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Techno-economic analysis of the viability of thermal energy storage within Hamilton's Bayfront Industrial Area

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The Centre for Climate Change Management
at Mohawk College

Prepared for:
Hamilton Community Enterprises

In support of Canada's Thermal Corridor Project

Prepared by The Centre for Climate Change Management

The Centre for Climate Change Management (CCCM) is an applied research institute focused on supporting the transition to a thriving, low-carbon economy.

Our research focuses on working collaboratively with industry, government and community to develop and implement climate change solutions. Given the urgency of the climate crisis, we focus on "deep mitigation" strategies: opportunities to significantly reduce the greenhouse gas emissions that cause climate change.

The CCCM also acts as a hub for climate action on campus and in the Hamilton-Burlington community. We have a "coalitions-in-residence program" for collective action initiatives such as the Bay Area Climate Change Council and the centre is home to the college's Sustainability Office.

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Energy Harvesting Study Committees

The CCCM thanks members of both the Energy Harvesting Study Steering Committee, and Study Task Team for their inputs and support throughout.

Study Steering Committee

This committee meets on a quarterly basis to review the Study's progress, promote alignment with other key community initiatives, and recommend enhancements. Members as of August 2024 are:

- Jeff Cowan, President and CEO, Hamilton Community Enterprises (Committee Chair)
- Steven Dejonckheere, Senior VP, Development, Slate Asset Management
- Greg Dunnett, President and CEO, Hamilton Chamber of Commerce
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- Richard Allen, Consultant, Hamilton Community Enterprises and Committee Secretary

Study Task Team
This interdisciplinary team provides support to advance the Study and ensure completion of the deliverables. Members as of August 2024 are:

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II Terminology and Definitions

Units of measure

GW gigawatt
GWh gigawatt hour
GWth gigawatt thermal
K kelvin
kJ/kg kilojoules per kilogram
kW kilowatt
kWh kilowatt hour
MW megawatt
MWh megawatt hour
m2 square metre
m3 cubic metre
W/m·K watts per metre-kelvin thermal conductivity
°C degree Celsius

Performance Indicators

Storage Capacity [Wh, MWh]	The quantity of stored energy in the storage system in design conditions.
Charge/Discharge Power [MW]	The amount of energy a storage unit can update or discharge at one time.
Mass and Volume Densities of Energy [kWh/kg , kWh/m^3]	The amount of energy stored per unit mass or volume of material.
Thermal Conductivity [W/m·K]	The measure of a material's ability to conduct heat. Important to conceptualize storage charge and discharge rates.
Marginal Abatement Cost of Carbon [$/t$CO_2$e]	The cost of reducing one ton of carbon dioxide equivalent.
Specific Cost of Stored Energy [$/kWh]	The cost of total investment for a storage system divided by the total energy provided over the lifetime of the system.

Abbreviations

ATES Aquifer Thermal Energy Storage
BTES Borehole Thermal Energy Storage
CAPEX Capital Expenditure
COP Coefficient of Performance
CRL Commercial Readiness Level
CSP Concentrated Solar Power
LTES Latent Thermal Energy Storage
OPEX Operational Expenditure
PCM Phase Change Material
PTES Pit Thermal Energy Storage
TCM Thermochemical Storage
TES Thermal Energy Storage
TRL Technology Readiness Level
TTES Tank Thermal Energy Storage (usually with water as thermal storage medium)
UTES Underground Thermal Energy Storage
WGTES Water-Gravel Thermal Energy Storage (usually in a pit with water as heat transfer fluid)

III Executive Summary

The Centre for Climate Change Management (CCCM) at Mohawk College was engaged by Hamilton Community Enterprises (HCE) to contribute to the Hamilton Energy Harvesting Study, assessing the feasibility of constructing a thermal corridor which would transport waste heat sourced from Hamilton's Bayfront Industrial Area for use within HCE's downtown district energy network. This initiative is coined "Canada's Thermal Corridor Project."

The CCCM proposed a sub-project which would investigate the viability of thermal storage integration into the proposed thermal corridor.

A technology scan was completed, followed by a technical fitment assessment which compared the operational characteristics of the thermal energy storage (TES) systems with the proposed thermal corridor parameters.

The following shortlist of high-alignment technologies was drafted and analyzed.

1) Water Tank TES (TTES)
2) Borehole Field (BTES)
3) Pit Storage (PTES)
4) Solid-State, Fluidized Bed
5) PCM - Inorganic Salt (sodium acetate)

Further economic analysis was completed comparing the cost of meeting peak under a Business as usual vs TES storage scenario across multiple demand thresholds and supply temperature ranges.

Economic analysis showed negative net present value (NPV) for all TES deployment scenarios when a price on waste heat of more than 1 cent was applied.

Economic breakeven conditions were met when the price of waste heat was set to zero and price of electricity was set to 5.7-6.4 cents/kWh. This emphasises the importance of securing low-cost thermal energy, as well as shaving peaks throughout the year to access low electricity rates.

Marginal Abatement Cost Curve (MACC) was lowest ($2000/tCO$_2$e reduced) under a low temperature supply scenario with TES equipment activating after network demand exceeds 30MW.

The MACCC was highest ($4500/tCO_2e reduced) under a high temperature supply scenario with TES equipment activating when network demand exceeds 24MW.

This difference is explained by several dynamics.
1) the differential in cost per kWh between natural gas and electricity,
2) that under a high-temperature scenario, electric heat pump operations are foregone. Therefore, we see a relative increase in the cost of charging TES equipment compared to scenario where heat pumps are active, and
3) the cost differential between acquiring low grade and high-grade heat.

Recommendations and Future Outlook

- HCE is encouraged to prioritize acquiring thermal energy at a low price whenever possible.
- HCE is encouraged to further investigate and monitor the progress of Phase Change Materials suitable for low temperature range (i.e. CentralBank)
- If a higher temperature supply becomes available, HCE is encouraged to investigate solid-state technologies like Magaldi – MGTES
- Due to high capital costs, and uncertain returns, it is not recommended that HCE size thermal storage for seasonal duration if using sensible technologies.
- HCE is encouraged to monitor the progress of Thermochemical storage systems such as salt hydrates and sorption-based systems. While unlikely to become commercially available in a feasible timeline, advances in TCM technology are steadily occurring.

