

# Government of Yukon

## Thermal Energy Storage

### Literature Review



Prepared by High Latitude Energy Consulting

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## 1. Introduction

The Yukon has a unique energy landscape characterized by an isolated grid system with an abundance of renewable hydroelectric power, particularly in the summer. However, the Yukon faces significant winter demand spikes as residents rely on electricity for heating and lighting during long, dark winters. This seasonal imbalance presents a challenge for grid reliability as the population grows and the territory aims to integrate more intermittent renewable energy sources like solar and wind.

This literature review was commissioned by the Yukon Government (YG) to explore the potential of heat batteries and thermal storage systems for seasonal energy storage and energy decarbonization in the Yukon. Heat batteries offer a promising solution to store surplus energy from the summer and utilize it during high-demand periods in the winter. By capturing excess renewable electricity or waste heat and storing it for later use, heat batteries could help balance seasonal energy demands, reduce reliance on fossil fuels, and support YG's efforts to achieve its greenhouse gas (GHG) emissions reduction targets outlined in their *Our Clean Future* strategy.

This literature review will examine existing research and case studies on heat battery technologies, assessing their viability and applicability to the Yukon's energy needs.

### Why Heat Batteries?

The global energy transition, driven by the goals outlined in the Paris Agreement, necessitates the swift and widespread adoption of renewable energy sources across all sectors. The increasing deployment of solar, wind, and other renewable energy technologies is key to reducing greenhouse gas emissions and limiting global warming. However, these energy sources are inherently intermittent, with output that fluctuates on both daily and seasonal scales. This variability presents challenges for energy systems, which must continuously balance energy supply and demand to ensure reliability and stability. These renewable energy sources are also largely targeting electricity emission reductions, and significant GHGs are due to heating loads. Heat batteries have the potential to aid in stabilizing electricity grids with high renewable energy penetration as well as helping to tackle emissions in the heating sector.

According to the Yukon Bureau of Statistics [1], at least 53.9% of residential dwellings used fossil fuels as a heating source in 2022. Moreover, the heating sector ranks as the second-largest consumer of fossil fuels, following the transportation sector. It relies heavily on heating fuels such as heating oil and liquid

petroleum gas (propane), contributing significantly to overall fossil fuel consumption. Reducing fossil fuel usage for heating services in Yukon is one of the most effective strategies for achieving sustainability goals.

Figure 1 and Figure 2 illustrate the energy sources used for electricity generation in Yukon. As shown, renewable sources, particularly hydro, play a significant role in the region’s power sector. Additionally, Yukon’s electricity demand peaks during the colder months and drops substantially in the summer. As more renewable independent power producers (IPPs) are integrated into the Yukon power grid, there will be an excess of energy available during the warmer months, in particular from solar energy production. This surplus can be harnessed using seasonal energy storage systems and deployed during the winter to reduce reliance on diesel generators and diesel heating, thereby cutting carbon emissions in both the heating and power sectors [2].

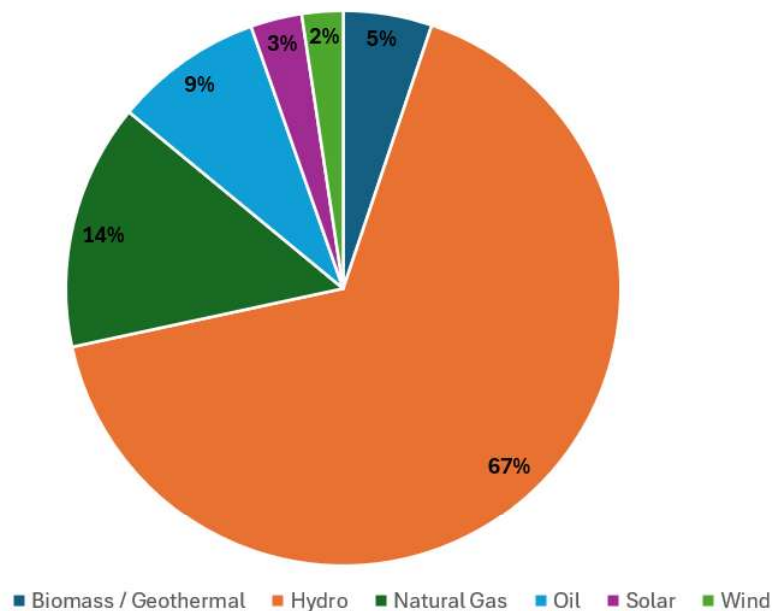


Figure 1. Electricity generation by fuel type in Yukon (2023)<sup>1</sup>.

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<sup>1</sup> Canada Energy Regulator. *Canada's Energy Future Data Appendices*. DOI: <https://doi.org/10.35002/zppg-yr91>

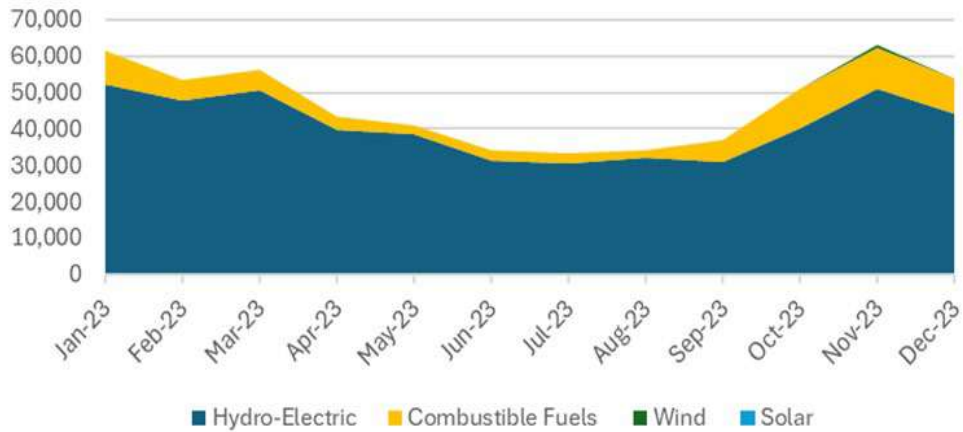


Figure 2. Monthly electricity generation by fuel source in Yukon (2023)<sup>2</sup>.

To address the challenges of mis-matched renewable energy production and energy demand, thermal energy storage (TES) technologies, commonly referred to as heat batteries, can play a crucial role in energy system flexibility. Figure 3 shows the concept of a thermal energy storage system.

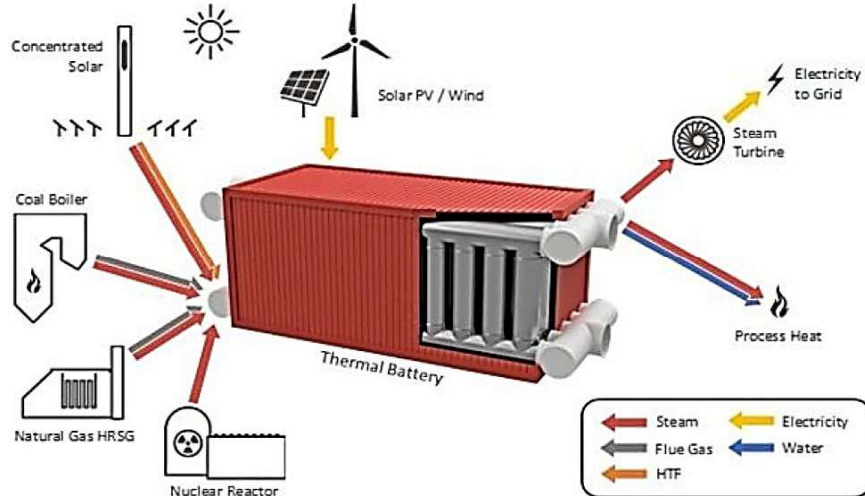


Figure 3. Diagram of a thermal energy storage [3].

<sup>2</sup> Statistics Canada. [Table 25-10-0016-01 Electric power generation, monthly receipts, deliveries and availability](https://doi.org/10.25318/2510001601-eng)  
 DOI: <https://doi.org/10.25318/2510001601-eng>

TES systems are particularly beneficial in power generation, industry, and buildings, where they enhance the efficiency of heating and cooling processes. In the power sector, they can help stabilize grids with high penetrations of renewables, reducing the need for fossil fuel backup power plants. In industry, TES systems can provide heat for manufacturing processes, while in buildings, they can supply heating and hot water more efficiently. By improving system flexibility, thermal energy storage contributes to the creation of more stable, cost-effective, and resilient energy systems.






## Definition of Thermal Energy Storage (TES) and Use Cases

According to the European Association for Storage of Energy [4], thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling an insulated storage medium so that the stored heat energy can be used at a later time for heating and cooling applications and power generation. These TES technologies are mainly categorized into three groups as follows [4]:

- **Sensible heat storage:** This type of TES can store and release thermal energy by raising or lowering the temperature of a storage medium, such as water, air, sand, molten salts, oil, or rocks.
- **Latent heat storage:** In this type, harnessing the energy absorbed or released at a constant temperature during a phase change, typically between solid and liquid states, allows for efficient thermal storage. In most cases, heat is stored during the melting process and released during solidification.
- **Thermochemical heat storage:** This type of storage operates through two mechanisms: chemical reactions and sorption processes. In chemical reactions, energy is stored as the heat of the reaction in reversible processes. In sorption, thermal energy is stored either through adsorption, where energy is captured via physical bonding or absorption, where energy is stored through the uptake or dissolution of a material.

Thermal energy storage systems are generally categorized as either centralized or distributed. Centralized systems are commonly used in large industrial facilities, combined heat and power plants, district heating and cooling networks, or integrated with High-Temperature Heat Pumps (HTHP). Distributed systems are typically found in residential or commercial buildings, serving water and space heating or cooling needs, often in conjunction with heat pumps. Table 1 highlights various use cases for TES, illustrating different combinations of input and output energy types, whether thermal (heat) or electrical (power).

Table 1: TES input-output energy types and their use cases [5]

Input-Output Energy Types	Description	Examples
Heat →  → Heat	Input: Heat Output: Heat	Waste Heat Recycling District Heating
Heat →  → Power	Input: Heat Output: Heat converted to power	Waste Heat Recycling
Power →  → Heat	Input: Power converted to heat Output: Heat	Industrial Processes Domestic & District Heating
Power →  → Power	Input: Power converted to heat Output: Heat converted to power	Utility Energy Storage Industrial Processes
Power →  → X	Input: Power converted to heat Output: X (an energy carrier, processes like electrolysis)	Domestic & District Heating

## Importance of Heat Storage in Energy Systems

One of the primary benefits of TES is its ability to store excess energy when renewable generation is high and release it during periods of low generation or peak demand. This helps reduce the need for costly grid reinforcements and lowers peak electricity demand. By smoothing out the supply and demand imbalance, TES enhances grid stability and resilience, while also reducing greenhouse gas emissions and operational costs. Furthermore, TES systems can help balance seasonal demand, making renewable energy more viable for heating and cooling applications. The longer thermal energy can be stored, the more value TES adds to the grid.

In general, TES technologies can benefit energy systems in the following areas:

- **Demand shifting:** By decoupling supply from demand, TES significantly enhances the flexibility of delivering heat and cold.

