 Thermal energy storage technologies

TES plays a critical role in enhancing energy system flexibility and resilience. Figure 11 depicts the workflow diagram of TES. A typical TES system includes a storage medium housed in a reservoir or tank, along with heat exchanger, piping, pump, and control components. Energy can be input into the system through different means: some TES technologies utilize electricity via resistive heating elements to raise the temperature of the storage medium, while others capture excess heat, such as steam, from industrial processes or power generation. During the charging process, heat is stored in the medium and later released during discharging for applications like electricity generation or industrial processes.

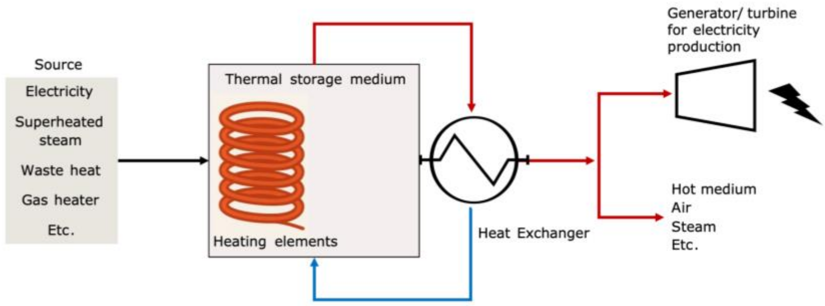

Figure 11. Thermal energy storage workflow diagram.

TES systems can be classified based on various criteria. Regarding storage duration, TES can be categorized into short-term or long-term storage. Based on the energy storage mechanism, TES technologies fall into three main types, as illustrated in Figure 12.

- Sensible heat storage (SHS): Stores and releases heat by raising or lowering the temperature of a liquid or solid medium without undergoing a phase change.
- Latent heat storage (LHS): Uses phase change materials (PCMs) to store and release heat through physical state transitions, such as melting or solidification, with minimal temperature variation.
- Thermochemical storage (TCS): Involves storing and releasing heat through reversible endothermic and exothermic chemical reactions between two or more components.

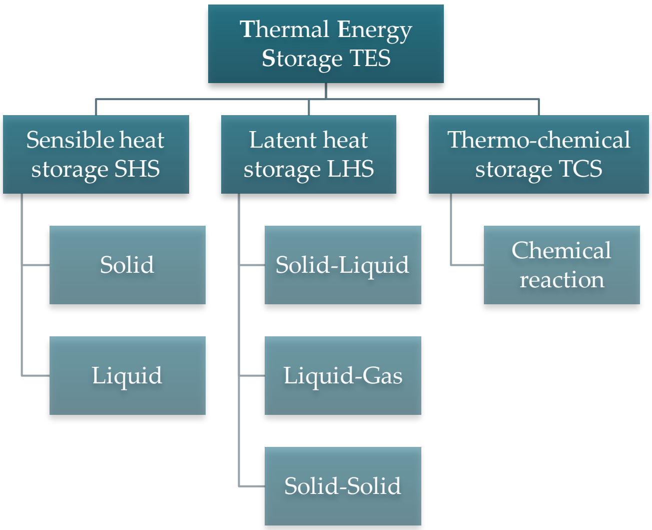

Figure 12. Classification of TES systems [4].

One of the key advantages of TES is its capacity to support demand management by storing energy during periods of low demand and releasing it during demand peaks. For example, TES facilitates the integration of intermittent renewable energy sources like solar and wind by storing surplus thermal energy generated during periods of high availability and releasing it when generation dips. This load-shifting capability helps alleviate stress on energy infrastructure and promotes more stable grid operation. Thus, TES improves overall energy efficiency and contributing to more sustainable energy use.

Despite these benefits, TES technologies face several challenges. Sensible heat storage is a mature and commercially proven approach, but latent heat storage and thermochemical storage remains emerging technologies that have yet to achieve widespread market adoption. Additionally, some TES systems exhibit lower efficiency compared to alternatives like batteries, largely due to heat losses during storage and energy conversion processes.

Selecting an appropriate TES system requires careful consideration of several factors, including the specific application, technical requirements such as storage capacity and temperature range, the required storage duration, and economic factors like cost-effectiveness and market readiness.

2.1 SENSIBLE HEAT STORAGE

SHS is the most commonly applied form of TES, using both solid and liquid storage media such as water, oil, molten salts, concrete, bricks, steel, and other dense materials. In SHS systems, thermal energy is stored by raising the temperature of the storage medium without inducing a phase change, see Figure 13.

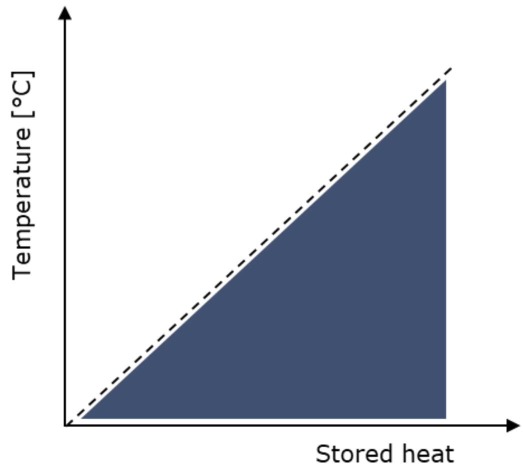

Figure 13. SHS typical diagram during sensible heating or cooling with no phase transition [4].

The amount of heat stored is directly related to the material's specific heat capacity and the temperature change within the system's operating range. The energy stored or released can be calculated using the equation [6]:

$$Q = mC_p\Delta T = \rho V C_p \Delta T$$

- Q is the amount of heat stored [J]
- m is mass of the storage material [kg]
- Cp is specific heat of the storage material [J/kg K]
- ΔT is the temperature change [K]
- ρ is the density of the storage material [kg/m^3]
- V is the volume of the storage material [m^3]

According to equation, the amount of stored energy is proportional to material mass, the charging/discharging temperature change, and the specific heat capacity. Minimizing heat loss is also critical; losses are primarily dependent on the temperature gradient between the storage medium and the surrounding environment, emphasizing the importance of proper insulation.

Table 2 provides a summary of thermophysical properties of various sensible solid and liquid storage media. Water stands out for low-temperature applications due to its affordability and high specific heat capacity. For higher-temperature applications, oils and molten salts are commonly used. Solid storage materials, such as sand, rocks, concrete, firebricks, and ferroalloys, are typically used in systems operating between 200 °C and 1200 °C. These materials also tend to offer good thermal conductivity, which supports efficient heat transfer.

Table 2. Thermophysical properties of sensible storage media [2].

Material	Type	Specific heat [kJ/kg/K]	Density [kg/m³]	Temp. range [°C]
Water	liquid	4.19	1000	0-100[1]
Nitrate salts	liquid	1.6	1815	300-600
Silicone oil	liquid	2.1	900	300-400
Carbonate salts	liquid	1.8	2100	450-850
Hydroxide salts	liquid	2.1	1700	350-1100
Silicon	liquid	0.71	2300	1900-2400
Concrete	solid	0.9	2200	200-400
Silica fire bricks	solid	1	1820	200-700
Magnesia fire bricks	solid	1.2	3000	200-1200
Cast iron	solid	0.6	7200	200-400
Cast steel	solid	0.6	7800	200-700
Aluminium oxide	solid	1.3	4000	200-700
Slag	solid	0.84	2700	200-700
Graphite	solid	1.9	1700	500-850

SHS offers several advantages, including its technological maturity and proven performance in large-scale applications. It uses cost-effective and readily available materials such as water, concrete, and bricks, making it economically attractive.