1 Background

Hamilton Community Enterprises (HCE) is currently leading an Energy Harvesting Study to assess the viability of constructing a thermal corridor which would transport waste heat harvested from industrial processes in Hamilton's Bayfront Industrial Area to HCE's existing downtown district energy network. This initiative is coined Canada's Thermal Corridor Project.

1.1 Project Scope

The Centre for Climate Change Management (CCCM) has partnered with HCE to investigate thermal storage solutions. The CCCM completed a scan of thermal energy storage (TES) systems for the purpose of identifying technologies with high-alignment with the system parameters outlined in Section 1.2.

A short list of technologies was selected in collaboration with HCE, and in consultation with the Energy Harvesting Study Task Team. A technology fitment assessment was then completed to further assess TES systems.

Last, economic analysis of proposed operational conditions was completed to assess financial viability of peak-shaving operations across various supply and peaking threshold scenarios. Carbon emission reductions were calculated between Business as Usual (BAU) and, TES deployment scenario.

1.2 HCE District Energy System Parameters

In order to provide applicable results, the subsequent technology overview and analysis are based on the recommended operational parameters of the proposed thermal corridor.

Supply Dynamics

At this time, a **low temperature** heat supply is expected for the network. Waste heat is expected to be harvested from cooling towers at approximate 35°C. It is assumed supply is consistent and constant year-round.

Throughout this report, a **high temperature** heat supply scenario is also considered. It is assumed this heat falls into the mid-grade category between 180-250°C.

Demand Dynamics
Fully built, the District Energy network expects the following demand dynamics:

- Annual 143,000 MWh (fully built out)
- Peak 50.9 MWh (fully built out)

Distribution Dynamics

As proposed, the system would provide thermal energy for space and water heating at the following temperatures:

- Winter Peak - 90 °C
- Shoulder Peak - 80 °C
- Summer (domestic hot water only) - 65 °C

Water is the proposed heat transfer fluid for the supply and distribution networks.

Figure 1 outlines the key components of the Thermal Corridor as designed. The red box indicates the section under the purview of this report.

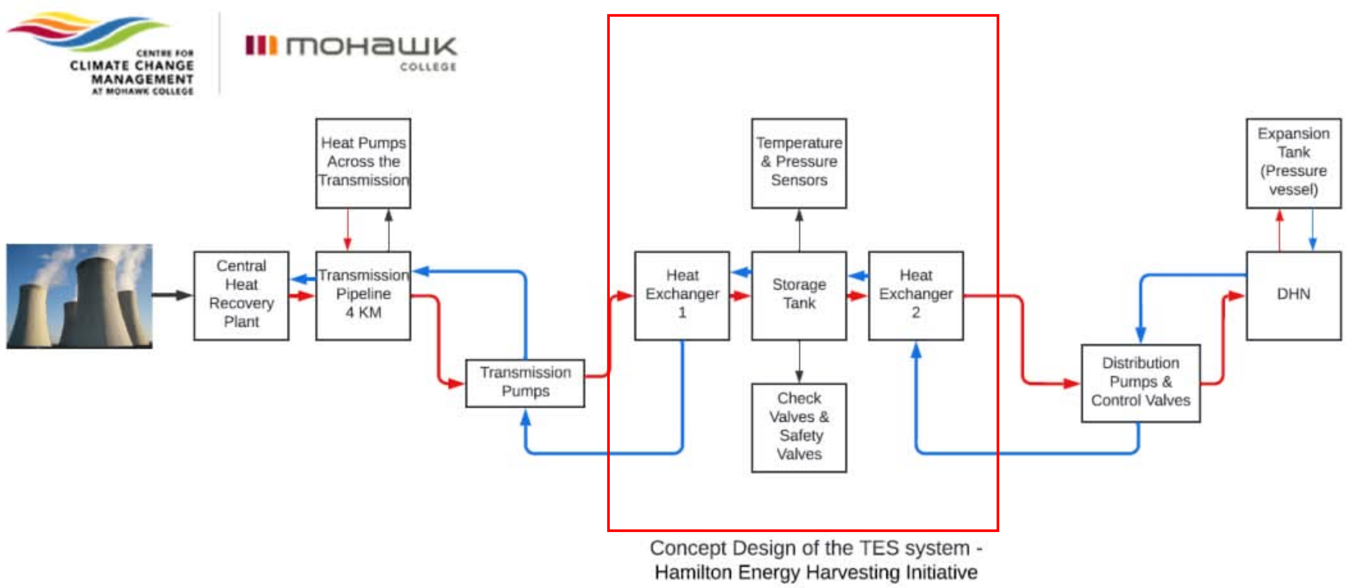

Figure 1 Conceptual Design of TES system fitment within HCE Energy Harvesting Study

2 Thermal Energy Storage Sizing Exercise

Before research into TES options could begin, it was critical to first understand the scale of storage required to support the proposed Thermal Corridor.

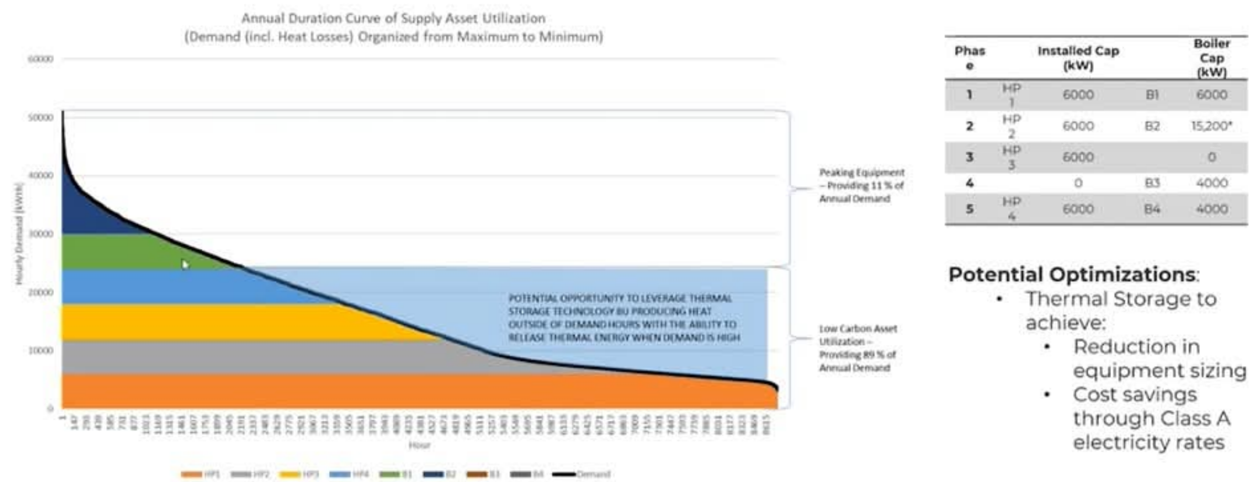

Figure 2 Annual Duration Curve for supply asset utilization [Rathco Conceptual Design]

First, the CCCM reviewed Rathco ENG's Conceptual Design Report, and analyzed the proposed peaking equipment.