- **Intermittent power supply integration:** Even when renewable energy sources like sunlight and wind are inactive, heat and cold generated during peak supply periods can fulfill demand.
- **Energy sector Integrity:** Through improved integration across various sectors, TES enables renewable electricity to consistently meet a larger portion of overall energy requirements, resulting in widespread system benefits.
- **Energy system management:** Deploying TES increases system flexibility, which can help reduce stress on electricity networks and lower the need for costly upgrades to the grid.
- **Seasonal Storage:** Utilizing thermal energy collected on sunny summer days, TES can provide heating during winter, while also ensuring that summer cooling needs are met with cold stored from winter months.

Figure 4 indicates how the International Renewable Energy Agency envisions the integration of TES into energy systems.

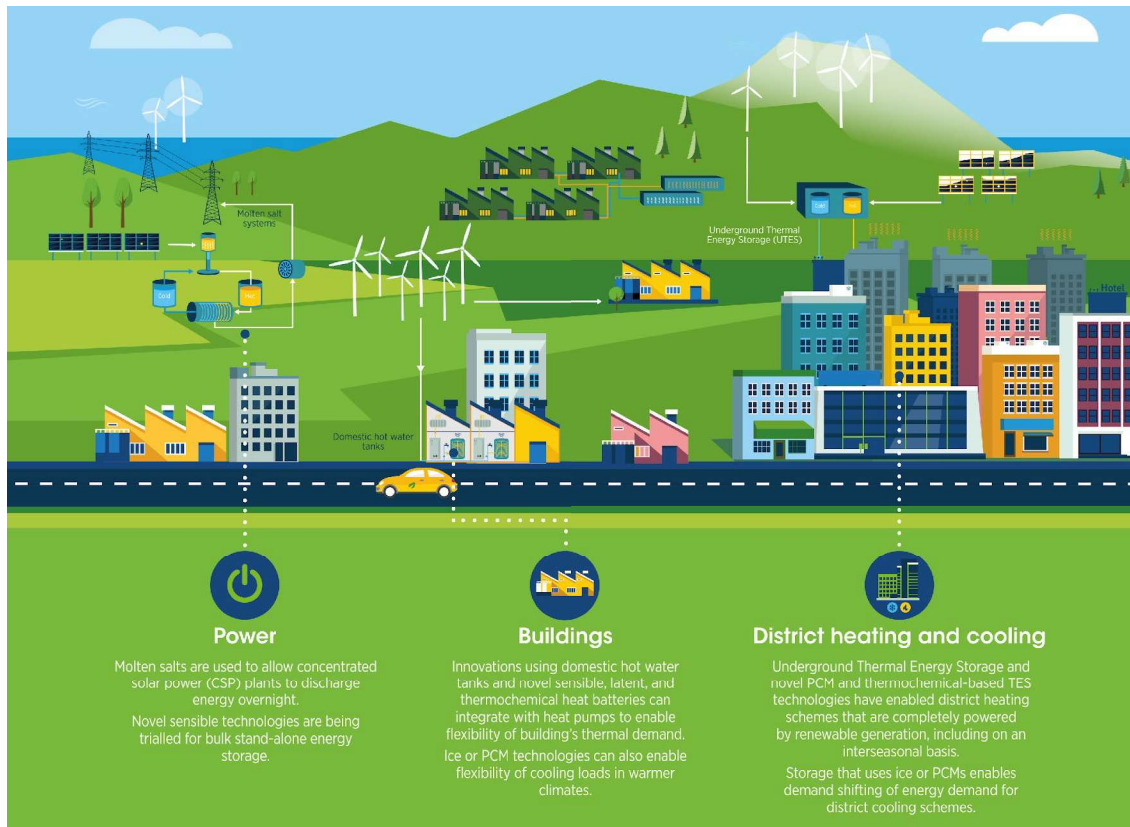


Figure 4. Thermal energy storage application in energy systems [6].

## 2. Heat Storage Technologies Overview

As mentioned earlier, heat batteries can be categorized into three primary types based on their thermal energy storage methods: sensible heat, latent heat, and thermochemical heat storage systems. The selection of a particular type often depends on specific application requirements, including energy density, storage duration, and the operational temperature range. A wide range of technologies have been developed or are in progress for each type of thermal energy storage. These technologies can be deployed at various scales, either in distributed, centralized, or hybrid configurations, and applied across power systems, industries, cold chains, buildings, and district heating and cooling networks.

### Sensible Heat Storage Systems

Sensible heat storage is the most widely used, simplest, commercially mature, and often cheapest form of TES. It works by storing thermal energy through the heating or cooling of a storage medium without undergoing a phase change. This medium can be either liquid or solid. The amount of energy stored in this type of TES depends directly on the temperature variation during the charging process, which should be within the operational temperature range and the thermal capacity of the chosen material. Typically, materials with a high specific heat capacity, such as water or concrete, are used for sensible heat storage, making this method ideal for a variety of applications, from residential heating systems to large-scale industrial processes. This technology's simplicity, reliability, and scalability contribute to its broad adoption across different sectors. On the other hand, sensible heat storage technologies have some disadvantages including their large physical footprint, the increased need for thermal insulation as temperature or storage duration requirements rise, and the potential need for additional energy inputs to maintain the stored heat at the desired temperatures.

Common materials and technologies include:

- Water-based tank TES
- Solid-state TES
- Molten salts
- Underground TES

Each of these sensible-heat TES are explained in more detail in this section.

### **Water-Based Tank Thermal Energy Storage**

As one of the most widespread, cost-effective, and technically mature forms of thermal energy storage, water-based tank thermal energy storage primarily uses water as the storage medium. Water can be heated or cooled via electricity from conventional power plants or renewable sources like solar thermal panels, ambient temperature, or excess energy from the grid. This technology allows for flexible energy management and can accommodate short-term storage (a few hours) as well as long-term or seasonal storage, extending up to several months [7].

The range of applications of this technology is vast. For smaller residential use, water tanks holding a few hundred liters are common, providing hot water for domestic needs. For larger systems, such as those found in commercial or industrial settings, water tanks can be scaled up to 80,000 cubic meters, particularly in district heating and cooling systems. These large systems are essential for urban-scale energy management and can leverage high-temperature storage for industrial processes or grid support.

Water tanks can store heat for hours or even months, depending on the application and design. In residential and smaller commercial uses, storage typically delivers hot water at temperatures between 55°C and 60°C, which is sufficient for space heating and domestic hot water needs. However, in large-scale systems or seasonal applications, high-temperature storage reaching 90°C can be maintained for extended periods, making it possible to store heat throughout summer and use it for winter heating, especially when integrated with heat pumps to extract usable temperatures even as low as 10°C [6].

The simplicity of water-based sensible heat storage makes it highly adaptable and effective across various sectors. Its scalability allows it to meet energy demands from single homes to entire districts, providing a sustainable energy solution for both residential and industrial applications. Figure 5 depicts a schematic of this technology integrated into a domestic district heating system, illustrating how it works in conjunction with solar thermal panels to provide efficient seasonal storage and year-round heating.

While highly effective, the primary constraints of this technology are the physical footprint and the need for effective thermal insulation to reduce heat loss over time. The size of the storage tanks is often limited

by available space and the materials used for construction. For larger applications, land and construction costs become significant factors in design considerations.

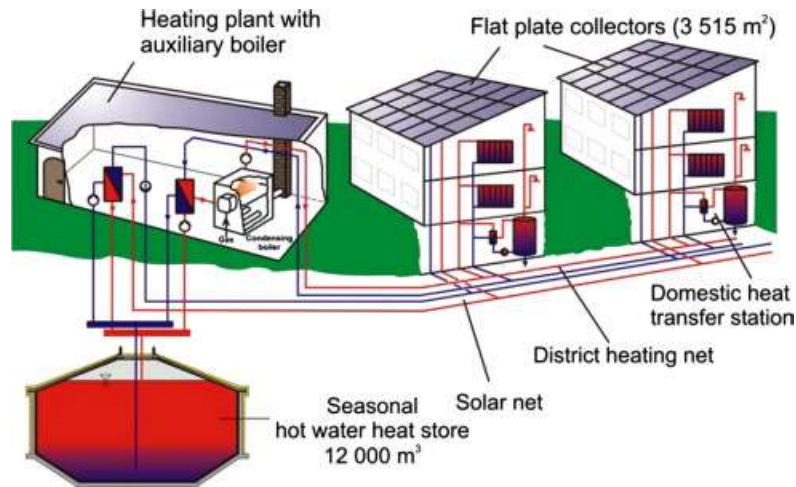


Figure 5. Schematic of the application of a water-based tank thermal energy storage in a district heating system [8]

### Solid-State Thermal Storage

Solid-state thermal storage is widely regarded as a simple, cost-effective, and scalable form of sensible heat storage. This technology utilizes solid materials, such as ceramic bricks for residential applications and larger-scale mediums like rocks, concrete, or packed beds for commercial and industrial purposes, to store thermal energy. Heat is transferred between the source, storage, and end-use points via a working fluid, which circulates through the storage medium.

For high-temperature applications, refractory bricks composed of oxides—such as silica, alumina, magnesia, and iron oxide (feolite)—are employed. Carbonate materials like magnesite also serve as viable options due to their high-temperature resilience. These materials have proven effective in commercial settings, offering reliable heat retention capabilities. In addition to traditional materials, researchers have explored other promising options to enhance performance and sustainability. Concrete with improved thermal properties has been proposed for large-scale energy storage systems due to its affordability and structural strength [9]. According to EPRI, relative to lithium-ion batteries, concrete can provide thermal energy storage for longer durations and at lower cost [10]. Moreover, the use of industrial waste ceramics, such as Cofalit, shows potential as a sustainable alternative, offering both economic and environmental benefits by repurposing waste materials for thermal storage purposes [11].

Solid-state thermal storage systems are highly versatile and can be adapted to both short-term and long-term energy storage needs. Their scalability allows them to support a variety of applications, from small-scale household heating to large industrial processes. The simplicity of the technology, combined with its ability to leverage cost-effective materials, makes it an attractive option for both residential and commercial energy storage, particularly in sectors that demand high-temperature storage and efficient energy management. Figure 6 shows the charge and discharge cycles of a concrete thermal storage system. The working fluid in this system is air.

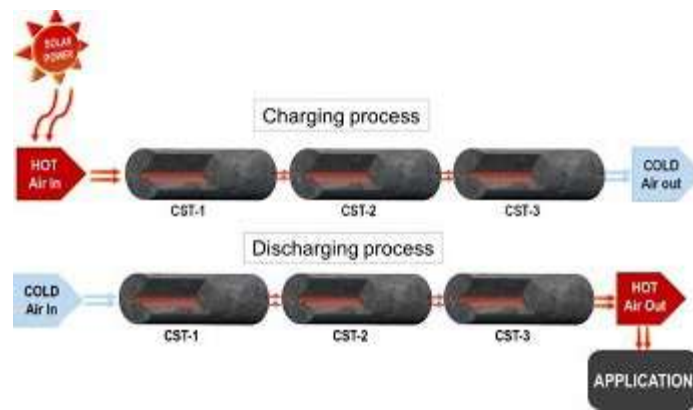


Figure 6. Simplified dynamic modeling of concrete TES module during the charging and discharging processes [12]

## Molten Salts

This technology utilizes molten salts as the storage medium, which remain in a liquid state once they have absorbed heat and surpassed their melting points. These salts are highly effective in storing thermal energy, particularly for applications requiring high-grade heat at elevated temperatures. Molten salts are commonly used in the power generation sector, especially in concentrated solar power (CSP) plants, where they store excess energy generated during the day to be used later, such as at night or during periods of reduced sunlight, ensuring a continuous power supply.