However, this technology also presents some challenges. Effective thermal insulation is essential to minimize heat losses, especially over long storage durations. Furthermore, due to its relatively low energy density, SHS systems often require large physical volumes to store significant amounts of energy. In high-temperature systems, materials like molten salts are commonly used, but their high freezing points, typically around 200 °C, can pose operational difficulties and increase system complexity.

2.2 LATENT HEAT STORAGE

LHS operates on the principle of heat absorption or release when a storage material undergoes a phase transition, such as from solid to liquid or liquid to gas, and vice versa, see Figure 14. This process utilizes PCMs to store thermal energy. During the charging process, the PCM absorbs heat, raising its temperature until it reaches its melting point. At this point, the material absorbs additional heat to change phase, while its temperature remains constant. The most common phase transition used is from solid to liquid, although other phase changes, such as liquid to gas or the reverse processes, can also be employed.

[1] At atmospheric pressure. In a pressurized system temperature range can be extended.

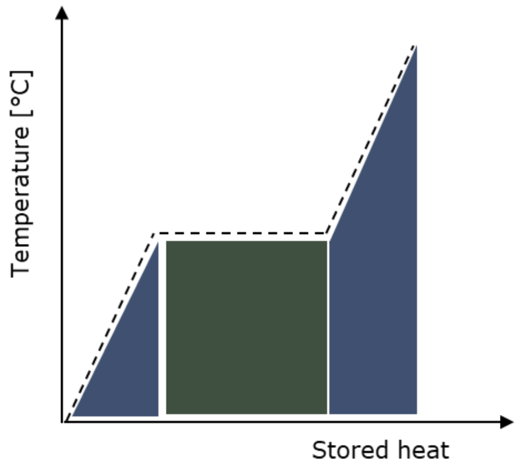

Figure 14. THS typical diagram during sensible heating or cooling with phase transition [4].

Since PCMs do not effectively transfer heat on their own, a separate heat transfer medium is required. This medium, together with a heat exchanger, enables the transfer of energy from the heat source to the PCM during charging and from the PCM to the load during discharging. Therefore, a typical LHS system includes at least the following three key components:

- A suitable PCM with a melting point within the desired temperature range
- An appropriate heat exchange surface
- A compatible container to house the PCM

The amount of heat stored in THS can be calculated using the following equation [6]:

$$Q = m(C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m))$$

- Q is amount of heat stored [J]
- m is mass of heat storage medium [kg]
- T_m is melting temperature [°C]
- T_i is initial temperature [°C]
- T_f is final temperature [°C]
- C_{lp} is average specific heat between Tm and Tf [J/kg K]
- C_{sp} is average specific heat between Ti and Tm [kJ/kg K]
- a_m is fraction melted
- Δh_m is heat of fusion per unit mass [J/kg]

PCMs can be categorized into three main types: organic, inorganic, and eutectic, as illustrated in Figure 15. Organic PCMs include compounds such as paraffins and non-paraffinic substances like fatty acids, esters, alcohols, and glycols. Inorganic

PCMs primarily consist of materials such as salt hydrates, and various salts including nitrates, carbonates, chlorides, sulphates, fluorides, as well as hydroxides and certain metals. Eutectic PCMs are a distinct category formed by the combination of two or more components, organic, inorganic, or a hybrid of both.

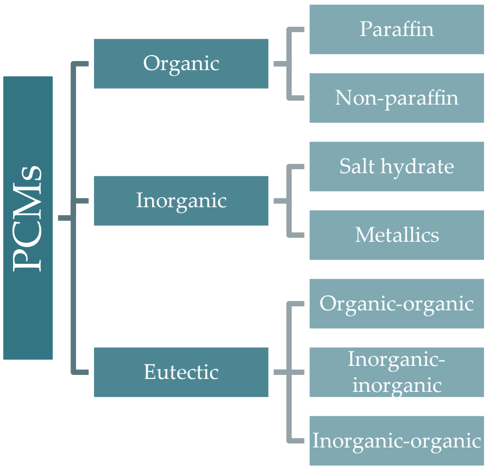

Figure 15. Classification of phase-change materials (PCMs) [3].

Figure 16 presents the typical storage capacities of various material classes used in LHS, categorized according to their melting temperatures and volumetric storage densities. Storage density is defined by the specific latent heat of fusion, the amount of internal energy absorbed or released per unit volume during the phase transition from solid to liquid.

Commonly used materials for thermal energy storage include paraffins, salt hydrates, nitrate salts and their mixtures, as well as water and water-salt solutions. These materials are widely applied in industrial processes, particularly for capturing and utilizing waste heat at temperatures up to 500 °C. Paraffinic organic compounds are commercially available for applications within the temperature range of approximately 6 °C to 80 °C. They have low storage densities, but are non-toxic, non-corrosive and cycle stable. Nitrate salts and their mixtures are particularly effective for storing process heat in the temperature range of approximately 130 °C to 400 °C.

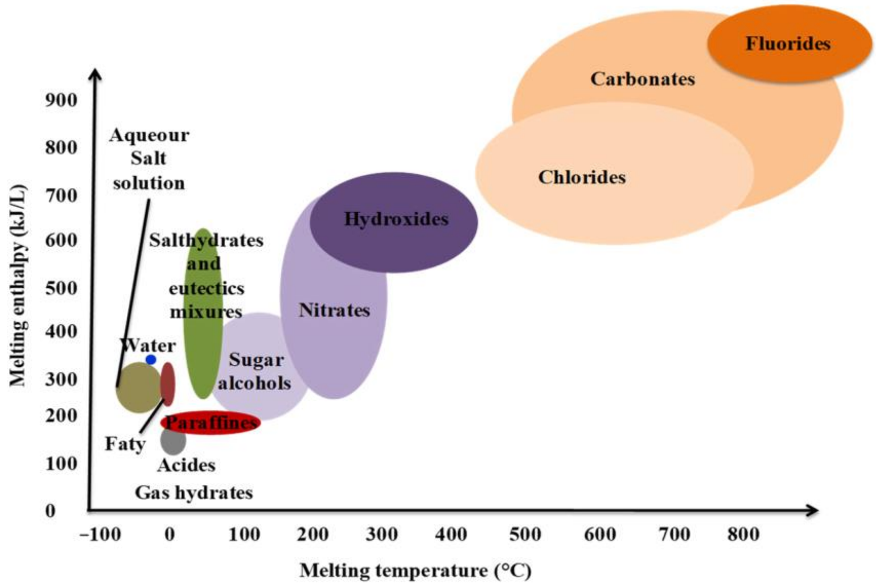

Figure 16. Melting enthalpy vs. melting temperature for some PCMs [3].

Compared to SHS systems, LHS systems offer the key advantage of releasing thermal energy at a consistent, well-defined temperature. However, due to generally poor thermal conductivity of the material for LHS, one limitation is that the heat transfer between the solidifying PCM and the tank wall—through which heat is discharged—gradually decreases over time. This leads to a progressive reduction in heat flow during the discharge process.

2.3 THERMOCHEMICAL STORAGE

TCS employs thermochemical materials (TCMs) and provides a notably high energy density, making it a promising technology, particularly for high-temperature applications. In these systems, heat is stored and released through endothermic or exothermic chemical reactions between two components, see Figure 17.