From here, the research team agreed upon two thresholds

Demand (KW)	Peaking Equipment Output (KW)							
	HP1	HP2	HP3	HP4	B1	B2	B3	B4
Demand Threshold #1: 30MW, ~20MW Peaking Equip Capacity								
30000	6000	6000	6000	6000	6000	0	0	0
Demand Threshold #2: 24MW, ~26MW Peaking Equip Capacity								
24000	6000	6000	6000	6000	0	0	0	0

*HP1-4 = Heat Pumps 1-4, B1-4 = Boiler Numbers 1-4.

Demand Threshold 1 assumes the TES system will activate whenever system demand exceeds 30 MW. In this scenario, 6MW of generation is met by a proposed natural gas boiler (B1). In this scenario the TES system provides ~20 MW of peaking power in lieu of operating Boilers 2-4.

Demand Threshold 2 targets a 'fully decarbonized' operational state whereby base load is handed by electric heat pumps and harvested waste heat. TES equipment is set to activate when distribution demand exceeds 24MW, requiring the TES to provide ~26MW of peaking power in lieu of natural gas boilers 1-4.

Therefore, throughout this report, these scenarios will be reflected upon in reference to both technology fitment assessment, as well as economic & carbon reduction analysis.

3 Overview: Thermal Energy Storage Systems

The following section provides an overview of thermal storage technologies. This is not an exhaustive list technology type. It should be noted that this overview is oriented to explore technologies capable of storing heat at low temperature ranges (35-95°C), with moderate consideration given to a high temperature supply scenario (>180°C).

Moreover, technologies showing high-alignment with the proposed thermal corridor, and HCE's downtown district heating system operating conditions were explored at a deeper level.

Figure 3 Key applications of Thermal Energy Storage (TES) systems [8]

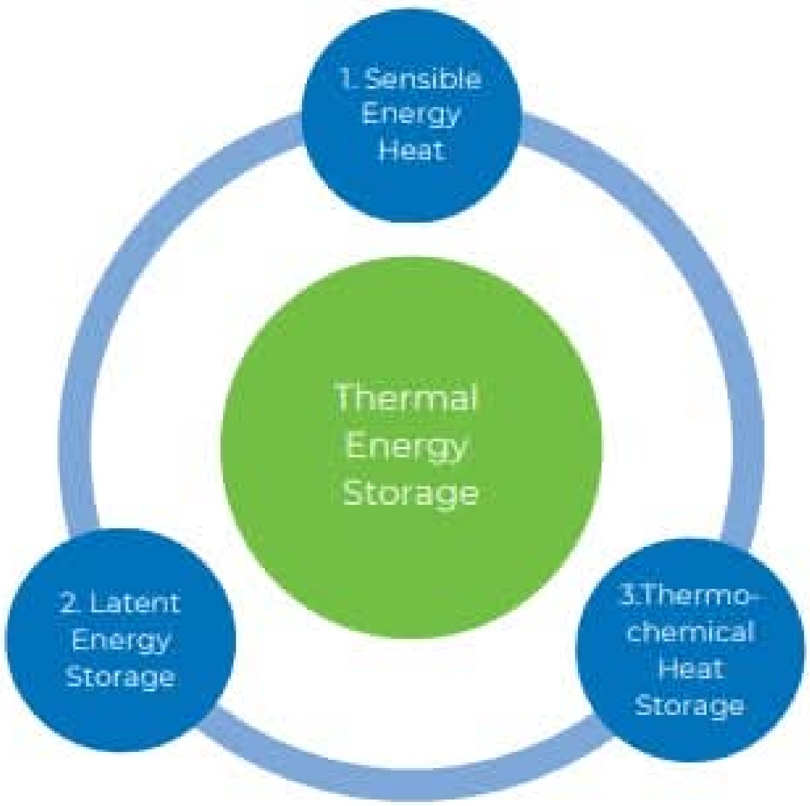

Figure 4 Major classifications of Thermal Energy Storage (TES) systems [2]

For the purpose of this report, sensible, latent and thermochemical TES systems were examined.

3.1 Sensible Thermal Energy Storage

Sensible thermal storage describes a system where the amount of energy stored is proportional to the temperature change of the storage material. Sensible TES systems operate within a temperature range that is below the phase change temperature of the storage material. The stored energy within the system can be described by the equation and can be visualized in Figure 5:

$$Q=m*C_p*\Delta T$$

Q = the total energy [kJ],
m =mass [kg],
Cp = is specific heat capacity [kJ/kg K],
ΔT = the change in temperature [K].