One of the core advantages of molten salt storage systems is their ability to retain heat efficiently over extended periods, enabling thermal plants to operate even when direct sunlight is unavailable. However, a notable drawback of this technology is its vulnerability to solidification [6]. If the temperature of the molten salts drops below their melting point, they can solidify within the system, potentially causing blockages or damage to critical components, such as pipes, valves, and heat exchangers. This issue

necessitates constant monitoring and the use of auxiliary heating to prevent solidification, which can increase operational complexity and costs. Despite this challenge, advancements in system design and materials are helping to mitigate these risks and improve the long-term viability of molten salt storage solutions.

A simplified schematic of the technology developed by Seaborg Technologies, a Danish company specializing in molten salt nuclear reactors, is depicted in Figure 7. This innovative system is designed to generate electricity and provide district heating services, utilizing renewable energy sources. The system operates by heating sodium hydroxide (NaOH) salt with electric heaters, leveraging a two-tank molten salt storage design, which pumps the molten salt between a cold and a hot storage tank for charging and discharging. One of the key advantages of this system is the use of sodium hydroxide, which can be produced at a relatively low cost from seawater as a byproduct of chlorine production. Sodium hydroxide is about six times cheaper than the conventional salts typically used for thermal storage, making it an economically viable alternative. The system's storage capacity is highly flexible, ranging from 250 MWh to 5 GWh. The molten salt is heated to temperatures as high as 700°C. Heat loss is impressively low, with a daily loss rate of only 0.5% to 1%, ensuring long-term energy retention [13].

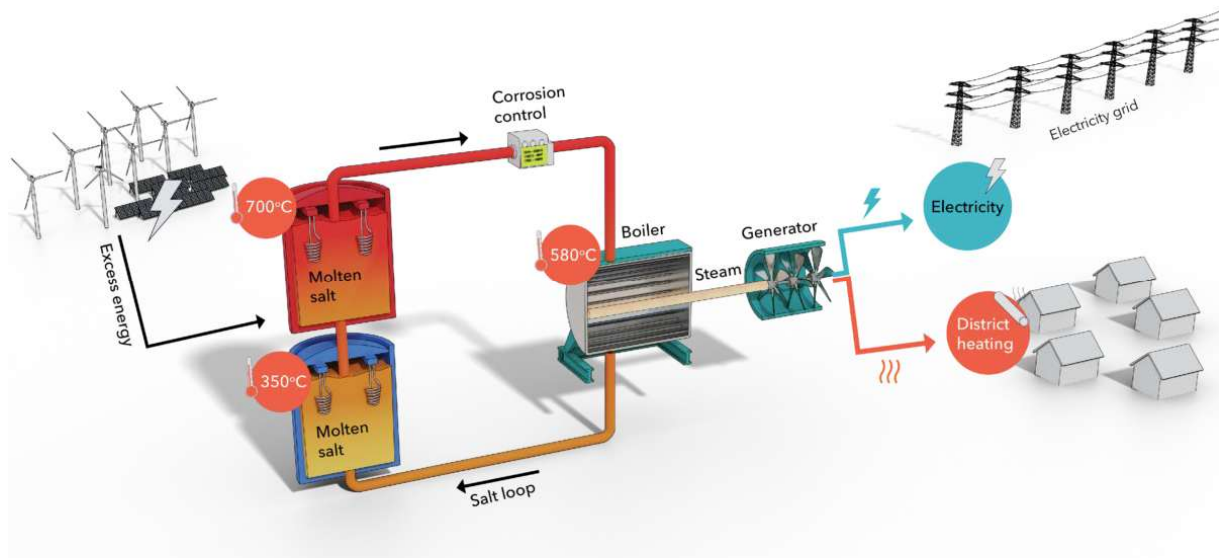


Figure 7. Simplified schematic of a molten salt-based heat storage system [13]

## Underground Thermal Energy Storage

This relatively mature technology, known as Underground Thermal Energy Storage, leverages natural or artificial underground spaces to store large amounts of thermal energy for seasonal use. The storage medium typically consists of geological formations such as soil, sand, solid bedrock, or water in aquifers or artificial pits. Underground TES is particularly effective in district heating systems, where excess heat from solar collectors or industrial processes can be stored and used when needed. While Underground TES offers significant capacity for long-term thermal energy storage, it does have certain limitations. One of the primary drawbacks is its relatively low efficiency, largely due to heat loss over extended periods and challenges in thermal recovery. Despite this, the system is widely applied due to its ability to store substantial energy amounts and its compatibility with renewable energy sources. Figure 8 illustrates several practical examples of this technology in action.

Aquifer Thermal Energy Storage (ATES) and Pit Thermal Energy Storage (PTES) systems are efficient solutions for providing seasonal heating and cooling to buildings by leveraging natural resources. ATES operates by utilizing underground water from naturally occurring aquifers, featuring both hot and cold wells to store and retrieve thermal energy. It delivers heating during winter and cooling during summer through the thermal exchange of groundwater. In contrast, PTES systems consist of underground pits insulated to minimize heat loss. These pits are typically filled with a mixture of gravel and water, which acts as a storage medium. PTES is noted for its low specific cost, comparable to that of ATES, and can be charged or discharged with heated water either via direct contact or through pipes embedded in the gravel. However, PTES requires a larger storage volume compared to ATES, though it has fewer geographical limitations, making it more adaptable for diverse locations. Lastly, Borehole Thermal Energy Storage (BTES) employs vertical heat exchangers to store or extract heat from the ground. The soil surrounding the boreholes, often composed of a mixture with high specific heat and thermal conductivity, serves as the storage medium. This system also exhibits very low hydraulic conductivity, ensuring minimal fluid movement, which helps maintain thermal efficiency over time. Each of these TES technologies offers distinct advantages depending on site-specific conditions, storage needs, and energy requirements. While PTES and ATES are more suited for large-scale operations, BTES offers flexibility in terms of geographical adaptability and smaller applications.

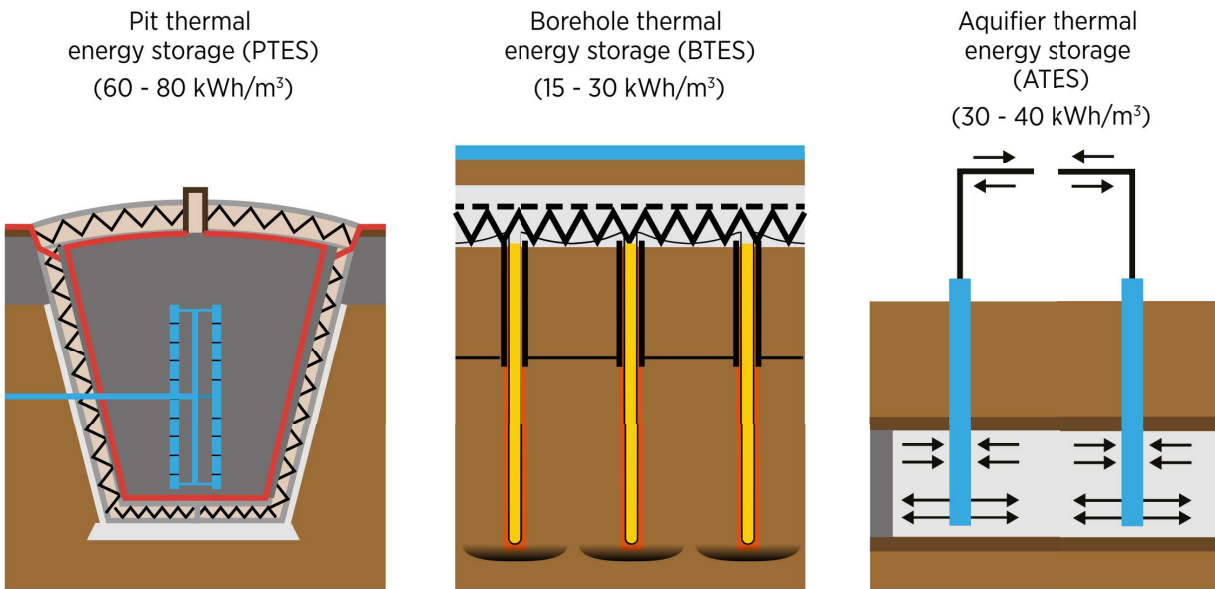


Figure 8. Three types of underground thermal energy storage [6].

## Latent Heat Storage Systems

Latent heat storage involves storing energy during a phase change, such as from solid to liquid (melting) or liquid to solid (freezing). A large amount of heat is absorbed or released during the phase transition without a significant change in temperature. Phase Change Materials (PCMs) such as paraffin, salts, and metallic alloys are the main components of this type of TES. PCMs can store more energy per unit mass than sensible heat systems due to the energy released/absorbed during the phase change. The temperature remains nearly constant during the phase change. This additional control is particularly useful for sensitive applications such as in the cold chain, where drugs or food have to be maintained within narrow temperature ranges. Latent heat storage is used in compact heat batteries for storing heat from renewable sources or providing space heating and hot water in buildings.

When selecting a phase change material, the most critical factor is ensuring that the phase change temperature aligns with the application's requirements. This ensures that the material will effectively store and release energy at the desired operational range. In addition to the phase change temperature, other thermophysical properties must be considered, such as the material's latent heat of fusion, which defines the amount of energy stored or released during the phase change, and its thermal conductivity,

which affects the rate at which heat can be absorbed or transferred. Different PCMs exhibit varying thermophysical properties, and their characteristics must be matched to the specific energy storage needs. Figure 9 outlines the properties of several commonly used PCMs, which will be further discussed in the following sections.

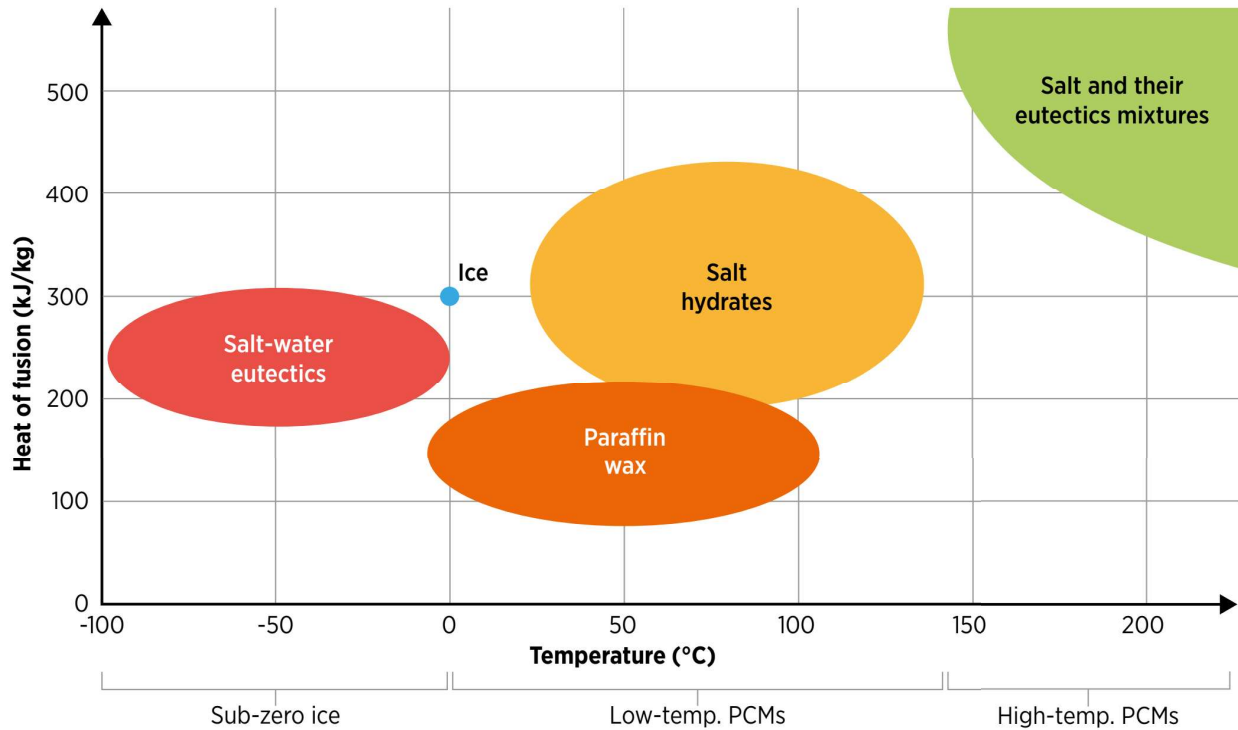


Figure 9. The heat of fusion and melting points of some of the main PCMs [6].