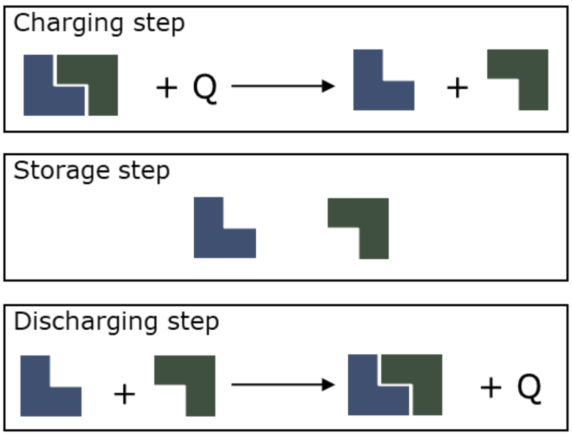

Figure 17. TCS typical storage mechanism description [4].

TCS is generally categorized into two types:

- Reversible reaction-based storage: This approach relies on a reversible chemical reaction between two substances, where heat is released during exothermic reaction and absorbed during the endothermic reverse reaction.
- Sorption-based storage: In this method, heat is stored by breaking the bond between a sorbent and a sorbate. The energy is later released when the sorbate is reabsorbed, driven by differences in chemical potential.

Common TCMs used in these systems include metal hydrides, metal oxides, and various salts, selected for their reactivity, reversibility, and thermal properties. The amount of heat stored in TCS can be calculated using the following equation [7]:

$$Q = n_A \, \Delta H_r$$

- Q is amount of heat stored [J]
- n is the number of moles of the components taking part in the chemical reaction
- H denotes the enthalpy of the reaction

Table 3 lists some chemical reactions for TCS, while sorption storage can only work at temperatures of up to 350 °C, temperatures of chemical reactions can go much higher.

Table 3. Some chemical reactions for thermochemical storage [2].

Material	Energy density [kJ/kg]	Temperature range [°C]
Carbonates $CaCO_3(s) \leftrightarrow CaO(s)+CO_2(g)$	1764	850-1273
Hydroxides $Ca(OH)_2(s) \leftrightarrow CaO(s)+H_2O(g)$	1406	400-600
Hydrides $MgH_2(s) \leftrightarrow Mg(s)+H_2(g)$	2880	300-480
Ammonia $NH_3(g) \leftrightarrow 1/2N_2(g)+ 3/2H_2(g)$	3924	400-700

A major advantage of TCS is its capacity to store thermal energy in chemical form, allowing for virtually loss-free, long-term storage. Compared to sensible and latent heat storage systems, chemical heat accumulators offer significantly higher energy storage densities. The risk of self-discharge is greatly reduced because the energy is stored in stable chemical bonds rather than as temperature gradients. Thanks to its high energy density and ability to retain energy over extended periods with minimal losses, TCS holds strong potential for applications such as seasonal storage, peak load shifting, industrial process heat with heat transformation, industrial waste heat recovery, and district heating. However, these applications remain in the early stages of development.

2.4 COMPARISON OF STORAGE TECHNOLOGIES

Table 4 provides an overview of key parameters for selected TES systems, including operating temperature, storage duration, capacity, energy density, efficiency, technology readiness level (TRL), and investment cost.

Table 4. Key technical parameters of TES technologies [5, 23].

TES Type	SHS	LHS			TCS		
TES technology	Solid state	Molten salts	Low temp. PCMs	High temp. PCMs	Absorption	Salt hydration	Chemical looping
Operating temp. °C	-160 – 1300	250 – 550	Up to 120	Up to 1000	5 – 165	30 - 200	500 – 900
Storage duration	Hrs to months	Hrs to days	Hrs	Hrs to days	Hrs to days	Months	Months
Capacity ranges	kWh - GWh	MWh - GWh	kWh	kWh - GWh	kWh	kWh	MWh
Energy density kWh/m³	70-150[2]	70-200	56-60	30-85	180-310	200-350	800 – 1200
Efficiency	>90%	>98%	>90%	>90%	N.A.	60%	45-63%
TRL	8-9	8-9	4-5	6-7	6-7	4-5	4-5
Investment €/kWh	15-40[3]	20-70[4]	20-100[5]	40-80	N.A.	N.A.	N.A.

SHS primarily includes two technologies operating above 100 °C: solid-state materials and molten salts. Solid-state systems cover a wide temperature range and support storage durations from hours to several months. Their capacity spans from kilowatt-hours (kWh) to gigawatt-hours (GWh) making them suitable for both medium and large-scale applications. Molten salt systems typically store energy for hours to days. They offer capacities from MWh to GWh and slightly higher energy densities. Overall, SHS technologies are relatively mature, reliable, and flexible solutions for a broad range of storage durations.

LHS utilizes PCMs, which can be classified as low- or high-temperature types. Low-temperature PCMs are suited for short-duration storage lasting a few hours, with small capacities in the kWh range. High-temperature PCMs can reach up to 1000 °C and store energy for hours to days, with capacities ranging from kWh to GWh. Their energy density is generally lower than SHS. LHS technologies are

[2] Energy density for about 160-180 °C temperature differential
[3] The specific cost refers to the storage unit, excluding transport and installation
[4] The specific cost depends largely on the temperature spread
[5] The cost given includes the charging and discharging stations and the mobile latent heat storage unit excluding transport.

moderately developed and particularly useful in scenarios where precise thermal control is required, such as building systems and industrial processes.

TCS encompasses absorption systems, salt hydration, and chemical looping. Absorption-based systems are intended for short-term use (hours to days) and provide high energy densities. Salt hydration systems can store energy for up to a month. Chemical looping stands out with high operating temperatures and high energy densities, making it suitable for long-duration, high-capacity storage. However, TCS systems remain less mature, with greater complexity and limited commercial deployment compared to SHS and LHS.

When selecting one TES technology, two primary considerations are the required; operating temperature range and the intended storage duration, as illustrated in the accompanying Figure 18.

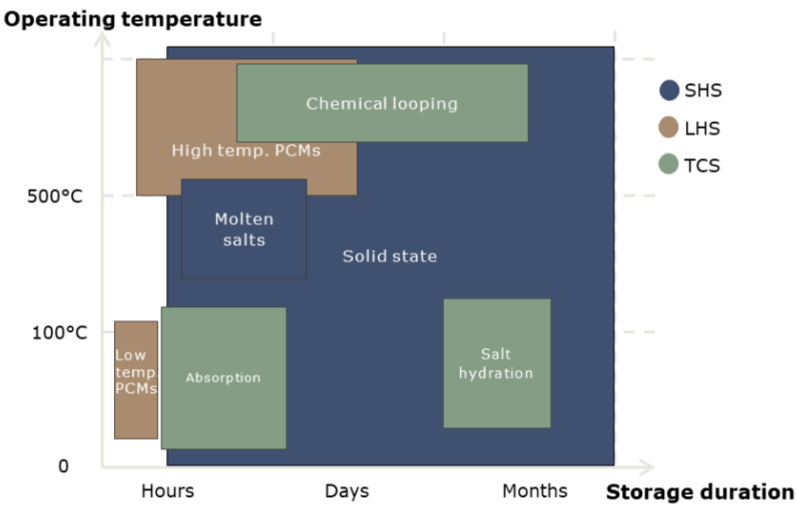

Figure 18. Operating temperatures and storage duration ranges for TES technologies studied [5].

The three TES technologies differ significantly in their mechanisms, applications, and performance characteristics. SHS stores energy as a temperature difference in solid materials like concrete or rock, or in liquids such as molten salts. Solid SHS is used in industrial regenerator systems, while molten salt SHS is common in solar thermal plants and industrial process heat. It is a relatively mature, cost-effective solution with long-duration capability but requires good insulation and large volumes due to low energy density.