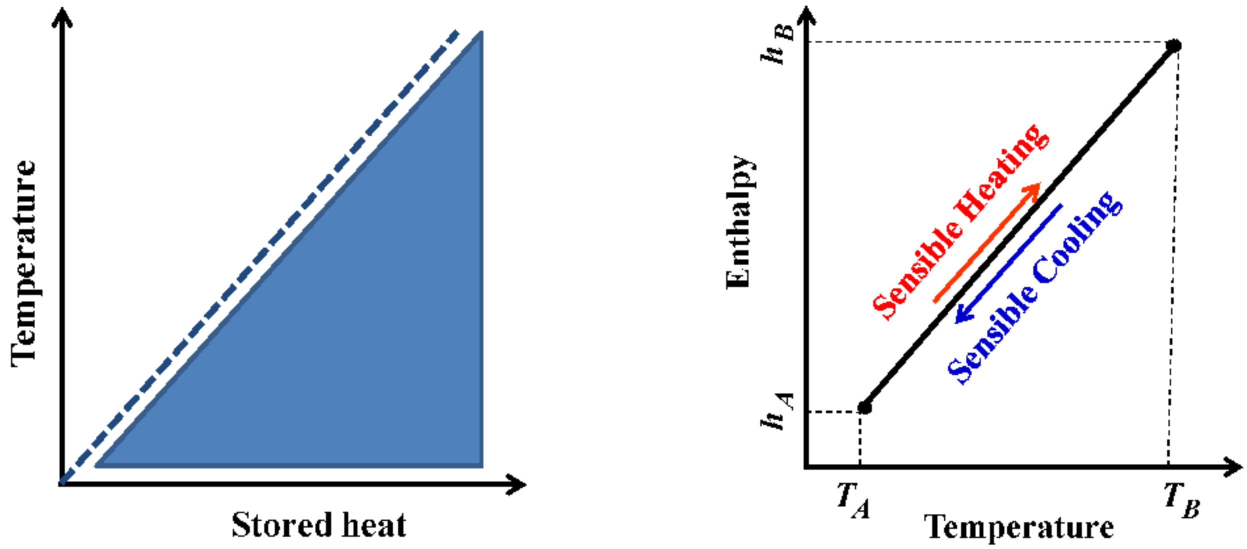

Figure 5 General heat curve for sensible heating and cooling with no phase change.[1]

3.1.1 Water Tank

Water tank thermal storage (TTES) is one of the most commonly deployed storage systems globally. Water has been a longstanding medium of choice for thermal storage systems owing to water being non-toxic, stable at standard pressures and having high specific heat capacity. TTES systems have an average specific energy capacity of 15-80 kWh/m^3, and a quick charge/discharge rates making them ideal for peak shaving scenarios. TTES have high alignment with storage of low temperature heat supplies (>95 °C) in order to avoid production of steam within the vessel, although pressurized vessels can exceed 100°C.

TTES systems come in a variety of configurations, most commonly as above-ground cylindrical tanks. Tanks may be oriented vertically, or horizontally. TTES systems sometimes are stored underground, although this presents an additional capital cost. TTES systems are often close-looped, meaning the supply and distribution networks do not come into contact with the tank's contents. Rather, heat is transferred via heat exchangers.

TTES systems exhibit thermal stratification, a process by which there is a temperature gradient in the tank. This allows system operator flexibility, increasing the efficiency of charge and discharge activities.

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[1]Image Source: https://encyclopedia.pub/entry/25632

A contemporary example of a TTES system, is the Well Project from Enwave. Located within the King West neighbourhood within Toronto, Ontario, the Well is a 7.6 million litre underground storage tank which will provide low-carbon district heating and cooling services to over 17 million square feet of building space[2]

3.1.2 Underground Storage (Borehole, Pit and Aquifer)

Borehole, Pit and Aquifer TES systems have been grouped together as they all utilize the same principal of using the ground as insulation. These systems operate most efficiently at lower temperate ranges (>95 °C), and under ideal conditions have the ability to store heat for weeks to months [8]. However, the efficiency of underground storage depends heavily on the geologic and hydrological conditions.

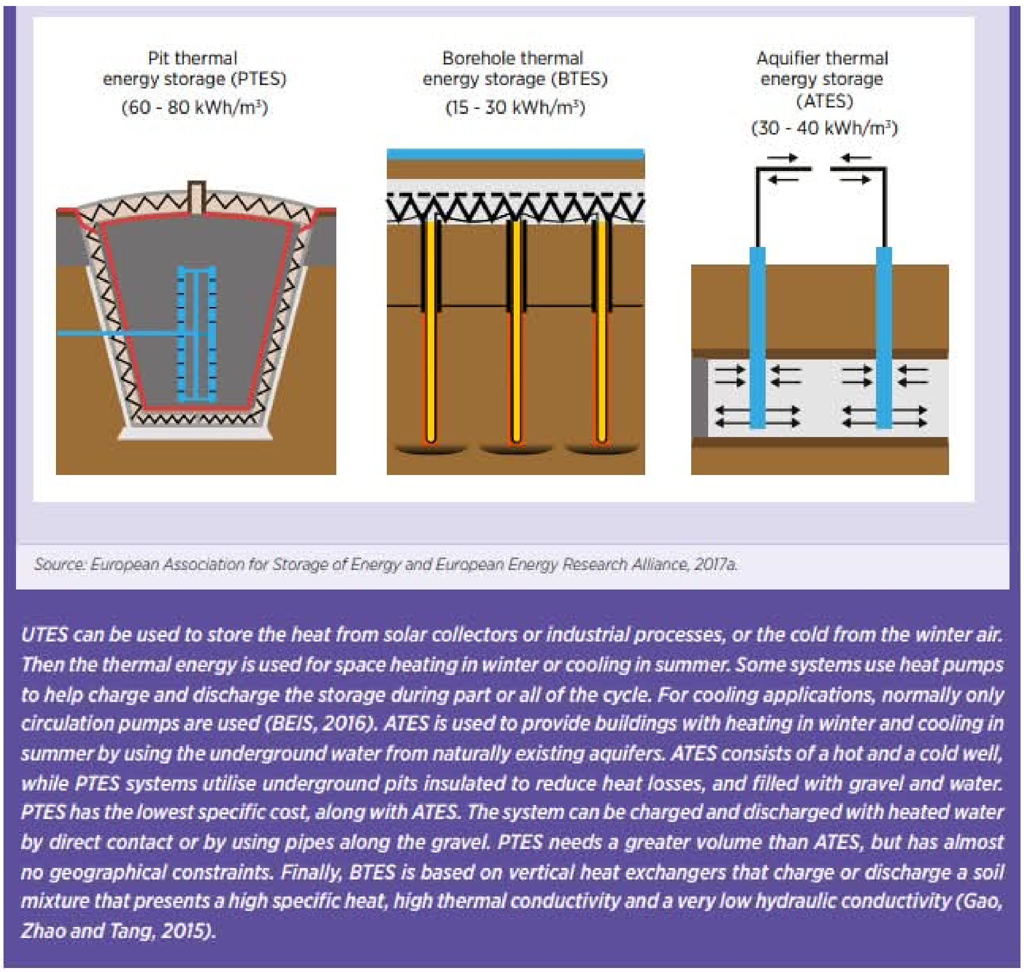

Figure 6 Underground TES system overview [8]

[2] https://www.enwave.com/case-studies/groundbreaking-expansion-project-brings-water-to-the-well/

Pit Thermal Storage (PTES) has an average energy density of 60-80 kWh/m^3. Capital costs due to land acquisition and construction generally pose barriers. There is a large body of research centred around the addition of phase-change materials, or solids (i.e. gravel, ceramics) to increase the thermal capacity of PTES systems.