### Sub-Zero Temperature PCMs

Sub-zero temperature phase change materials (PCMs) are particularly beneficial for applications needing temperatures lower than conventional cooling systems, such as refrigeration in cold chain logistics. These PCMs can sometimes outperform ice-based systems. They are available either as single-component materials or as multicomponent mixtures, such as eutectic blends. A eutectic mixture contains components in specific proportions, causing the blend to melt at a lower temperature than its individual elements.

Salt-water eutectics, for instance, are produced by dissolving salts into water to create a solution with a reduced melting point. The material selection for sub-zero PCMs depends on several factors, such as the

phase-change temperature, energy storage capacity, cost, and the material's potential to cause corrosion. This flexibility in design makes sub-zero PCMs adaptable for a range of refrigeration and cooling needs.

### **Ice Thermal Storage**

Ice is a widely available and cost-effective phase change material (PCM) commonly used for cold energy storage. In this technology, renewable energy sources power chillers or ice generators to freeze water during the charging phase. For the discharge cycle, cold energy is typically transferred using water or other heat transfer fluids such as glycol, depending on the system's design and requirements.

This method is particularly efficient in commercial applications, such as large buildings and district cooling systems, where cooling demand peaks during the day. By storing energy as ice during off-peak hours or when renewable energy is abundant, these systems can reduce energy costs and improve grid stability. Ice storage also helps balance cooling loads, making it an attractive option for areas where air conditioning is critical.

### **Low-Temperature PCMs**

Two of the most commonly used phase change materials in this category are paraffin waxes and inorganic salt hydrates. Paraffin waxes typically operate within a temperature range of around 0°C to 100°C, while inorganic salt hydrates function in a slightly higher temperature band, from approximately 20°C to 120°C. These materials are widely chosen for their ability to undergo phase transitions within this temperature range, making them suitable for a variety of thermal management applications. Salt hydrates, in particular, are known for their higher latent heat capacity—nearly double that of paraffin waxes—allowing them to store and release more thermal energy during phase transitions. Despite their superior energy density, both materials exhibit a wide array of melting points, which enables flexibility in matching specific thermal needs.

These technologies are primarily used in domestic heating and cooling systems, including air conditioning and space heating. In homes, they can store excess heat during warmer periods and release it when needed, making them ideal for improving energy efficiency. Moreover, recent developments have expanded their use to industrial and commercial buildings, where thermal storage systems can help balance load demand and reduce energy costs. In addition to their energy storage benefits, advancements in material engineering have improved the durability and thermal conductivity of these PCMs, allowing

them to be even more efficient. This makes paraffin waxes and salt hydrates increasingly relevant in sectors like renewable energy integration and sustainable building design, where effective thermal energy storage is essential. The schematic of an experimental setup of thermal heat storage using paraffin wax as PCM, solar energy as the heat source, and water as the heat transfer fluid is shown in Figure 10.

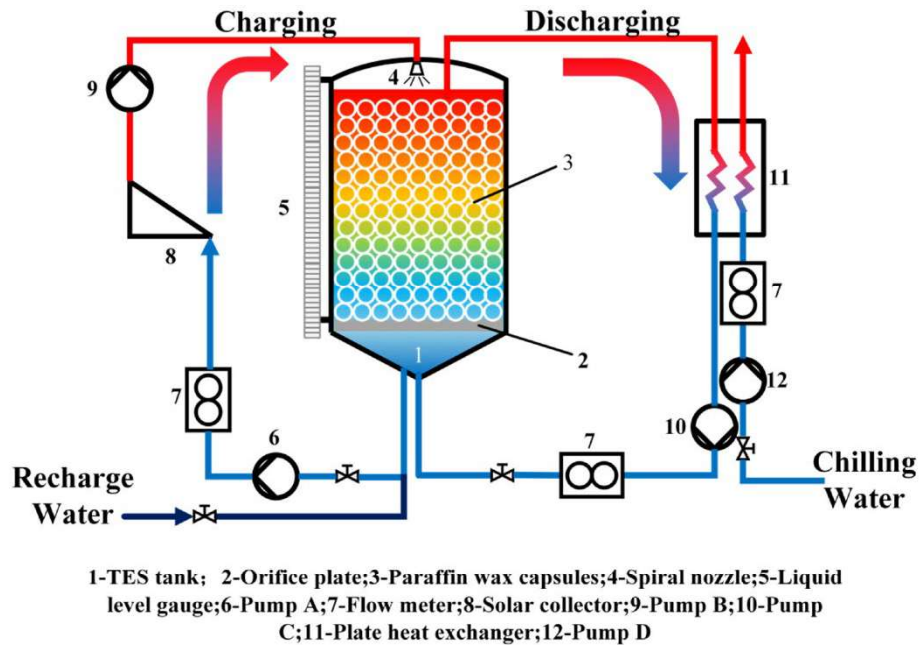


Figure 10. Schematic of an experimental setup of paraffin wax-based TES [14].

### High-Temperature PCMs

High-temperature phase change materials (PCMs) based on salts and eutectic mixtures are integral to advanced thermal energy storage systems, especially for industrial and concentrated solar power (CSP) applications. Salt-based PCMs, particularly nitrate salts like sodium nitrate or potassium nitrate, are well-suited for high-temperature applications due to their high latent heat capacity and wide temperature range (200°C to 600°C). Eutectic mixtures, composed of two or more components, offer the advantage of having a precise melting point, which is typically lower than the melting points of the individual components. This property allows them to operate efficiently at specific temperatures, optimizing energy storage and release in thermal systems. These high-temperature PCMs are often used in CSP plants to store excess solar energy during peak daylight hours, which can then be converted to electricity after sunset or used directly in industrial processes requiring consistent high heat levels [15].

High-temperature composite PCMs are another important class of materials for thermal heat storage. These composite materials typically consist of PCMs like salts embedded in a supporting matrix, often composed of graphite or metals, which improves thermal conductivity and energy transfer rates. This enhancement addresses a common limitation of conventional PCMs, such as poor heat transfer. High-temperature composite PCMs are increasingly being utilized in energy-intensive industries such as metallurgy, where processes require consistent thermal management. In addition to industrial applications, they also show promise in hybrid systems that integrate renewable energy sources, providing efficient storage solutions capable of reducing reliance on fossil fuels. This makes high-temperature composite PCMs a critical component in the shift toward decarbonized energy systems [16].

## **Thermochemical Heat Storage Systems**

Thermochemical storage is based on reversible chemical reactions. Heat is stored and released during the breaking and reforming of chemical bonds in reactions. This type of storage often provides the highest energy density among the other types including sensible and latent heat storage. Thermochemical reactions allow for long-term heat storage without energy loss over time. Thermochemical storage is still in the experimental phase for many applications but holds potential for industrial heat recovery, long-term seasonal storage, or integration with renewable energy systems [17].

The primary types of TCES fall into two categories: systems based on reversible chemical reactions and sorption-based systems. These systems can store heat for long durations, providing flexibility in matching supply and demand in both industrial processes and renewable energy grids. Sorption-based storage systems are limited to temperatures of approximately 350°C, while non-sorption thermochemical systems can function at significantly higher temperatures and provide greater energy storage densities. One of the key benefits of sorption systems is their ability to store thermal energy at ambient temperatures for extended periods without any heat loss. This makes them particularly promising for seasonal energy storage at lower temperatures, such as in building applications, where long-term energy retention is essential. At higher temperatures, non-sorption thermochemical systems become more advantageous, supporting industrial applications and providing higher storage capacities. The ability to store energy in chemical bonds, coupled with the potential for heat recovery and energy conservation over long

durations, makes these systems essential for future energy storage infrastructure, particularly for integration with renewable sources and district heating systems [6].

### Chemical Looping (Calcium Looping)

Chemical looping technology involves a reversible chemical reaction, typically using metal oxides, to capture carbon dioxide (CO<sub>2</sub>) and store heat. This process efficiently stores energy in the chemical bonds and later releases it by reversing the reaction. One notable method involves the reversible reaction between calcium oxide (CaO) and carbon dioxide (CO<sub>2</sub>) to form calcium carbonate (CaCO<sub>3</sub>), known as calcium looping. In this process, CaCO<sub>3</sub> is subjected to high temperatures, breaking it down into CaO and CO<sub>2</sub>. The energy provided by the heat is stored in the chemical bonds of these two products, which are then stored separately, effectively acting as the energy storage medium. A major advantage of the calcium looping system is the availability of low-cost materials, which enables it to achieve an impressive energy density of 3.2 gigajoules per cubic meter. However, the process requires high working temperatures, typically above 600°C [6].

The storage duration of CaO and CO<sub>2</sub> can extend for weeks or even months with minimal energy loss, making it an effective long-term energy storage solution. When energy is needed, CaO and CO<sub>2</sub> are recombined to form CaCO<sub>3</sub>, releasing the stored heat in a highly efficient manner. This makes the calcium looping process a compelling candidate for large-scale energy storage systems and carbon capture applications, particularly in industrial settings and the power sector where high temperatures are readily available. Figure 11 shows the looping process in this technology.

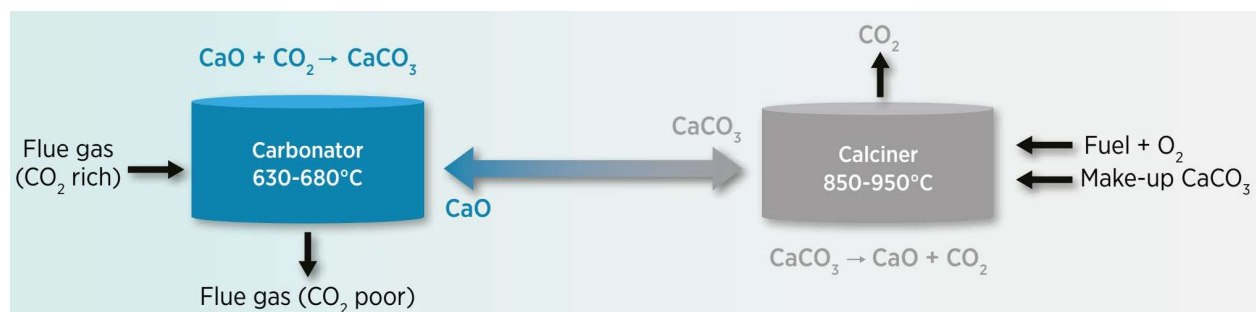


Figure 11. Calcium Looping process [6].