LHS stores energy via phase change in materials like salts, metals, or organics. It's applied in waste heat recovery, cooling, temperature stabilization, and district heating. LHS is particularly effective in isothermal applications where maintaining a constant discharge temperature is advantageous. Despite these benefits, it faces limitations including corrosion risks, low thermal conductivity, and a lower level of technological maturity compared to SHS.

TCS stores energy in chemical bonds and is used in waste heat recovery, solar thermal power, and seasonal building storage. It provides high energy density and long-term potential, especially with materials stable at high temperatures.

However, TCS is complex, costly, less mature, and may require managing gaseous byproducts.

Table 5 provides a concise overview of the main applications, benefits, and challenges associated with each TES type.

The global number of TES providers continues to grow. Appendix A presents a selection of suppliers in SHS, LHS, and TCS that are considered to have relatively high technological maturity. This shortlist is based on a market survey published by *Solarthermalworld* on March 3, 2024.

Table 5. Comparative overview of TES technologies [2] [3] [8].

	SHS	LHS	TCS
Storage mechanism	Energy is stored as a temperature difference within solid materials or liquid media.	Energy is stored through the phase change of materials.	Energy is stored within chemical bonds.
Application	SHS Solid: Used in regenerator systems for industries such as glass, metallurgy, and cement; also applied in thermal-regenerative exhaust air purification. SHS molten salt: Commonly employed in solar thermal power plants, for industrial process heat, and for storing electrical energy.	Utilization of waste heat, support for cooling applications, stabilization of temperature fluctuations, and use as buffer storage in district heating systems.	Capturing and reusing industrial waste heat; serving as buffer storage in district heating networks. Applications include solar thermal power plants, recovery of industrial waste heat, power plant systems, and building services such as seasonal thermal storage.
Advantages	Highly mature technology with proven large-scale energy storage capabilities. Cost-effective storage media. Long duration storage is achievable.	Good for isothermal applications. Can provide large energy density. Discharge temperatures are constant over discharging time.	High energy density. Potential for long-term storage. Oxide TCEs remains stable at high temperatures (>1000 °C).
Challenges	Requires effective thermal insulation to minimize heat loss. Lower energy density means larger physical storage volumes are needed.	Risk of material corrosion over time. Generally poor thermal conductivity. Relatively low technology maturity and limited commercial deployment.	Higher system complexity. Low maturity of the technology. Higher initial capital costs. May necessitate storage of gaseous byproducts.

3 Battery Energy Storage System

In industrial processes where electricity is used both to drive production and indirectly to generate heat such as in TMP, battery energy storage systems (BESS) can offer distinct advantages. By storing electricity and later discharging it with high efficiency, BESS enables flexible operation during periods of fluctuating electricity prices. This flexibility supports demand-side response and can reduce overall energy costs, especially in electrically dominated systems.

This section describes different battery technologies and acts like a background for later comparison with TES in terms of technical feasibility, cost and applicability to industrial steam production. Specific implications for the Hallsta paper mill are also later discussed.

A Battery Energy Storage System (BESS) is mainly composed of four parts, including battery system containing several battery stacks, battery management system (BMS), power conversion system (PCS), and monitoring system, as illustrated in the Figure 19. [9]

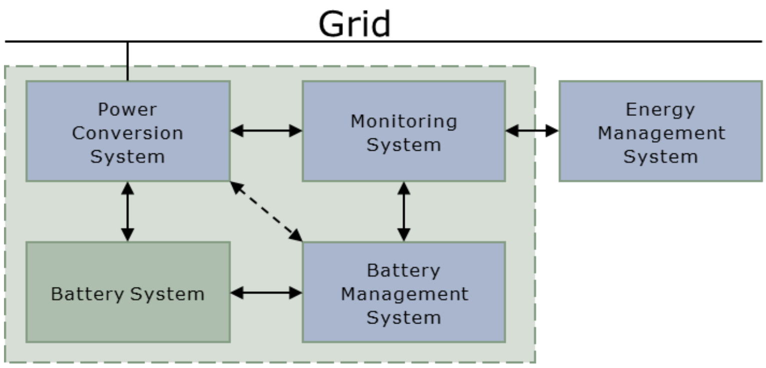

Figure 19. Battery energy storage system (BESS).

The battery system is the core storage unit, made up of interconnected battery packs that meet voltage and current requirements. The BMS monitors and protects the battery modules by preventing overcharging, over-discharging, and overheating, while balancing cell voltages to extend battery life. The PCS converts direct current (DC) from batteries to alternating current (AC) for grid use and vice versa, making its efficiency critical to system performance. The monitoring system coordinates all components through high-speed communication, ensuring smooth operation. An Energy Management System (EMS) optimizes charge/discharge cycles based on energy demand and pricing. Grid connection is handled via transformers, which adjust voltage levels for integration, with larger systems often using substations for high-voltage connections.

Batteries store energy in chemical form and produce electricity through electrochemical reactions. This process involves the ionization of molecules, the movement of charged ions, and the subsequent recombination of these charges to generate electrical energy. Common battery types include lead-acid, lithium-ion, nickel-based, sodium-based, and flow batteries.

3.1 LEAD-ACID BATTERY

Lead-acid (PbA) battery technology operates using positive and negative electrodes immersed in an electrolyte composed of sulfuric acid and water. Lead dioxide is used as a positive electrode and lead is used as a negative electrode [10]. During discharge, lead at both electrodes reacts to form lead sulphate, releasing electrons that flow through the external circuit. This process reduces sulfuric acid concentration, weakening the electrolyte and lowering the voltage. As the battery discharges, the electrodes become chemically similar, and the voltage drops until the battery can no longer supply power. Recharging reverses these reactions by restoring the chemical differences between the electrodes, allowing the battery to function again.

3.2 LITHIUM-ION BATTERY

The lithium-ion (Li-ion) battery is composed of a positive electrode, a negative electrode, a separator, an electrolyte, and two current collectors. The anode typically consists of a lithiated metal oxide, while the cathode is made of graphitic carbon with a layered structure. The electrolyte is a lithium salt dissolved in organic carbonates, enabling the movement of lithium ions between electrodes during charge and discharge cycles. [10] During discharge, lithium atoms in the anode ionize and migrate through the electrolyte toward the cathode, driven by a slight concentration gradient. At the cathode, they recombine with electrons from the external circuit and are deposited as lithium atoms. This movement generates free electrons at the anode, which flow through the external circuit to provide power. A separator prevents direct electron flow between electrodes. During charging, this process is reversed.

Lithium iron phosphate (LFP) is a type of lithium-ion battery chemistry that has seen significant growth in installations and is now commonly used in electric vehicles, solar energy storage, and stationary applications. Compared to other lithium-ion chemistries such as nickel-manganese-cobalt (NMC) or lithium cobalt oxide (LCO), LFP batteries are generally safer, have longer cycle life, and offer better thermal stability.

Apart from lithium, LFP batteries use iron, and phosphorus – materials that are more abundant, less expensive, and have significantly lower environmental and social impacts compared to the cobalt and nickel used in NMC batteries. This makes LFP a more sustainable and cost-effective option. However, LFP cells typically have lower energy density than e.g. NMC, meaning they are larger and heavier for the same energy capacity. That said, the difference in energy density tends to shrink at the system level due to factors like packaging and thermal management.

The performance differences between LFP and other chemistries are largely due to their distinct crystal structures: LFP uses an olivine structure, while NMC and LCO use a spinel or layered structure. These structural differences influence properties such as voltage range, temperature tolerance, and degradation behaviour. While LFP is more durable than NMC in many respects, other chemistries like lithium titanate (LTO) can outperform LFP in specific areas such as cycle stability.