Borehole Thermal Storage (BTES) has an average energy density 15-30 kWh/m^3. BTES systems are the largest in scale, unlocking seasonal storage opportunities but requiring high capital investment. BTES systems are sensitive to thermal losses, and operate best in low temperature supply scenarios. Table 1 shows a recently compiled summary of BTES for district heating networks. Research generally indicates BTES for district heating is best paired with low-cost heat sources such as solar thermal.

Table 1 Summary of borehole thermal storage systems for district heating applications [12]

High-temperature BTES	Heat source	Maximum temperature (°C)	Designed use of the heat stored
Anneberg, Solna, SE (Regander 2019)	Solar thermal	55	Space heating
Attenkirschen, Germany (Regander 2019)	Solar thermal	50	District heating (via heat pump) and space heating
Braedstrup, Danmark (Røgen et al. 2015)	Solar thermal	60	District heating (via heat pump)
Crailsheim, Germany (Schneider 2013)	Solar thermal	65	District heating (via heat pump)
Necklarsum, Germany (Nußbicker et al. 2003)	Solar thermal	65	District heating with auxiliary boiler
Oktokos, Canada (Rad, Fung, and Rosen 2017)	Solar thermal	74	Space heating
Paskov, Czech Republic (Klempa et al. 2014)	Combined heat and power	95	Experimental: rock behavior in different charging–discharging
GeoTermos, Norway (Justo-Alonso et al. 2020).	Outdoor air + solar thermal (photovoltaic-driven CO_2 heat pump)	60–65	Space heating

Aquifer Thermal Storage (ATES) utilizes underground aquifers to transfer heat between cold and hot wells. Research shows ATES has an average energy storage capacity of 30-40 kWh/m^3. Due to the geological constraints, this system was not examined thoroughly.

3.1.3 Solid State

Solid state storage describes a process by which a solid material stores thermal energy without changing phase. Solid state thermal storage makes use of a variety of materials from conventional rock/gravel to highly engineered ceramics and composites. Due to the large variety of materials, solid state systems operate within wide temperature band (-160 to 1300°C) [8].

For heating applications, solid state thermal storage is usually charged with electricity, or high temperature exhaust gases.

Companies like Rondo's Heat Battery store electricity in specialized bricks, reaching temperatures of 1400°C. When there is a need for electricity, steam is generated for use in a conventional turbine. Rondo's product lines can store up to 300 MWh with a max discharge of 20MWth. A similar process is deployed by the Company 1414[3] using their innovated SiBox technology.

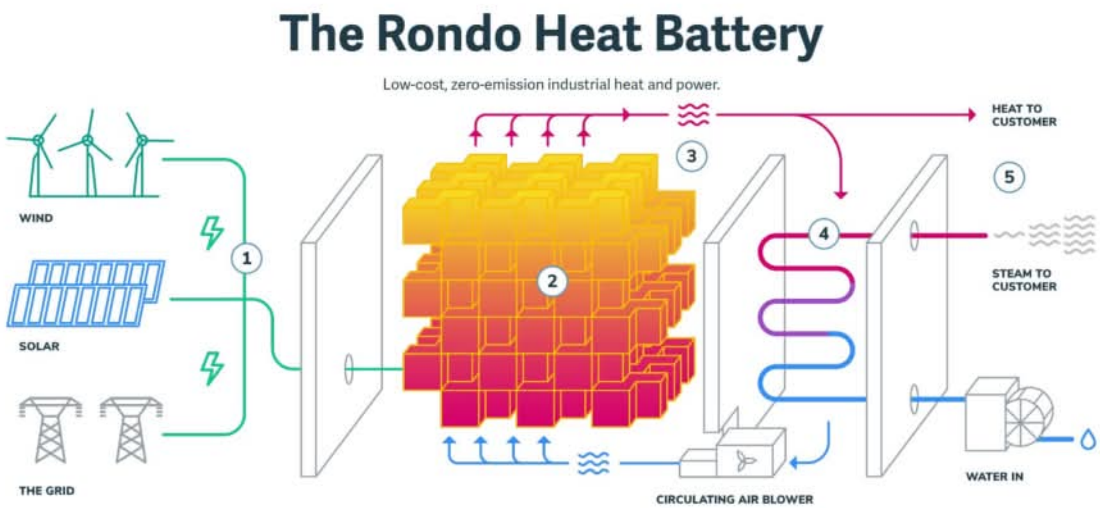

Figure 7 Visualization of Rondo solid state heat battery. Image Source[4]

Through our research, we only came across one solid-state storage system which could interface with industrial waste heat via a heat exchanger.

The **Magaldi MGTES system** stores heat in fluidized sand. This system is examined in more detail in section 4.1.4.

3.1.4 Molten Salt

Molten Salt systems have little alignment with low-grade waste heat recovery. Rather, molten salt systems are often deployed as part of a Concentrated Solar Power (CSP) array. As shown in Figure 8, CSP arrays operate by concentrating solar energy to heat a salt to its melting point. The molten salt is then used to generate electricity through a conventional steam generator [8]. Molten salts typically operate between 265-565°C, and have an energy density between 70-200 kWh/m^3. Due to the low alignment with HCE's storage needs, this system was not explored in depth.