## Salt Hydration

Salt hydration is an innovative method for thermochemical thermal energy storage, utilizing the heat released or absorbed during the hydration and dehydration processes of specific salts. Commonly used salts include sodium sulfide ( $\text{Na}_2\text{S}$ ), magnesium sulfate ( $\text{MgSO}_4$ ), strontium bromide ( $\text{SrBr}_2$ ), and magnesium chloride ( $\text{MgCl}_2$ ), which can effectively store thermal energy through reversible hydration reactions. When anhydrous salts absorb water vapor, they undergo hydration, releasing heat that can be harnessed for heating applications or steam generation. Conversely, when heated, the hydrated salts release water, storing energy in the form of heat. This mechanism offers high energy densities making it a compelling option for residential applications and large-scale applications such as concentrated solar power systems and industrial waste heat recovery [6].

The advantages of salt hydration as a heat storage method are significant, particularly in terms of sustainability and scalability. The use of non-toxic and abundant materials aligns with environmental goals, while the technology can be adapted for various applications, from small-scale systems to large power plants. This technology has high energy storage density, suitable turning temperature, self-separation of reactants, and using water vapor as a safe and cheap gaseous partner [18]. Figure 12 illustrates the salt hydration cycle employed for space heating and hot water production.

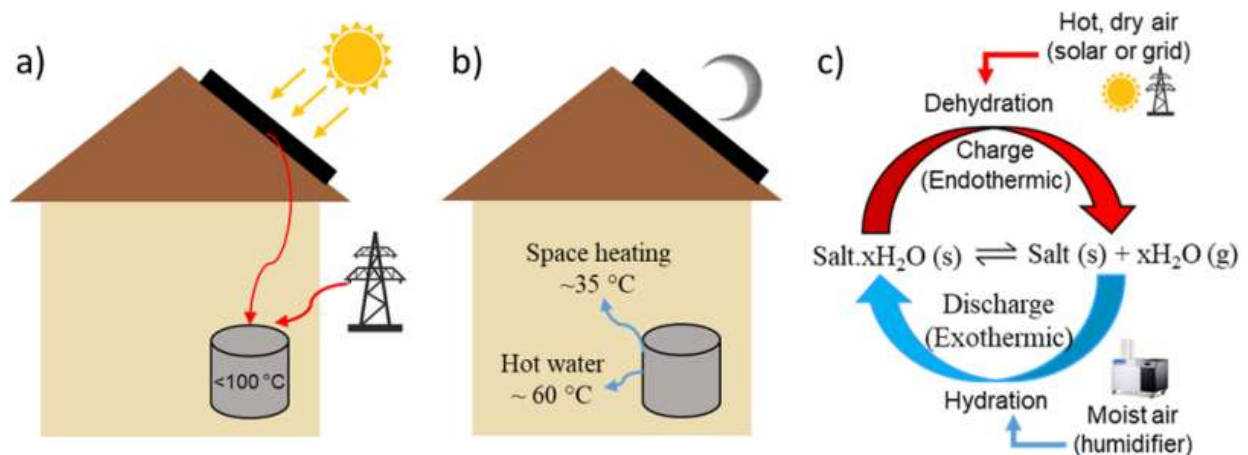


Figure 12. Salt hydration - dehydration cycle [19].

## Absorption Systems

Absorption systems rely on the reversible interaction between a liquid absorbent and a gaseous refrigerant. In these systems, thermal energy is stored during the absorption process, where the refrigerant is absorbed into the liquid solution, releasing heat. This process is reversed during energy discharge, where heat is applied to the solution, causing the refrigerant to evaporate and thus store the energy thermochemically. The use of common working pairs, such as water-lithium bromide or ammonia-water, enables these systems to efficiently store and release thermal energy over long periods, making them suitable for applications like solar energy storage or waste heat recovery [6].

One of the primary advantages of absorption systems is their potential to achieve higher energy storage densities compared to conventional sensible and latent heat storage methods. This is particularly beneficial in scenarios requiring long-duration storage or seasonal energy storage. Additionally, absorption systems can operate across a wide temperature range, depending on the choice of materials, allowing them to be integrated into various industrial processes and renewable energy systems for the utilization of solar energy, waste heat, and off-peak electricity. However, challenges remain in optimizing the system's efficiency and material durability, particularly in maintaining the stability of the absorbent-refrigerant pair over numerous charge and discharge cycles.

Figure 13 illustrates the schematic of an absorption thermal energy storage system. During the charging phase, heat from an external source is applied to the generator, causing vapor to be desorbed from the solution. This vapor moves to the condenser, where it releases the heat of condensation and turns into a liquid. At the end of this process, the solution becomes concentrated and is returned to the storage tank, while the liquid condensate is collected in a separate absorbate storage tank. This allows the absorbent and absorbate to be stored independently, preserving the potential for future heating or cooling. Since the heat is stored in the form of chemical potential, heat loss during the storage period is minimal. In the discharging phase, the process is reversed to recover the stored energy in the form of heat or cooling. A low-temperature heat source, representing cold storage, is used to evaporate the stored liquid, generating vapor in the evaporator. When this vapor is absorbed by the concentrated solution in the absorber, heat is released, representing the stored thermal energy. However, part of the stored heat is used to raise the pressure of the concentrated solution to its equilibrium condition, resulting in the total recovered heat being slightly lower than the initial heat input during the charging phase [20].

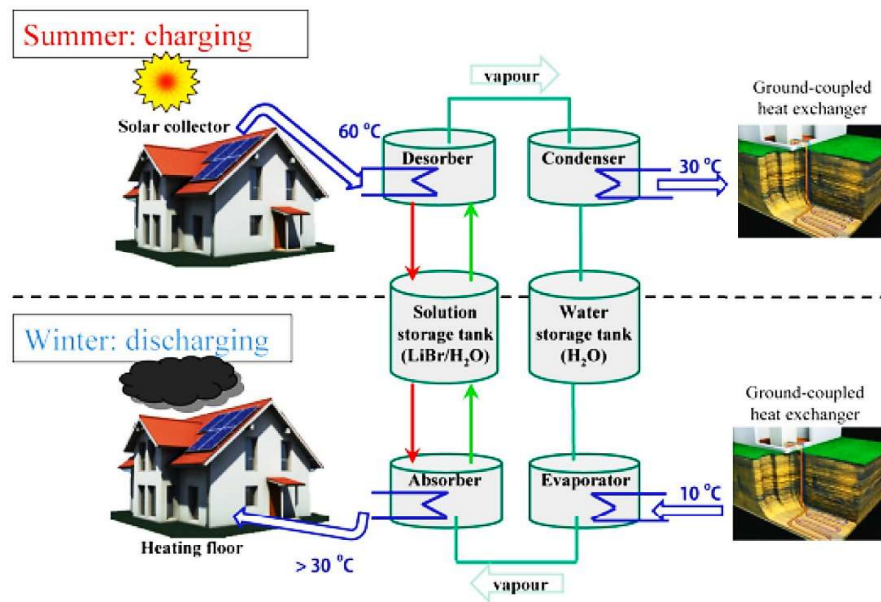


Figure 13. Schematic of an absorption thermal energy storage [20].

## Mechanical-Thermal Coupled Systems

Mechanical thermal energy storage (MTES) systems store energy by converting thermal energy into mechanical energy, typically through processes like compressed air energy storage (CAES). In these systems, surplus electricity or heat is used to drive mechanical processes, such as compressing air or heating and expanding working fluids. The stored mechanical energy can later be converted back into electricity or used directly for heating or cooling. For instance, CAES stores energy by compressing air and releasing it to drive turbines when needed. These systems offer high energy storage capacity and long discharge times, making them suitable for grid-scale applications, particularly in balancing intermittent renewable energy sources.

### Adiabatic Compressed Air Energy Storage

Adiabatic Compressed Air Energy Storage (A-CAES) is an advanced form of traditional CAES designed to improve overall efficiency from 40-50% to 70-80% by capturing and reusing the heat generated during air compression. In conventional CAES, off-peak renewable electricity compresses air, storing it in subterranean caverns, and later expanding it to drive a turbine and generate electricity. However, this process involves significant energy losses due to the cooling of compressed air and the need to reheat it

before expansion. A-CAES addresses these inefficiencies by incorporating a high-temperature thermal energy storage (TES) unit, such as pebbles, ceramic bricks, or phase change materials (PCMs), which stores the heat produced during compression. This stored heat is then used during the expansion process, eliminating the need for external heat sources and improving the system's efficiency. The schematic of such a system in charging and discharging cycles are shown in Figure 14.

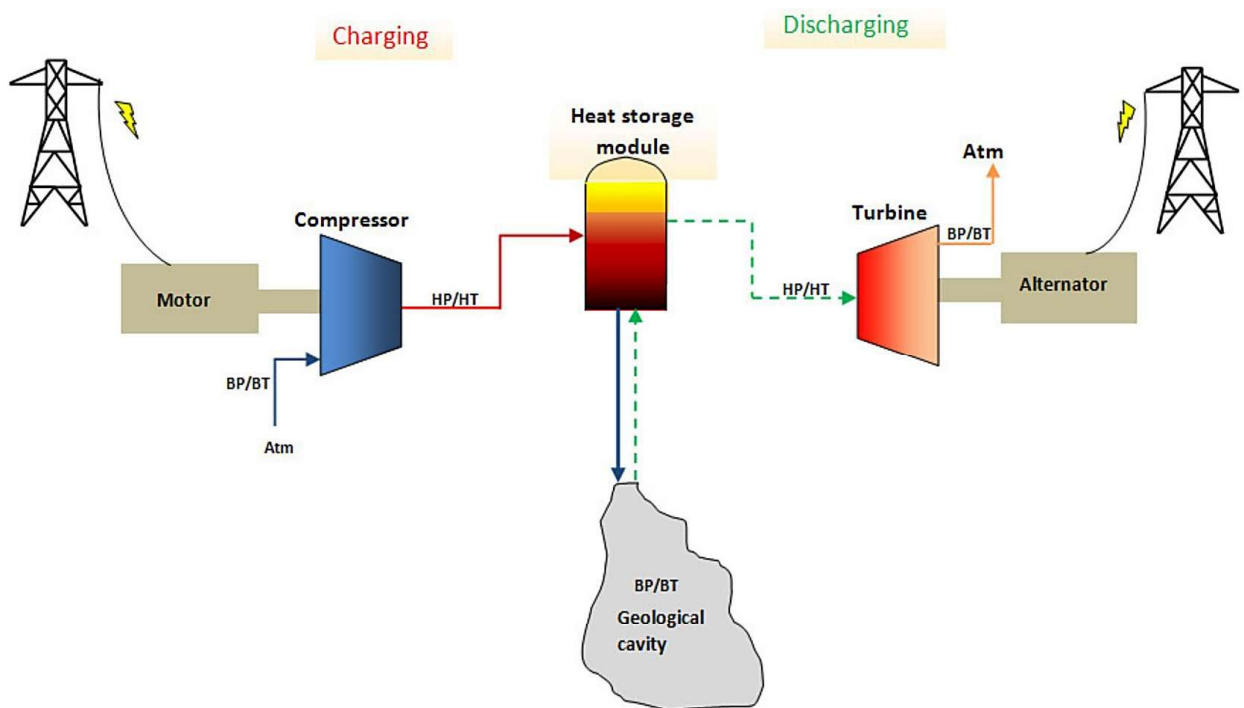


Figure 14. Schematic of an adiabatic compressed air energy storage [21].