3.3 NICKEL-CADMIUM BATTERY

Nickel-cadmium (Ni-Cd) batteries use nickel oxyhydroxide as the positive electrode and metallic cadmium as the negative electrode, with potassium hydroxide as the electrolyte. A nylon separator prevents direct charge transfer between the electrodes. The battery operates through a redox reaction between nickel oxyhydroxide and cadmium. During discharge, nickel oxyhydroxide at the positive electrode reacts with water to form nickel hydroxide, while cadmium at the negative electrode forms cadmium hydroxide. This reaction is reversed during charging.

3.4 SODIUM-SULFUR BATTERY

Sodium-sulphur (NaS) batteries use molten sodium as the anode and molten sulphur as the cathode, separated by a beta-alumina ceramic electrolyte. During discharge, sodium atoms at the anode release electrons and become Na^{+} ions, which migrate through the electrolyte to the cathode, where they react with sulphur to form sodium polysulfides. The electrons travel through the external circuit, generating electricity. NaS batteries operate at high temperatures (300 °C to 350 °C) to keep both electrodes in a molten, conductive state. The reactions are reversible, allowing the battery to be recharged by converting sodium polysulfides back into elemental sodium and sulphur.

3.5 VANADIUM-REDOX FLOW BATTERY

As the most mature and commercially established flow battery, vanadium redox flow battery (VRFB) technology operates using two separate tanks containing vanadium-based electrolytes, one with a positively charged electrolyte and the other with a negatively charged one. During operation, the electrolytes are pumped through an ion-selective membrane, where redox (oxidation and reduction) reactions occur, generating the flow of electrons and thus producing electricity.

By employing vanadium redox couples V^{2+}/V^{3+} in the negative and V^{4+}/V^{5+} in the positive half-cell the energy is stored in the VRFB. Both electrolytes typically consist of vanadium sulphate dissolved in sulfuric acid. During charge and discharge, hydrogen ions (H^{+}) move across the membrane, which selectively allows H^{+} transfer while blocking other ions like HSO_4^{-}. This controlled ion flow maintains charge balance and enables reversible energy storage.

3.6 COMPARISON OF BESS TECHNOLOGIES

The overview of listed battery technologies is done according to different technical characteristics, see Table 6. The technical characteristics are defined below.

- Specific energy: The amount of energy stored per unit mass of the storage material.
- Specific power: The rate at which energy can be delivered per unit mass of the storage material.
- Energy density: The amount of energy stored per unit volume of the storage material.
- Power density: The rate at which energy can be delivered per unit volume of the storage material.
- Energy cost: The cost of battery storage per unit of stored energy, considering only the investment cost of the battery itself, excluding auxiliary systems such as BMS, PCS, and cooling systems.
- Power cost: The cost of battery storage per unit of power output.
- Lifetime: The number of years the storage system can operate at its rated capacity and power.
- Life cycles: The total number of complete charge-discharge cycles the storage system can perform over its lifetime.
- Cell voltage: The voltage measured across the positive and negative terminals of a battery cell.
- Maximum depth of discharge: The maximum proportion of charge that can be used in a single cycle.
- Daily self-discharge: The loss of stored energy per day when the battery is not in use.
- Efficiency: The ratio of energy retrieved from the battery to the energy used to charge it.
- Operating temperature: The temperature range within which the battery can function reliably.
- Technology maturity: A technology is considered mature when it has been in use long enough to overcome most of its initial limitations and challenges.
- Storage duration: The length of time a battery can retain stored energy without significant self-discharge.

Table 6. Comparison of battery technologies with colour green for high-performance, pink for low performance [10] [12] [13][17][18].

Parameter	PbA	Li-Ion	Ni–Cd	NaS	VRFB
Specific energy [Wh/kg]	25-50	80-250	30-80	150-240	10-130
Specific power [W/kg]	150-400	200-2000	80-300	90-230	50-150
Energy density [kWh/m³]	25-90	95-500	15-150	150-350	10-33
Power density [kW/m³]	10-400	50-800	40-140	1.2-50	2.5-33
Energy cost [€/kWh][6]	40-170 [11,13] 170-350 [17]	500-2100 [11,13] 90-2100 [17]	680-1300 [11,13] 410 [18]	250-420 [11,13] 430 [18]	130-850 [11,13] 510-1290[18]
Power cost [€/kW] [7]	250-500 [11,13]	1000-3400 [11,13,24]	420-1300 [11,13] 340-2060[18]	850-2500 [11,13] 300-2570 [18]	500-1300 [11,13] 130-860 [18]
Lifetime [year]	2-15	5-15	10-20	10-15	5-15
Life cycles	250-2000	1000-10000	1000-5000	2500-40000	10000-16000
Cell voltage [V]	2-2.1	2.5-5	1.2-1.3	1.8-2.71	1.2-1.4
Max. depth of discharge	80%	100%	80%	100%	100%
Daily self-discharge	0.1-0.3%	0.1-0.3%	0.2-0.6%	0%	0%
Efficiency	63-90%	75-97%	60-90%	75-90%	75-90%
Working temperature [°C]	18-45	20-65	-40 – 50	300 – 350	5 – 45
Maturity	Mature	Mature	Mature	Mature	Developing
Suitable storage duration	Minutes–days	Minutes–days	Minutes–days	Long term	Hours–months

Lead-acid batteries have been in use for a long time, primarily due to their very low cost. They are well-suited for various stationary applications thanks to their decent efficiency and relatively high cell voltage. However, their main drawback is a short cycle life, meaning they cannot be charged and discharged as many times as newer technologies. Lead-acid batteries are commonly found in vehicles and applications requiring high load currents.

[6] The specific costs were taken from public sources form 2017-2021, actual current costs may vary, for instance, the current market price of Li-ion batteries can range between 100 and 120 €/kWh.
[7] The specific costs were taken from public sources form 2017-2021, actual current costs may vary, for instance, the current market price of Li-ion batteries can range between 100 and 120 €/kWh.

Lithium-ion batteries are currently the most advanced and widely used battery technology. They are ideal for a broad range of applications because they offer the highest specific power and energy, the highest power and energy density, high cell voltage, and excellent efficiency. The primary drawback of lithium-ion batteries is their relatively high upfront cost compared to other technologies, driven by expensive raw materials and complex manufacturing processes. However, production costs have been steadily declining in recent years thanks to improved efficiencies. Lithium-ion batteries are extensively used in portable electronics like smartphones, tablets, and laptops due to their high energy density.

Nickel-Cadmium batteries perform well in extreme temperature conditions, especially in low temperatures, which makes them reliable in harsh environments. However, they have harmful environmental impact due to toxic cadmium. Ni-Cd batteries are often used in applications requiring long service life under demanding conditions.

Sodium-Sulphur batteries are best suited for applications demanding a high number of charge/discharge cycles. They offer high specific energy, good energy density, relatively high cell voltage and good efficiency. The main limitation is that they require very high operating temperatures, which complicates their use. NaS batteries can deliver high capacity, making them ideal for large-scale energy storage systems. [10][11][12]

VRFBs are considered a promising technology for long-duration energy storage. They can support a very high number of cycles and are ideal for grid-scale applications. However, their energy and power densities are quite low, and they require a large amount of space, which limits their practicality in compact installations. [10] [11] [12] [13].