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[3] https://1414degrees.com.au/
[4] https://rondo.com/how-it-works

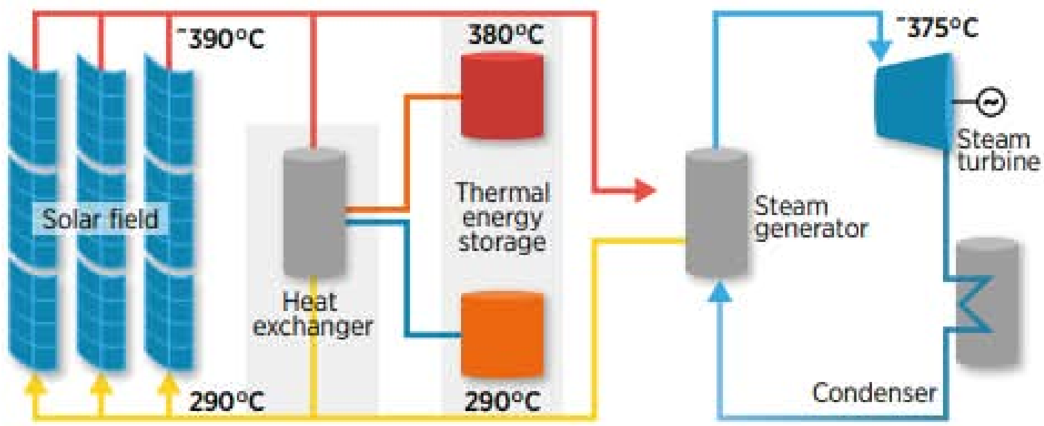


Figure 8 Molten salt storage with CSP array [8]

3.1.5 Key findings: Sensible Thermal Storage Systems

Research shows that Sensible Thermal Storage technologies:

- Are the most commonly deployed TES category globally, with Tank (TTES) systems being the most commonly used technology.
- Sensible TES system sizing scales proportionally with the amount of energy storage required.
- Sensible TES has challenges such as; land acquisition, structural integrity (above ground tanks), high construction costs and large system footprints.

3.2 Latent Thermal Energy Storage

Latent TES systems, often called phase-change TES systems, are an emerging group of technologies that utilize the process of heat absorption at the point where a material changes physical phase (i.e. solid to liquid). As a solid material absorbs energy, its temperature increases until it reaches the latent heat of fusion, triggering a phase change. When a liquid absorbs heat to the point of undergoing a transition to a gaseous state, this threshold is called the latent heat of vaporization **Error! Reference source not found.**. While latent storage systems have utility in both cooling and heating applications, the bulk of this investigation will centre on latent storage for heat-to-heat applications.

Latent TES systems take advantage of materials with a high energy density, thereby allowing for large amounts of energy to be stored within a system with minimal changes to the material's temperature. Owing to the increased energy density, latent TES systems often require a much smaller spatial footprint than sensible TES systems of a similar capacity.

The energy storage potential of Latent TES systems can be described by the general equation:

$$Q=m[Cp1*\Delta T+L+Cp2*\Delta T]$$

Where:

Q is the total energy [kJ],
m = mass [kg],
Cp1 is specific heat capacity of the first phase [kJ/kgK],
L is the latent heat energy [kJ/kg],
Cp2 is specific heat capacity of the second phase [kJ/kgK] and
ΔT is the change in temperature [K].

This generalized equation illustrates the higher energy capacity of a latent-based storage system versus a sensible system (as seen in Section 3.1). The larger the L value (latent heat energy) of a material, the more energy a Phase Change TES system can store. The high energy capacity of phase-change thermal energy storage systems is visualized in Figure 9.

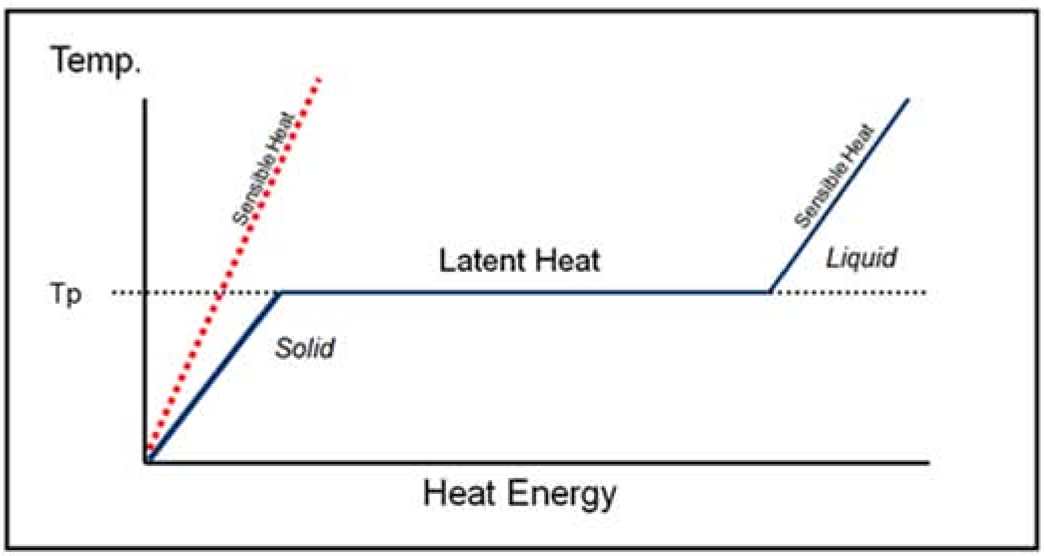


Figure 9 General heat curve showing phase change of latent material[5]

3.2.1 Latent TES Classifications

Latent TES systems are categorized in several ways. Often, the first description is based on the type of phase change a material undergoes (i.e. solid-solid, solid-liquid, and liquid-gas).