### Liquid Air Energy Storage

Liquid Air Energy Storage (LAES) is a type of energy storage system that leverages the physical properties of air, which can be cooled and liquefied at very low temperatures. In this system, off-peak electricity or surplus energy from renewable sources is used to compress and cool air to around  $-196^{\circ}\text{C}$ , transforming it into a liquid state that is stored in insulated tanks at low pressure, and the heat produced during compression is stored in a thermal energy storage. When electricity is needed, the liquid air is exposed to ambient temperatures, causing it to rapidly expand and revert to a gaseous state. The air is further heated by stored heat and is used to drive a turbine and generate electricity. LAES is scalable, offers long-duration

storage, and does not require specific geological conditions, making it more flexible than some other mechanical energy storage technologies like CAES [22].

The main difference between LAES and A-CAES lies in their respective energy storage processes. In A-CAES, air is compressed and stored at high pressure in underground caverns, and the heat from compression is captured using a thermal energy storage system for later use during expansion. In contrast, LAES liquefies air, which is stored at cryogenic temperatures in above-ground tanks. While both systems store air to drive turbines, LAES avoids the need for specific geological formations, making it more versatile in terms of location. However, A-CAES is generally more efficient due to its ability to capture and reuse heat from compression, while LAES typically requires more energy to liquefy air, resulting in lower round-trip efficiency. Liquid air can serve as a fuel for engines, while its cold energy can be utilized for refrigeration purposes. Figure 15 shows the schematic of a liquid air energy storage.

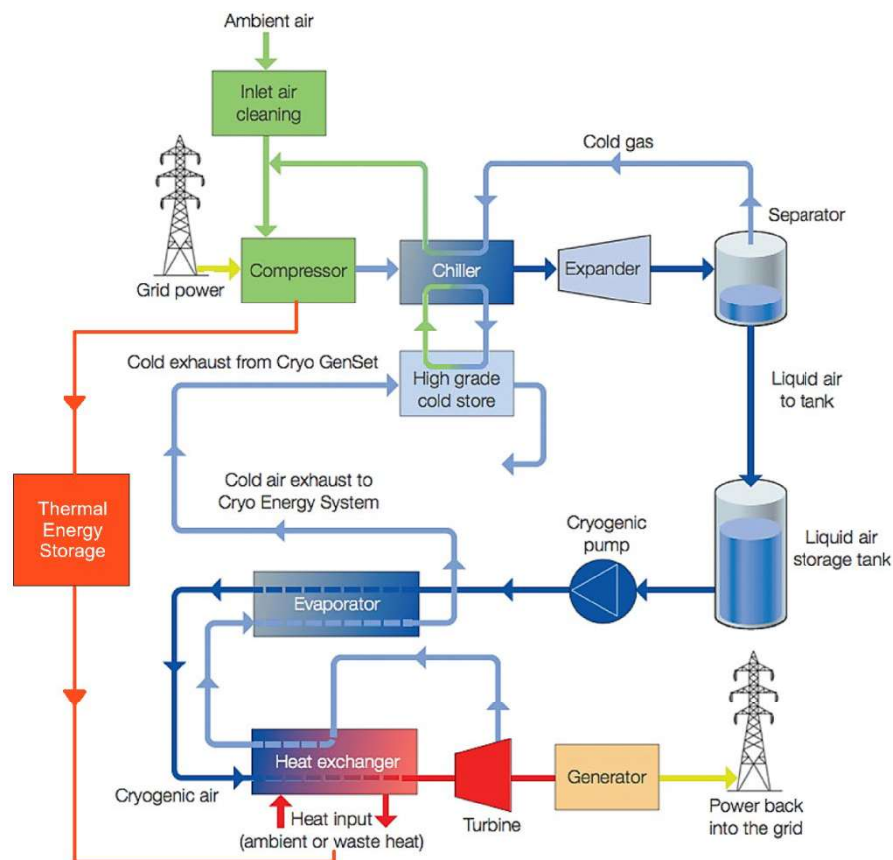


Figure 15. Schematic of a liquid air energy storage [23] (edited).

### 3. Technology, Performance, and Efficiency Comparison

Choosing the right TES technology, size, storage duration, and efficiency is crucial for optimizing performance across various applications, such as industrial waste heat recovery, renewable energy integration, and district heating. Tailoring the technology to the specific application, with the right size and capacity, ensures a balance between cost, energy savings, and sustainability. In this section, different TES technologies are compared in terms of several important characteristics and capabilities.

#### Operating Temperature of TES Technologies

Thermal energy can be stored across a wide range of operating temperatures, categorized from sub-zero to extremely high temperatures, depending on the application and type of storage technology. These systems are designed to meet diverse operational needs, from low-temperature heat storage for residential use to high-temperature solutions suited for industrial processes. The categorization of TES systems by temperature helps define their suitability for various applications.

Sub-zero TES operates at temperatures below 0°C and is often used in applications like refrigeration or cold storage. Low-temperature TES operates between 0°C and 100°C, typically utilizing sensible heat materials like water or latent heat materials that undergo phase changes in this range. Medium-temperature TES functions between 100°C and 500°C, making it ideal for heating, power-to-heat applications, and some industrial processes. High-temperature TES systems operate between 500°C and 900°C and are often used in concentrated solar power (CSP) plants or large-scale industrial applications. High+ systems, between 900°C and 1600°C, are particularly suited for more advanced industrial processes, while High++ TES, at temperatures above 1600°C, is used for specialized applications, such as ultra-high-temperature furnaces or advanced material processing. These categories outline the broad spectrum of TES operating temperatures, each playing a vital role in optimizing energy efficiency across different sectors. The operating temperatures of different TES technologies are presented in Table 2.

Table 2: Operating temperature of different TES technologies [6] [24]

Storage Technology	< 0°C	0°C > & < 100°C	100°C > & < 500°C	500°C > & < 900°C	900°C > & < 1600°C	1600°C > & < 2400°C
	Sub-Zero	Low	Medium	High	High+	High++
<b>Sensible Systems</b>						
Graphite (SSTS)						High++
Ceramics, Silica, and Sand (SSTS)	High	Low	Medium	High	High+	
Concrete (SSTS)		Low	Medium	High		
Rocks (SSTS)	High	Low	Medium	High		
Steel (SSTS)			Medium			
Molten Salts			Medium	High		
Underground Water (UTES)		Low				
Water (TTES)		Low				
<b>Latent Systems</b>						
Microencapsulated Metals			Medium	High	High+	
Inorganic Salts and Eutectic Mixtures			Medium	High		
Sodium			Medium	High		
Other Liquid Metals			Medium			
Molten Aluminum Alloy		Low	Medium			
Paraffin Waxes, Fatty Acids		Low				
Salt Hydrates		Low	Medium			
Salt-Water Mixtures		Low	Medium			
Ice and Salt-Water Eutectics	High					
<b>Thermochemical Systems</b>						
Chemical Looping		Low	Medium	High		
Salt Hydration		Low	Medium			
Absorption		Low	Medium			
<b>Mechanical-Thermal Systems</b>						
Adiabatic Compressed Air Energy Storage			Medium			
Liquid Air Energy Storage	High					

## Storage Duration, Efficiency, and Lifetime of TES Technologies

Thermal Energy Storage technologies vary significantly in terms of key performance characteristics, such as storage duration, efficiency, lifetime, and typical applications. These characteristics are compared in Table 3. The duration of energy storage is primarily determined by the commercial and operational requirements of the system, as well as the specific TES technology employed. While some TES systems are designed for short-term energy storage, others can be optimized for extended or even seasonal storage through improvements in system design, such as enhanced insulation and other energy retention techniques. Table 3 highlights the typical storage durations associated with different TES technologies, reflecting their ability to store energy for hours, days, or even weeks.

Round-trip efficiency—another critical parameter—indicates how well a TES system converts and stores thermal energy during charging and discharges it when needed. A higher efficiency reflects a more effective energy transfer process with fewer losses, making the system more cost-effective over time.

Expected lifetime is another factor outlined in Table 3, expressed either as the number of years the storage system can operate at acceptable efficiency levels or the number of full charge-discharge cycles it can complete before significant degradation occurs. While the lifetime can vary depending on the type of TES, actual performance is influenced by several factors, including the system's operational conditions (such as temperature cycles and usage patterns) and maintenance practices.

Table 3 also categorizes the forms of input and output energy for each TES technology, identifying whether it can receive energy in the form of Heat, Cold, or Power (H, C, or P, respectively) and whether the output energy is used for heating, cooling, or electricity production. This classification helps determine the most suitable applications for each TES technology, whether it's for residential heating, industrial cooling, or integration with power generation systems.

It's important to note that while Table 3 provides typical performance characteristics, these can vary based on the specific design and operational environment of the system. Factors like insulation quality, environmental conditions, and operational strategies can significantly impact the actual performance of TES systems.

Table 3: Storage characteristics of different TES technologies [5] [6] [24]

TES Technology	Efficiency (%)	Lifetime	Storage Duration			Energy In			Energy Out			
			Hours	Days	Weeks	H	C	P	H	C	P	
<b>Sensible Systems</b>												
Graphite (SSTS)	50 < & < 90	10 – 30 years	■	■	■	■	■	■	■	■	■	
Ceramics, Silica, and Sand (SSTS)			■	■	■	■	■	■	■	■	■	
Concrete (SSTS)			■	■	■	■	■	■	■	■	■	■
Rocks (SSTS)			■	■	■	■	■	■	■	■	■	■
Steel (SSTS)			■	■	■	■	■	■	■	■	■	■
Molten Salts	> 98	> 20 years	■	■	■	■	■	■	■	■	■	
Underground Water (UTES)	< 90	50 years	■	■	■	■	■	■	■	■	■	
Water (TTES)	50 < & < 90	15-40 years	■	■	■	■	■	■	■	■	■	
<b>Latent Systems</b>												
Microencapsulated Metals	> 90	> 5000 cycles	■	■	■	■	■	■	■	■	■	
Inorganic Salts and Eutectic Mixtures			■	■	■	■	■	■	■	■	■	
Sodium			■	■	■	■	■	■	■	■	■	■
Other Liquid Metals			■	■	■	■	■	■	■	■	■	■
Molten Aluminum Alloy			■	■	■	■	■	■	■	■	■	■
Paraffin Waxes, Fatty Acids	> 95	300 – 3000 cycles	■	■	■	■	■	■	■	■	■	
Salt Hydrates			■	■	■	■	■	■	■	■	■	
Salt-Water Mixtures			■	■	■	■	■	■	■	■	■	
Ice and Salt-Water Eutectics	> 95	> 20 years	■	■	■	■	■	■	■	■	■	
<b>Thermochemical Systems</b>												
Chemical Looping	45 < & < 63	> 30 years	■	■	■	■	■	■	■	■	■	
Salt Hydration	50 < & < 60	20 years	■	■	■	■	■	■	■	■	■	
Absorption	50 < & < 65	50 years	■	■	■	■	■	■	■	■	■	
<b>Mechanical-Thermal Systems</b>												



Table 4: Technology readiness and application level of different TES technologies [5] [6] [24]