4 Steam production

4.1 STEAM GENERATION IN COMBINATION WITH TES

A TES can be used to generate steam suitable for paper machine operation by transferring stored heat to a generator in a steam boiler. Steam is often produced from combustion of a fuel burnt in a boiler furnace. Heat from flame radiation and convection is transferred from the flue gas to the steam cycle before the cooled flue gases are released to atmosphere. A TES connected to a steam boiler will not generate any flue gases which have to be exhausted to atmosphere. Instead, the heat transfer media from the TES to the steam generator must be returned to the TES to minimize heat losses. The principles for steam generation from a heat discharge from a TES is shown in Figure 20.

The transfer media transfers heat to the steam generator which in its simplest form is an air heated steam boiler, like a flue gas boiler. Other possible transfer media is hot oil. The advantage of the circulation transfer media heated boiler compared to the flue gas heated boiler is the cleanliness of the media. When the TES heat transfer media leaves the heated boiler, it can be returned by a blower or a pump to the thermal energy storage without any further loss of sensible heat. The recycling of the media on a rather higher energy level increases the efficiency. The air heated boiler is generating steam from feed water which is supplied by the feed water/condensate system. The boiler feeds steam into the steam header which distributes steam to the paper machine and for auxiliary usages such as the feed water system deaeration.

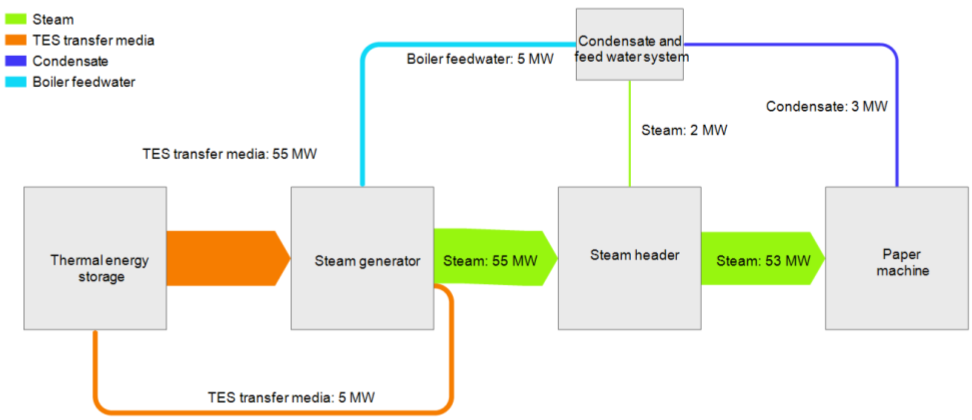

Figure 20. TES steam generation process.

4.2 FUTURE STEAM PRODUCTION FOR INDUSTRIAL APPLICATION

Combining high-temperature heat pumps (HTHP) with energy storage technologies offers a further alternative for operational flexibility for industrial steam production. HTHPs have potential to deliver heat at high temperatures, making them suitable for generating saturated steam up to several bar. When integrated with energy storage, they enable industries to shift electricity consumption to low-price periods and decouple steam generation from real-time electricity use.

Heat pumps operate by transferring heat from a low-temperature source to a higher-temperature sink, typically using a vapor compression cycle (see Figure 21). This allows for the recovery and upgrading of waste heat. Globally, heat pumps are well-established in residential and commercial sectors, especially for heating and domestic hot water. However, their application in industry, particularly at high temperatures, is still developing. Most commercial heat pumps today are limited to supply temperatures below 90 °C, which limits their use in many industrial processes that require higher temperatures [14].

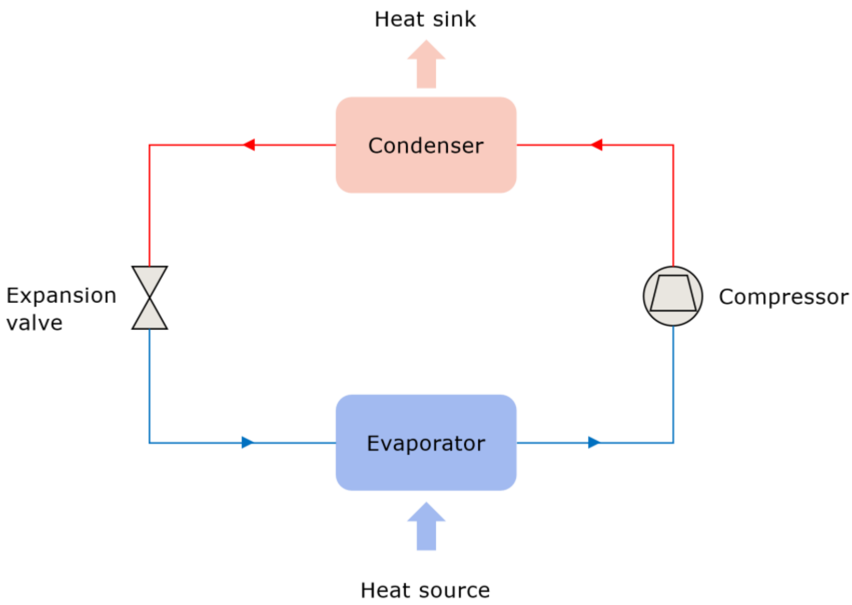

Figure 21. Schematic sketch of a simple heat pump cycle.

High temperature heat pumps (HTHPs) can deliver heat in the range of 100-200 °C, and even higher, due to innovative cycle configurations and advanced refrigerants. HTHPs are increasingly moving from pilot to demonstration stages to commercial deployment, particularly in industrial applications. While research continues to improve efficiency and expand operating ranges, several commercially available systems are already being implemented in applications such as food processing, chemical manufacturing, and district heating.

Recent studies and prototypes have demonstrated the feasibility of reaching up to 250 °C, using advanced refrigerants with low global warming potential (GWP) and multi-stage compression [14]. For example, Høeg et al. (2023) writes about a new ultra-high temperature heat pump HoegTemp from Enerin, that works on the Stirling cycle, with helium as working medium. The heat pump can generate heat up to 200 °C from sources down to -10 °C with high efficiency. A 400-kW prototype installation is described at a biogas facility.

Turboden offers large heat pumps and industrial heat pumps. For example, under construction a large heat pump in combination with mechanical vapor recompression (MVR), that will upgrade low temperature waste heat produced by a paper mill in Northern Europe to useful steam (12 MWth of superheated steam at

170 °C) utilized within the paper mill itself. The refrigerant in the large heat pump will be hydrocarbons. [15]

Baker Hughes also offers industrial heat pumps with mechanical vapor recompression (District heating, Pulp & Paper, Chemical Refinery, Food Beverage, Mining, and Metals) that can deliver 5-50 MW of steam between 12-24 bar (temperatures up to 280 °C, using low temperature waste heat as heat source. The working fluid is also hydrocarbons. [16]

HTHP still face several challenges such as high cost, complexity, refrigerant safety, and integration into existing industrial setups. The TRL of HTHP is increasing, as some configurations are now commercially available or close to market deployment. [14]

5 Storage integration and applications

As stated in the objective of this project, the project shall compare the cost of a suitable high temperature energy storage for steam production at the Hallsta paper mill with the alternative of storing electricity in a Li-ion battery.

In the specific case of the Holmen Hallsta paper mill, storage integration for BESS consists of the battery along with auxiliary systems such as the power conversion and management systems, whereas for TES it comprises auxiliary systems including the thermal storage unit, heat transfer interface, and steam generator.

In other paper mills, where the heat is not generated by electrical power, an electric boiler as steam generator may have to be considered supplementary to a BESS.

The results are shown in Table 7 below.

Table 7. Comparison of investment cost for different energy storage alternatives (excluding auxiliary system) for steam production at Holmen Hallsta paper mill.