[5] Image credit: https://phase-energy.com/

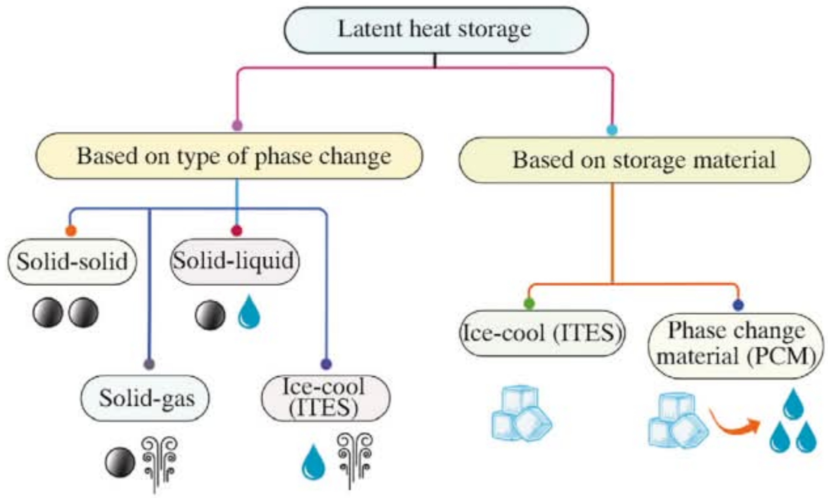


Figure 10 Classification of latent heat storage systems by phase change and storage material [10]

From here, systems may be further organized according to the operational temperature range of the system.

- **Sub-Zero PCMs** systems which have a phase-change temperature below 0 C. Typically used for chilling applications (e.g. salt-water mixtures)

- **Ice Systems** take advantage of the phase-change temperature of water at 0 C. Typically used in cooling and chilling applications.

- **Low-temperature PCMs** systems which have a phase-change temperature between 0-120 C (e.g. paraffin waxes and salt hydrates).

- **High-temperature PCMs** systems with a phase-change temperature above 120 C (e.g. inorganic salts, eutectic mixtures and composite PCMs with ceramic infusion). [8]

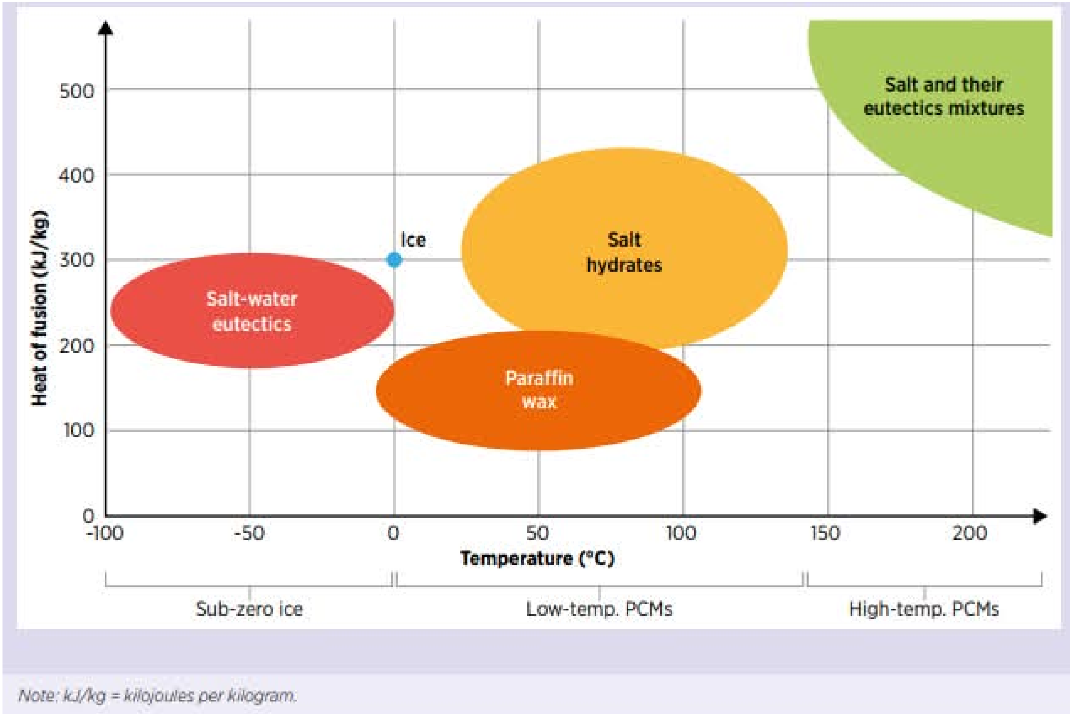


Figure 11 Heat of fusion and melting points of various PCM systems [8]

Further, within Phase-Change systems, several sub-groupings are defined based on the chemical properties of the storage medium. Figure 12 provides a visualization of the three major categories of organic, inorganic and eutectic materials.

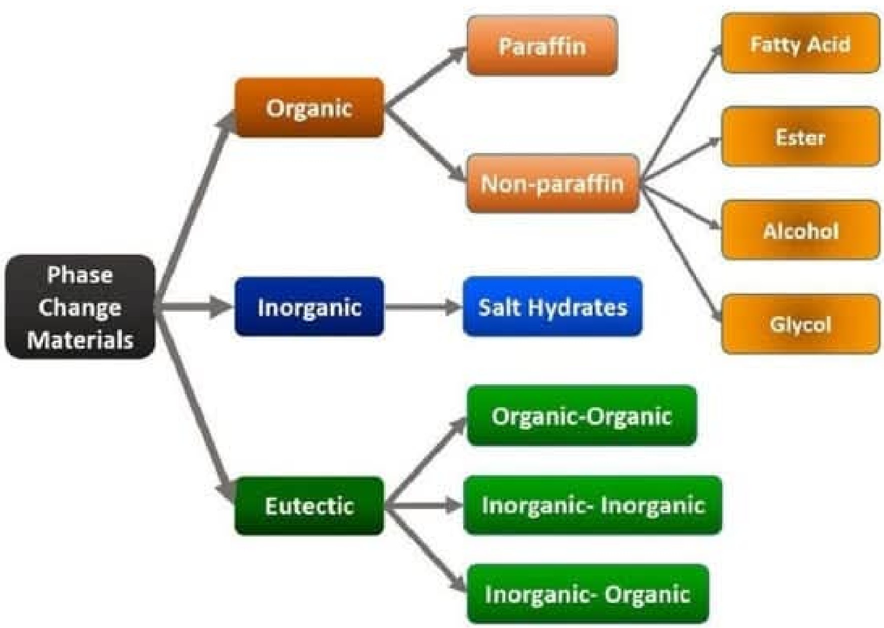


Figure 12 Categorization of phase change materials [1]

The following section provide a general overview of the technical specifications associated with each PCM material category. As a general note, high temperature PCM materials are excluded from this analysis owing to two major factors 1) Mis-alignment with the district heating system temperature range (35-95°C), and 2) High temperature PCMs are often charged using excess renewable electricity, or high temperature flue gas rather than via water-based heat transfer fluid charged by low-grade industrial waste heat. [8]

3.2.2 Organic PCM: Paraffin Waxes

Paraffin waxes are straight-chain, saturated alkane hydrocarbon chains derived from petroleum sources. Paraffin waxes exhibit different thermal properties based on the “purity” of the wax.