TES Technology	Technology Readiness Level			Application Level		
	1 - 3	4 - 6	7 - 9	Small	District	Utility
<b>Sensible Systems</b>						
Graphite (SSTS)			High	Medium	Medium	Medium
Ceramics, Silica, and Sand (SSTS)			High	Medium	Medium	Medium
Concrete (SSTS)			High	Medium	Medium	Medium
Rocks (SSTS)			High	Medium	Medium	Medium
Steel (SSTS)	Low	High	Medium	Medium	Medium	Medium
Molten Salts	Medium		High	Medium	Medium	Medium
Underground Water (UTES)			High	Medium	Medium	Medium
Water (TTES)			High	Medium	Medium	Medium
<b>Latent Systems</b>						
Microencapsulated Metals		High	Medium	Medium	Medium	Medium
Inorganic Salts and Eutectic Mixtures			High	Medium	Medium	Medium
Sodium		High	Medium	Medium	Medium	Medium
Other Liquid Metals	High			Medium	Medium	Medium
Molten Aluminum Alloy		High		Medium	Medium	Medium
Paraffin Waxes, Fatty Acids		High		Medium	Medium	Medium
Salt Hydrates			High	Medium	Medium	Medium
Salt-Water Mixtures			High	Medium	Medium	Medium
Ice and Salt-Water Eutectics			High	Medium	Medium	Medium
<b>Thermochemical Systems</b>						
Chemical Looping		High	Medium	Medium	Medium	Medium
Salt Hydration		High		Medium	Medium	Medium
Absorption		High		Medium	Medium	Medium
<b>Mechanical-Thermal Systems</b>						
Adiabatic Compressed Air Energy Storage		High		Medium	Medium	Medium
Liquid Air Energy Storage		High		Medium	Medium	Medium

## 4. Case Studies and Real-World Applications

The case studies shared here are existing projects in regions similar to the Yukon, and for use case scenarios that match what may be needed to stabilize the Yukon grid and support broader decarbonization efforts. Three studies looking at different scale end-use scenarios are focused on: Residential heating; Commercial district heating; and Industrial applications (either heat or power).

### Case Study #1: Residential Heating from Excess Renewable Energy

One of the most famous examples of using excess renewable energy through TES on a small, Arctic microgrid is the Puvurnaq Wind Project in the Native Village of Kongiganak, Alaska. A schematic of this set-up can be seen in Figure 16.

The wind and heat system in Kongiganak includes:

- 5 x 95 kW Windmatic wind turbines
- Electric Thermal Storage devices, or TES (Steffe stoves)
- Community-wind smart grid metering and smart grid controls

In a small, remote, diesel-dependent community, it is important to use all the available energy to reduce costs and emissions. Without either BESS or TESS, much of the wind energy would be lost due to a mismatch between the time of generation and the time of use. Step one of this project coupled the wind turbines with a TES that could be controlled through a centralized microgrid controller and automatically turned on when there was excess wind energy being produced that would otherwise go to waste. A second phase involved installing a BESS in 2018, and the increase in electricity to the grid and to the TES can be seen in the numbers in Table 5.

Electric energy for heating is controlled, metered, and billed enabled by the smart meter. The electricity sold for heating is sold at a cheaper price than diesel (~60% of diesel cost), and the program has been very popular with community members, cutting fuel costs in half for some homes (anecdotally, from video on [25]).

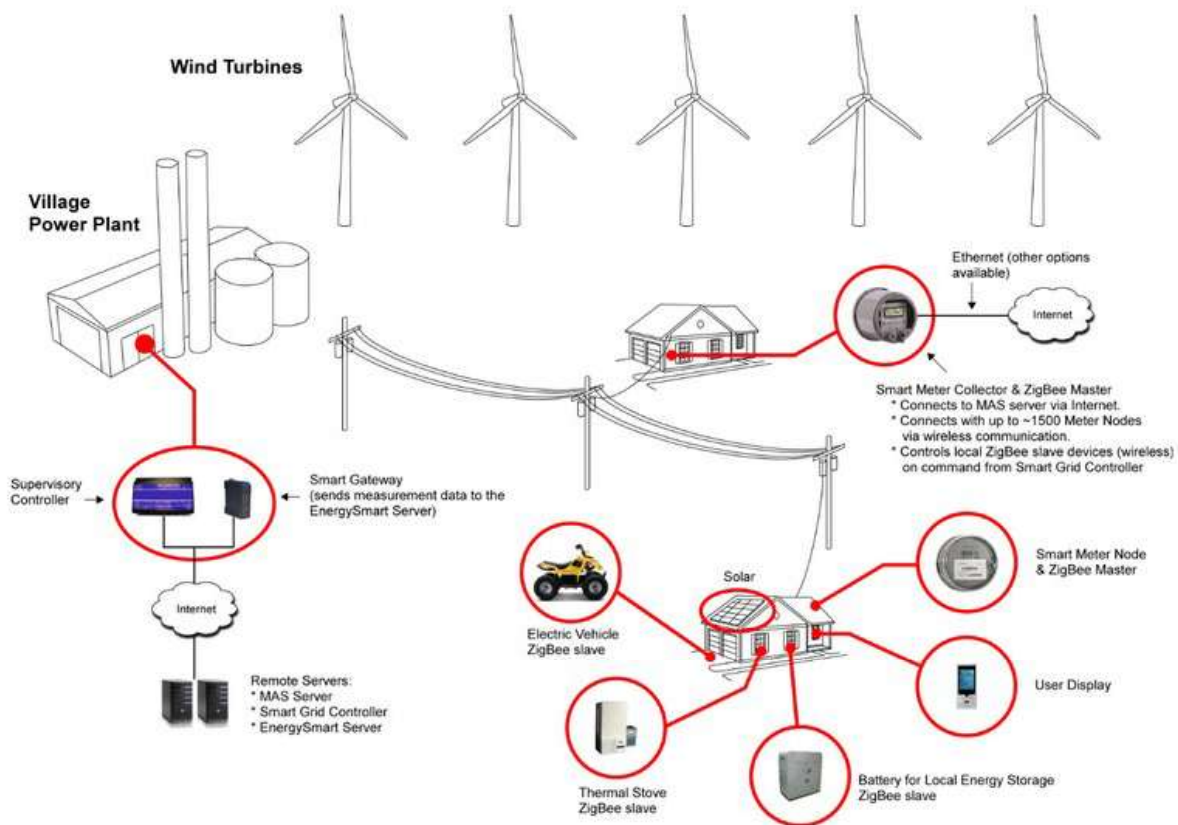


Figure 16: Schematic of the smart grid set-up in Kongiganak, Alaska [25].

Table 5: Diesel offset for heating and electricity in Kongiganak, Alaska, using wind energy + TES [25]

Year	Total Wind Electricity Generated (kWh)	Displaced Diesel - Electricity (gal.)	Displaced Diesel - Heat (gal.)	GHG Offset (tons CO <sub>2</sub> )	% Diesel Displacement (Elec. Only)
2015	466172	25692	2457	315	24
2016	573636	31383	2794	383	31
2017	473113	26286	2132	318	25
2018	726154	45122	2780	537	44
2019	728657	43698	2969	523	43

It should be mentioned that Hydro-Quebec also runs a residential TES program, however this only makes sense in an urban environment on a larger grid if time-of-use pricing and smart grid controls can also be implemented.

## Case Study #2: District Heating in Kankaanpää, Finland

Kankaanpää is located in a sub-Arctic region of Finland, so an analogous climate zone to parts of the Yukon. A start-up company, Polar Night Energy, partnered with the local electricity utility in Kankaanpää to install the first commercial-scale sand battery, seen in Figure 17 [26]. The TES is charged off the electricity grid, which in Finland is over 87% generated by renewable or low carbon energy sources [27].



Figure 17: Sand-based TES at the Vatajankoski power plant in Kankaanpää, Finland [26]

The TES is charged at off-peak times when electricity is cheapest, and the heat feeds into a pre-existing district heating system operated by Vatajankoski. The TES stores the sand at temperatures up to 500°C and that heat then provides heating to homes and the local swimming pool through the district heating system [26].

So far this system has been reported to be working well for Vatajankoski, however it should be noted that similar to the Hydro-Quebec program mentioned in the previous section, heat batteries charged from the grid will only make financial sense if time-of-use pricing is in place with smart meters, and will only reduce GHG if the grid is largely comprised of clean electricity.

### Case Study #3: Industrial Heat and Power, Italy

While not a northern example, this case study is one of the few examples globally where long-term stored heat in a TES is used for power generation. In 2022, the Italian electricity utility installed a Brenmiller TES at its Santa Barbara power plant in Tuscany. The TES is charged with heat using off-peak power, up to temperatures over 500°C. When extra power is needed on the grid, the accumulated heat is released to heat pressured water to create steam for electricity generation [28].



*Figure 18: TES for power generation installed at Enel's Santa Barbara power station in Italy [29]*

This TES project in Italy is a pilot project, but is operational and working. Funding support for the test was provided by the Israeli government. Close analysis of the costs and energy efficiency should be done to ensure the round-trip efficiency of such a power-to-heat-to-power system would work in a colder climate or grid with fewer renewables.

## 5. Conclusion

As governments push for greater decarbonisation to align with the Paris Agreement, national and territorial climate change commitments, and local environmental goals, the need to enable more renewables onto electric grids is essential. Decarbonizing heating and transportation sectors is also key, and less has been done on these fronts than electricity to date. TES offers an opportunity to maximize our existing renewable energy assets, store excess summer renewable energy for use during the winter, and start decarbonizing our heating use.

In terms of technology, the most wide-spread and robust TES technologies lie within the “sensible heat” range. While research is being done on phase change materials and other techniques, for the most part these technologies are still in development or pilot phases, and are not at the Technology Level of confidence needed for wide-spread deployment.

Successful TES demonstrations have been completed for a range of applications from domestic space heating, to commercial heating through district heating systems, up to energy and heat for utility and industrial use. By far the most common use of heat batteries is for end-uses of space heating, district heating, and industrial process heating. Converting the heat stored in a TES back into electricity comes with additional process losses, and while this has been done in various projects around the world, examples in a Northern context could not be found and efficiencies may be low. Long term energy storage in a TES should be compared against other established long term energy storage, such as pumped hydro or compressed air systems, to assess what is the best option for the Yukon.

Some grid modernization and update policies may be required to fully enable TES to be harnessed in the Yukon, and this will be assessed in the next phases of this project.