Energy Storage Technology	Solid State Sensible Heat Storage + Steam boiler (SB)	Li-Ion battery
Specific Investment	TES: 15-40 €/kWh SB: 200-500 €/kW	Li-Ion: 100-120 €/kWh SB: not required in the Hallsta case otherwise 50-100 €/kW
Investment cost for 300 MWh (MEUR)	TES: 4.5-12 SB: 16-40 Total TES and SB: 20.5-52	Li-Ion: 30-36 SB: not required in Hallsta otherwise 4-8 Total TES only 30-36 or with e-boiler 34-44
Investment cost for 500 MWh (MEUR)	TES: 7.5-20 SB: 16-40 Total TES and SB: 23.5-60	Li-Ion: 50-60 SB: not required in Hallsta otherwise 54-68

As clarification to Table 7 following can be added:

The Li-ion battery is chosen as example for the BESS technology due to the most mature state and the current drastic price drops to 100 -120 €/kWh, considering the foot note of Table 6.

Depending on the boundary conditions, the CAPEX of the TES may comprise only around 30% of the entire CAPEX necessary to transfer the heat, generated and stored in the TES, to the consumer. The portion of the CAPEX attributed to the steam generator is highly dependent on the thermal power. Since the power demand in this case is high the steam generator portion of the CAPEX will be high. If the thermal power demand in relation to thermal energy storage capacity is lower the CAPEX portion of the steam generator will be lower.

Depending on the boundary conditions on a specific site, the specific costs of the entire systems may be similar for the TESS/SB and BESS systems. The theoretical numbers must be verified under the real conditions.

Batteries store electricity, which must be converted to heat to produce steam. In the specific case of the Holmen Hallsta paper mill most of the heat is generated by the refiner and partially by an e-boiler. In other paper mills steam can be generated by a natural gas boiler or a biomass boiler.

The simplest transfer medium for the heat transfer from TES to the steam boiler is air, which just needs to be conveyed by a blower from TES to the boiler. But the heat transfer to the storage media (probably concrete or similar material) is rather poor. The volume specific energy density is poor and even the mass specific density is smaller than for a liquid. A liquid medium like thermal oil or molten salt enables a better heat transfer to both, TES and steam boiler, but makes the system more complex and requires a new media system.

For processes where electricity is simultaneously used to produce a product and losses are recovered to produce heat used in the process, like in a TMP mill, storing electricity in a form that yields electricity back with high efficiency has an advantage. The Hallsta mill is such an example where the overall electrical energy consumption will be lower for batteries compared to a TES. With a TES, the pulp production during low-cost times must be so large that there will be a steam surplus from the refiners that cannot be used. However, from an economical point of view, TES might be better.

5.1 ENERGY STORAGE IN KRAFT PULP MILLS

Energy storage technologies can play a strategic role in enhancing operational flexibility at Kraft pulp mills, particularly in response to fluctuating electricity markets and internal process constraints. In these mills, the balance between steam and electricity production is tightly coupled to the configuration of boilers and turbines. While TES, such as steam accumulators, can shift steam usage over time, has limited impact on electricity consumption and rarely supports economic optimization. This is because TES primarily influences the steam balance rather than enabling dynamic interaction with the power grid.

In contrast, BESS offer a more direct and versatile tool for managing electricity flows. By storing surplus electricity or enabling opportunistic trading during favourable market conditions, BESS can decouple electricity generation from immediate consumption. This capability is particularly valuable in mill configurations where marginal electricity production is sensitive to fuel costs and/or equipment limitations. The following Table 8 illustrates how TES and BESS perform across different Kraft pulp mill setups, highlighting their respective contributions to flexibility and economic viability.

Table 8. Comparison of thermal and battery energy storage in different Kraft pulp mill configurations, focusing on their potential to provide electricity-side flexibility.

	TES (Thermal Energy Storage)	**BESS (Battery Energy Storage System)**
Non-integrated Kraft without condensing tail	A thermal storage, such as a steam accumulator, displaces back-pressure steam both during charging and discharging. TES in this application hardly creates any flexibility in electricity consumption.	A battery storage can be used to create flexibility by either selling or storing the mill's electricity surplus.
Non-integrated Kraft with condensing tail (bark boiler controls marginal electricity production on the turbine; occurs with low electricity/heat ratio at the margin)	A thermal storage hardly creates any flexible electricity use. If the electricity price is so low that condensing operation with solid fuel is not profitable, the load on the solid fuel boiler is reduced and fuel is saved for hours when marginal electricity production becomes profitable again.	A battery storage can be used to create flexibility by either selling or storing the mill's electricity surplus, considering that the marginal fuel cost for condensing electricity is high.
Integrated Kraft – turbine capacity limits back-pressure production (mill with too small turbine)	TES in this application hardly creates any flexibility in electricity consumption. If the electricity price is too low to justify marginal firing with bark, the boiler output is reduced, and fuel is stored.	A battery storage can be used to create flexibility for opportunistic buying and selling of electricity.
Integrated Kraft – bark boiler capacity limits back-pressure production (mill with too small bark boiler)	TES in this application hardly creates any flexibility in electricity consumption. If the electricity price is too low to justify marginal firing with bark, the boiler output is reduced, and fuel is stored.	A battery storage can be used to create flexibility for opportunistic buying and selling of electricity.
Integrated Kraft – back-pressure demand limits production (overcapacity in both turbine and bark boiler)	TES in this application hardly creates any flexibility in electricity consumption. If the electricity price is too low to justify marginal firing with bark, the boiler output is reduced, and fuel is stored.	A battery storage can be used to create flexibility for opportunistic buying and selling of electricity.

6 Conclusions

Role of energy storage

- Essential in balancing supply and demand in sustainable energy systems.
- Thermal Energy Storage (TES) enhances system flexibility and resilience.

Focus of this study

- Comparison of high-temperature storage technologies for steam supply to a paper machine (3–12 bar). The relevant storage sizes are between 300–500 MWh, with a thermal power up to 80 MWth.
- Evaluation is based on technical validation such as efficiency, energy density, operating temperature, storage capacity, Technology Readiness Level (TRL) and economical parameters such as capital expenditure (CAPEX).

Sensible Heat Storage (SHS)

- Most commonly used TES method.
- Stores heat by changing temperature of a medium without phase change.

Solid-state SHS with ceramic or concrete-based material is the most technically and economically TES option for Holmen Hallsta paper mill due to:

- High efficiency (>90%), thermal stability, and durability at elevated temperatures.
- Low cost, good availability, and commercial maturity (TRL 8–9).
- Compatible with existing infrastructure
- Materials such as ceramics and concrete are non-toxic, non-corrosive, and require low maintenance.
- Wide operating temperature range (-160 °C to 1300 °C), suitable for the required saturated steam generation range of 134–188 °C (3-12 bar).
- Modular and scalable to 300–500 MWh. Suppliers offer commercial systems in this desired range.
- Low investment cost (15–40 €/kWh) compared to other storage technologies.
- Lower operational complexity and maintenance need due to robust materials.

Challenges with SHS:

- Due to its relatively low energy density, compared to other TES technologies, SHS requires a large physical volume to store significant amounts of energy. This can pose potential challenges in space-constrained environments.

Battery Energy Storage:

- Offers flexibility for electrical applications.
- Costs have decreased significantly and may be rather close to the TES considering the complete integration in an existing system.
- Drawbacks: low energy density (some BESS technologies), conversion losses, limited lifespan, and expected degradation.
- May be suitable for Holmen Hallsta paper mill, where heat already can be generated electrically.