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## Appendix 1: Market Research Study

– Reference [30]

Company name	Head-quarters	Year of foundation	Providing storage solutions to which sector	Level of commercialisation	Type of storage	Product name	Storage media	Heat Transfer fluid	Range of storage size	Max storage temperature	TRL level	Website
Alumina Energy	USA	2015	Industry sector and electricity sector	First demonstrator in operation in the USA (450 kWh)	Solid-particle storage	Particle Packed Bed Energy Storage (PB-TEs)	Solid particles (recycled ceramics, ceramics, sand)	Air or CO <sub>2</sub>	100 kWh up to 10 GWh	up to 1,600 °C	TRL 4-5	<a href="https://www.aluminaenergyl.com/">https://www.aluminaenergyl.com/</a>
Antora Energy	USA	2018	Industrial sector	First demonstrator in operation in USA	Solid-state storage	Antora Thermal Battery	Solid carbon blocks	Energy is transferred via thermal radiation (light) to deliver process heat, or is converted into electricity via TPV cells	n/a	up to 2,400 °C	n/a	<a href="https://antoraenergy.com/">https://antoraenergy.com/</a>
BrennMiller Energy	Israel	2012	Industry sector	Four commercial plants in operation in Italy (24 MWh), Brazil (1 MWh), USA (1 MWh) and Israel (1 MWh)	Solid-particle storage	bGen	Crushed volcanic rocks	Air or steam	2 MWh to 10 GWh	up to 750 °C	TRL 9	<a href="https://www.brennmiller.com/">https://www.brennmiller.com/</a>
Build to zero	Spain	2022	Industry sector	First commercial project under construction	Molten salt storage	ThermalBox	Molten salt	Molten salt	Modular up to several MWhs	400 °C	TRL 8	<a href="https://buildtozero.es/">https://buildtozero.es/</a>
Carbon-Clean Technology	Germany	2008	Industrial sector and power plant sector	Demonstrator in operation (1 MWh)	Carnot Battery	Carnot Battery	Packed bed of ceramic balls	Air	100 MWh to several GWh	up to 1,200 °C	TRL 6-7	<a href="https://www.carbonclean.de/">https://www.carbonclean.de/</a>
E2S Power	Switzerland	2019	Power plant sector	Pilot plant in operation in India (0.25 MWh)	Solid-state storage	TWEST	Graphite blocks	Water / steam	Modular design storing 8+ hours	up to 540 °C	TRL 7	<a href="https://e2s-power.com/">https://e2s-power.com/</a>
Eco-Tech Ceram	France	2014	Industry sector and renewable sector	Three commercial plants in operation in France (total 9.3 MWh)	Solid-state storage	Eco-Stock	Ceramic in a fixed bed	Air	2.3 MWh per Eco-stock module	up to 600 °C	TRL 9	<a href="https://ecotechceram.com/en/">https://ecotechceram.com/en/</a>
Electrified Thermal Solutions	USA	2021	Industry sector	No pilot plant yet	Solid-state storage	Joule Hive Thermal Battery	Electrically-conductive firebricks	Air	25 MWh up to multi GWh	up to 1,800 °C	TRL 6	<a href="https://electrifiedthermal.com/">https://electrifiedthermal.com/</a>
Element16	USA	2016	Industry sector and power plant sector	First demonstrator under construction in USA (1.5 MWh)	Molten sulfur storage	Element 16	Molten sulfur	Thermal oil or hot air	10 MWh to GWh range	up to 350 °C	TRL 7	<a href="https://element16.com/">https://element16.com/</a>
EnergyNest	Norway	2011	Industry sector and power plant sector	Two commercial projects in Belgium (5 MWh) and Norway (4 MWh)	Solid-state storage	ThermalBattery	Concrete tubes (Heatcrete)	Steam or thermal oil	Modular with 1 MWh units up to 1,000 MWh	up to 450 °C	TRL 9	<a href="https://energy-nest.com/">https://energy-nest.com/</a>

Company name	Head-quarters	Year of foundation	Providing storage solutions to which sector	Level of commercialisation	Type of storage	Product name	Storage media	Heat Transfer fluid	Range of storage size	Max. storage temperature	TRL level	Website
Exergy3	Great Britain	2023	Industry Sector	First demonstrator in Scotland under construction (36 MWh)	Solid-state storage	Thermal Storage	N/a	Air	Minimum 8 MWh and what ever the client needs	Up to 1,200 °C	TRL5	<a href="https://www.exergy3.com/">https://www.exergy3.com/</a>
Heliac	Denmark	2014	Industry sector and district heating sector	Pilot plant operated for 24 weeks in Denmark (0.5 MWh)	Solid-state storage	Rockstore	Granite rocks in a large steel tank	Thermal oil	Tailor-made for each user	up to 300 °C	TRL 6-7	<a href="https://heliac.dk/solutions/rockstore/">https://heliac.dk/solutions/rockstore/</a>
Hyme Energy	Denmark	2021	Industry sector and power plant sector	No pilot plant yet	Molten salt storage	Not named	Molten salt	Hydroxide salt	100 MWh -> 2 GWh	700 °C	n/a	<a href="https://www.hyma.energy/">https://www.hyma.energy/</a>
Kaaj Energy	Canada	2020	Industry sector (heat/electricity as a service)	No pilot plant yet	Solid-state storage	Thermal Energy Storage (TES)	Iron ore	Air	n/a	up to 1,000 °C	TRL 7	<a href="https://kaajenergy.com/">https://kaajenergy.com/</a>
Kraftanlagen	Germany	1923	Industry sector	Two demonstration plants in Germany (2 MWh and 20 MWh)	Solid-state storage	Green Heat Module	Ceramic honeycomb bricks	Air	5 to 1000 MWh	around 1000 °C	TRL 8	<a href="https://www.kraftanlagen.com/en/solutions/energy/green-heat-module/">https://www.kraftanlagen.com/en/solutions/energy/green-heat-module/</a>
Kraftblock	Germany	2014	Industry sector and electricity sector	Pilot plants in operation (70 to 150 MWh)	Solid-particle storage	Kraftblock	Composite material / 85 % recycled granulate from steel slag	Air (alternatively flue gas, helium, CO2)	4 MWh to GWh scale	up to 1,300 °C	TRL 7-8 for waste heat recovery TRL 6-7 for power-to-heat	<a href="https://kraftblock.com/de/">https://kraftblock.com/de/</a>
Kyoto Group	Norway	2016	Industry sector and power plant heat	Commercial demonstrator in operation in Denmark (18 MWh)	Molten salt storage	Heatcube	Molten salt	Water / steam	up to 120 MWh	Up to 415 °C	TRL 8	<a href="https://www.kyotogroup.no/">https://www.kyotogroup.no/</a>
Lumenion	Germany	2016	Industry Sector and electricity sector	Pilot project in operation in Germany (2.4 MWh). First demonstrator under construction in Germany (20 MWh)	Solid-state storage	TES (Thermal Energy Storage)	Steel rods	Nitrogen or pressureless air	5 to 500 MWh	up to 600 °C	TRL 9	<a href="https://lumenion.com/">https://lumenion.com/</a>
Magaldi Green Energy	Italy	1929	Industry sector	First demonstrator under construction	Solid-particle storage	Magaldi Green Thermal Energy Storage - MGTES	Silica sand in a fluidised bed	Steam	from 5 MWh (single module) up to GWhs size	up to 620 °C	TRL 6-7	<a href="https://www.maasaldizes.it/energy.com/en/">https://www.maasaldizes.it/energy.com/en/</a>
Malta Group	USA	2018	Electricity sector and industry sector	Demonstrator in operation in the USA	Molten salt storage with two tanks	Malta Pumped Heat Energy Storage (PHES)	Molten salt	Molten salt and air	10 to 100 hours of 100 MW electric discharge power	up to 565°C	TRL 6	<a href="https://www.maltainc.com/">https://www.maltainc.com/</a>
MGA Thermal	Australia	2019	Electricity sector and industry sector	First Demonstrator (5 MWh) under construction	Phase change material storage	MGA Thermal Energy Storage (MGA Block)	Tiny metal alloy particles (made from PCMs C-Al or C-Al-Si) are dispersed through a matrix	Argon or nitrogen	5 MWh to 6 GWh	650 °C	TRL 7	<a href="https://www.mgaothermal.com/">https://www.mgaothermal.com/</a>

Company name	Head-quarters	Year of foundation	Providing storage solutions to which sector	Level of commercialisation	Type of storage	Product name	Storage media	Heat Transfer fluid	Range of storage size	Max storage temperature	TRL level	Website
Pintail Power	USA	2014	Electricity sector	No pilot plant yet	Molten salt storage	Liquid Salt Combined Cycle (LSCC) or Liquid Air Combined Cycle (LACC)	liquid salt	Liquid salt	2000 MWh per tank pair	up to 427 °C	n/a	<a href="https://www.pintailpower.com/">https://www.pintailpower.com/</a>
Polar Night Energy	Finland	2018	Industry sector and district heating sector	First commercial plant in operation in Finland (8 MWh)	Solid-particle storage	Sand Battery	Sand or sand-like materials	Air	Two standard systems with 200 MWh and 1 GWh respectively	up to 500 or 600 °C	TRL 8-9	<a href="https://polarlightenergy.fi/">https://polarlightenergy.fi/</a>
Rondo Energy	USA	2020	Industry sector (heat-as-a-service)	First commercial project in operation in USA (2 MWh)	Solid-state storage	Rondo Heat Battery: RHB100 and RHB300	Bricks	Air	100 MWh or 300 MWh storage capacity	> 1,000 °C	TRL 7	<a href="https://rondo.com/">https://rondo.com/</a>
Rpow	Spain	2019	Electricity sector and industry sector	No pilot plant yet	Molten salt storage	No Name, client-specific products	Molten salt	Water/steam or Air/waste heat	from 100 MWh	up to 565 °C	N/a	<a href="http://www.rpow.es">www.rpow.es</a>
Solstor Energy	USA	2023	Electricity sector	No pilot plant yet	Molten salt storage	eTES	Molten salt	Molten salt	500 MWh and 1 GWh	up to 565 °C	N/a	<a href="http://www.solstor.energy">www.solstor.energy</a>
Storasol / enolcon	Germany	2013 (Storasol)	Electricity sector and industry sector	Pilot plants in operation	Solid-particle storage	Heat storage: HTES Thermal Electricity storage; OPTES- and OPTES-GT Battery	Sand, gravel, rocks or stones in a fixed bed	Air or gas	Modular design from 100 kWh to 1000+ MWh	up to 1,050 °C	HTES: TRL 8-9 OPTES: TRL 4-5	<a href="https://storasol.com/">https://storasol.com/</a>
Storworks Power	USA	2010	Industry sector and power plant sector	Demonstrator in operation	Solid-state storage	Storworks BoilerBlocs	Concrete blocks	Air or steam	Modular design from 10 to 250+ MW and from 4 to 24+ hours of storage	up to 600°C	TRL 6	<a href="https://www.storworks.com/">https://www.storworks.com/</a>
Sunamp	Great Britain	2005	Industry sector	Pilot projects realised	Phase change material storage	Central Bank thermal batteries	Multiple phase change materials	Thermal oil	up to 6 MWh	up to 600 °C	TRL 7	<a href="https://sunamp.com/">https://sunamp.com/</a>
Terrajoule Energy	USA	2022	Electricity sector	No pilot plant yet	Steel pressure vessel	Steam Accumulator Energy Storage (SAES) available as a component of the Dispatchable Solar	Pressurised hot water	water	n/a	n/a	n/a	<a href="https://www.terrajoule.energy/">https://www.terrajoule.energy/</a>
1414 Degrees	Australia	2009	Industry sector	Demonstrator of SiBrick in operation in Australia (1 MWh)	Phase change material storage	SiBrick / SiBox	Silicon-based bricks	Air	Modular up to GWh	up to 1,414 °C	TRL 6	<a href="https://1414degrees.com.au/">https://1414degrees.com.au/</a>
247Solar Inc	USA	2015	Electricity sector and industry sector	Demonstrator under construction in USA (3.6 MWh)	Solid-particle storage	HeatStorE battery	Silica sand, small pieces of ceramical or iron slag	Air	Minimum 200 kWe with storage 9+ hours	up to 1,000 °C	TRL 6	<a href="https://247solar.com/">https://247solar.com/</a>

Overview of high-temperature storage solution providers - status March 2024, based on a market survey carried out by soltrico ([www.soltrico.com](http://www.soltrico.com)) and financed by Natural Resources Canada Source: companies' information