Final Conclusions:

- At Holmen Hallsta paper mill, available space is not a limiting factor for implementing an energy storage system. However, for such a system to be viable, it must be efficient, robust, cost-effective, and commercially mature.
- In general, thermal energy storage, especially solid-state SHS, is an efficient, scalable, and cost-effective solution for high-temperature applications— in particular when thermal power output is low to moderate.
- The portion of CAPEX attributed to the steam generator in a TESS system can be high if the thermal power requirement is high. This implies that BESS in combination with an electric steam boiler in high power cases is favourable since CAPEX for electric boilers is lower than that of other steam boilers.
- For Kraft pulp mills, TES is not an effective solution or economically viable for electrical flexibility, whereas BESS offers clear advantages for market-driven electricity optimization.

7 Further work

This study has provided a comprehensive comparison of high-temperature thermal energy storage (TES) technologies for steam production in industrial applications. This chapter outlines several key areas that calls for further investigation to support future implementation and optimization.

A detailed analysis of Levelized Cost of Storage (LCOS) should be conducted, incorporating not only capital expenditure (CAPEX), but also operational expenditure (OPEX), and energy conversion losses, system lifetime, interest, and utilization. This would enable a more accurate economic comparison between different storage technologies in a real system integration. It may also be relevant to assess whether the mill has sufficient electrical capacity to accommodate an energy storage system. At Hallsta paper mill, the required storage capacity stated in this study is not a limiting factor. However, if additional capacity is required, it could result in increased subscription costs, which should be considered in the overall economic evaluation.

Future work could explore the potential of combining TES and/or BESS with high-temperature heat pumps (HTHPs) for steam production suitable for industrial applications. This enables load shifting and supports demand-side response, without compromising production. However, the effectiveness of heat pumps still depends on the availability of electricity storage to ensure operational flexibility. This study would evaluate the maturity, cost and performance of HTHPs in industrial settings, their compatibility with existing infrastructure and their impact on overall energy cost.

It is recommended to develop a more precise cost breakdown for steam generators or boilers required to convert stored thermal energy into usable steam. This should include installation cost, auxiliary systems, and operational factors specific to the selected paper mill.

An important area for future research is the development of control strategies for dynamic operation of TES systems in response to fluctuating electricity prices and varying steam demand, to significantly improve economic performance. This also includes an investigation on how the performance of the storage over time under such operational conditions. This includes modelling demand-side response (DSR) scenarios and optimizing charging/discharging cycles.

Implementing a pilot high-temperature TES system at the Hallsta paper mill or a similar industrial site would provide valuable real-world data on performance, reliability, and integration challenge. Continuous monitoring and evaluation would support future scale-up and replication. This would also require a further analysis of which type of steam generator would be most suitable in combination with a high-temperature TES at the Hallsta paper mill.

Future research into novel TES material with higher energy densities and improved thermal conductivity could unlock new possibilities for industrial steam applications. For example, molten salt which has several similar benefits to solid-state SHS regarding operating temperature, storage duration, capacity range and

TRL, but has slightly higher energy density and efficiency. Molten salt has higher investment costs compared to SHS and is more complex to operate, integrate and handle due to high freezing point (~200 °C).

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Appendix A: Shortlist of TES suppliers

Table 9. Shortlist of Thermal energy storage (TES) suppliers [19].

Company name	**Eco-Tech Ceram**	**Energynest**	**Kraftanlagen**	**Kyoto Group**	**Lumenion**	**Polar Night Energy**
Head-quarters	France	Norway	Germany	Norway	Germany	Finland
Year of foundation	2014	2011	1923	2016	2016	2018
Application	Industrial sector and power plant sector	Industrial sector and power plant sector	Industry sector	Industrial sector and power plant sector	Electricity sector and industry sector	Industrial sector and district heating sector
Level of commercialization	Three commercial plants in operation (total 9.3 MWh)	Two commercial projects in Belgium (5 MWh) and Norway (4 MWh)	Two demonstration plants in Germany (2 MWh and 20 MWh)	Commercial demonstrator in operation in Denmark (18 MWh)	Pilot project in operation (2.4 MWh). First demonstrator erected (20 MWh)	First commercial plant in operation (8 MWh)
Type of storage	SHS Solid-state storage	SHS Solid-state storage	SHS Solid-state storage	SHS Molten salt storage	SHS Solid-state storage	SHS Solid-particle storage
Product name	Eco-Stock	ThermalBattery	Green Heat Module	Heatcube	TES (Thermal Energy Storage)	Sand Battery
Storage media	Ceramic in a fixed bed	Concrete tubes (Heatcrete)	Ceramic honeycomb bricks	Molten salt	Steel rods	Sand or sand-like materials
Heat Transfer fluid	Air	Steam or thermal oil	Air	Water / steam	Nitrogen or pressure less air	Air
Range of storage size	2.3 MWh per Eco-stock module	Modular with 1 MWh units up to 1,000 MWh	5 to 1,000 MWh	Up to 120 MWh	5 to 500 MWh	Two standard systems with 200 MWh and 1 GWh respectively
Max storage temperature	Up to 600 °C	Up to 450 °C	Around 1000 °C	Up to 415 °C	Up to 600 °C	Up to 600 °C
TRL	9	9	6-8	8	9	8-9

Company name	**Rondo Energy**	**MGA Thermal**	**Sunamp**	**ZAE Bayern & Hoffmeier Industrieanlagen**	**SaltX Technology**
Head-quarters	USA	Australia	Great Britain	Germany	Sweden
Year of foundation	2020	2019	2005	1970 & 1991	2001
Application	Industry sector	Electricity sector and industry sector	Industry sector	Industrial sector and power plant sector	Industrial sector and power plant sector (Technology currently on hold)
Level of commercialisation	First commercial project in operation (2MWh)	First Demonstrator (5 MWth) realised	Pilot projects realised	One pilot plant (2,3 MWh)	Two pilot plants in Germany (10 MWh), and Sweden.
Type of storage	SHS Solid-state storage	LHS Phase change material storage	LHS Phase change material storage	TCS Sorption based TCS	TCS Salt hydration
Product name	RHB100 and RHB300	MGA Block	Central Bank thermal batteries	Mobile Sorption Heat Storage	SaltX NCS
Storage media	Bricks	Tiny metal alloy particles (made from PCMs C-Al or C-AL-SI) are dispersed through a matrix	Multiple phase change materials	Zeolite	Nano-coated salt (NCS)
Heat Transfer fluid	Air	Argon or nitrogen	Thermal oil	Air	Water/Steam
Range of storage size	100 MWh or 300 MWh	5 MWh to 6 GWh	Up to 6 MWh	2384 kWh per cycle / unit	500 kWh/ton
Max storage temperature	> 1,000 °C	650 °C	Up to 600 °C	Up to 160 °C	Up to 550 °C
TRL	7	7	7	5-7	3-4

HIGH TEMPERATURE STORAGE FOR STEAM PRODUCTION High temperature storage for steam production

This report explores how high-temperature thermal energy storage (TES) can improve operational flexibility and reduce electricity costs in industrial steam production. Using Holmen Hallsta paper mill as a case study, the analysis identifies solid-state sensible heat storage (SHS) with concrete or ceramics as the most suitable solution – offering high efficiency, low investment cost, commercial maturity, appropriate operating temperatures, and compatibility with existing infrastructure. Battery energy storage systems (BESS) are also considered a viable option, particularly in settings like Hallsta where heat is already generated electrically.

The findings provide valuable insights for industries seeking cost-effective and scalable energy storage solutions to optimize steam generation and respond to fluctuating electricity prices.

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