Pure paraffin waxes are refined to include only a single type of carbon chain, and are best suited for applications below 45 °C. Pure paraffin waxes have a relatively high energy cost (15-500 $/kWh) depending on the specific wax used.

In contrast, ***generic paraffin*** waxes are less refined substances containing carbon chains of varying lengths. This lack of refinement results in a lower energy cost (7-30$/kWh), but results in less discreet melting points-meaning the PCM material may undergo solid-liquid transition over a given temperature range. Generic paraffins are best suited for applications between 45-70°C. [6] Challenges with Paraffin waxes include moderate flammability, and generally have low thermal conductivity (0.2 W/m◦K), presenting operational challenges under a peaking scenario. [8]

3.2.3 Organic PCM: Fatty Acid

Organic fatty acids are carboxylic acids with the general formula $CH_3(CH_2)_{2n}COOH$ [9] Fatty acids are generally more expensive than paraffin wax systems (6-40 $/kWh) but have a better greater heat capacity (125-250 J/g) [6, 10]. However, fatty acids have a low density, resulting in poor volumetric storage capacity (32-80 kWh/m^3). [6]

3.2.4 Organic PCM: Alcohol

Organic fatty alcohols suitable for low-grade thermal storage applications are often primary alcohols with either saturated or unsaturated hydrocarbon chains. These materials have high material costs, and thus high energy storage costs (40-3000 $/kWh) and relatively poor volumetric energy storage (43-55 kWh/m^3). [6]

3.2.5 Inorganic: Salt Hydrates

Salt hydrates are materials which are composed of a mixture of a salt, and water in a specific molar ratio. Salt hydrates show relatively low energy storage costs (0.90 – 40 $/kWh), and a high volumetric energy storage (50 – 130 (kWh/m^3) with thermal conductivity varying widely across specific salt-hydrates. Some salt hydrates experience supercooling, whereby the liquid portion of the solution will spontaneously cool below the nominal solid-phase change threshold without the formation of a solid structure. This presents a barrier to adoption, and necessitates interventions such as nucleating additives, or mechanical work (shaking, vibrating, stirring etc). [6] In addition, inorganic salt hydrates are corrosive, often requiring specialized seals to maintain system integrity. (8]

3.2.6 Eutectic Phase Change Materials

The term Eutectic describes a hybrid material which is mixed in fixed proportions. While there is an abundance of literature relating to the physical and chemical properties of Eutectic PCMs, there is a lack of available information on eutectic-based thermal storage systems for the low temperature range thermal networks (<120 °C), as well as a lack of demonstration sites and/or technologies to draw upon for further analysis.

3.2.7 High temperature Phase Change Materials

High temperature phase change materials are defined as those which undergo a phase change above 500 °C. Since this temperature range varies so widely from the supply scenarios, this technology is largely excluded from further analysis.

3.2.8 Key Findings Latent Heat TES Systems

- Latent and phase-change materials have higher energy density, and a smaller footprint when compared to sensible technologies.
- Organic PCMs such a paraffin waxes, fatty acids and fatty alcohol are suitable for low-temperature storage applications, but operate in narrow temperature bands and have moderate flammability.
- Fatty Acids and Fatty Alcohols, have a relatively high material cost, leading to a high energy storage cost. Further, the low density of the materials leads to poor volumetric energy storage as well.

- Paraffin waxes vary widely in price based on the "purity" of the material, as well as the operational temperature range. Paraffins exhibit "temperature glide" whereby a phase change may not occur at a discrete temperature, but rather within a given temperature range. Paraffin waxes exhibit poor thermal conductivity, presenting a challenge if used to meet peaking demand through quick discharge.
- Inorganic salt hydrates show high thermal conductivity, relatively low thermal storage costs, and high volumetric energy storage capacity, making them an ideal material for many storage applications. Inorganic salts often experience "super cooling", and are moderately corrosive which can present a challenge for system operators.

Table 2 Summary of low temperature PCM properties & characteristics [6,10]

	Energy Storage Cost ($/kWh)	Volumetric Storage Capacity (kWh/m^3)	Temperature Range
Paraffin Wax (Pure)	16-25	45-60	8-28C °C
Paraffin Wax (General)	7-30	NA	45-65 °C
Fatty Acid	6-40	32-80	8-65 °C
Alcohol	40-3000	43-55	6-65 °C
Salt Hydrate	.9-40	50-130	0-120 °C

Generally speaking, the commercial readiness for low-grade latent and PCM TES systems for use within district heating systems is low. [6,7,8] Higher commercial readiness was seen in high temperature PCM TES applications; however, these technologies typically use electricity as an input, and the PCM materials have significant temperature range misalignment with HCE's proposed district heating network.

While research showed a lack of commercially viable PCM TES applications, the study team was able to engage with several manufacturers of PCM materials. Namely:

- Rubitherm[6]
- Unisol[7]
- PCM Products LTD[8]

Conversations with suppliers confirmed research findings which indicate a lack of availability of industrial/utility scale PCM TES systems.

[6] https://www.rubitherm.eu/en/productCategories.html
[7] https://www.unisol-inc.ca/pcm-phase-change-materials/
[8] https://www.pcmproducts.net/

3.3 ThermoChemical Storage

Thermochemical storage systems utilize two reaction mechanisms to store energy; **reversible** and **sorption-based** chemical reactions (See Figure 13). Thermochemical TES (TCTES) have the highest volumetric storage capacity of any thermal storage system (averaging 500 kWh/m^3) [13,14] Further, since TCTES stores energy in the form of chemical bonds, with little to no energy loss in the system, there is a high degree of interest in TCTES use as a seasonal storage technology. However, it should be noted that much of information found within this section relies upon laboratory or experimental trails. There is a notable lack of TCTES demonstration sites, with most technologies in the prototype phase. [8]

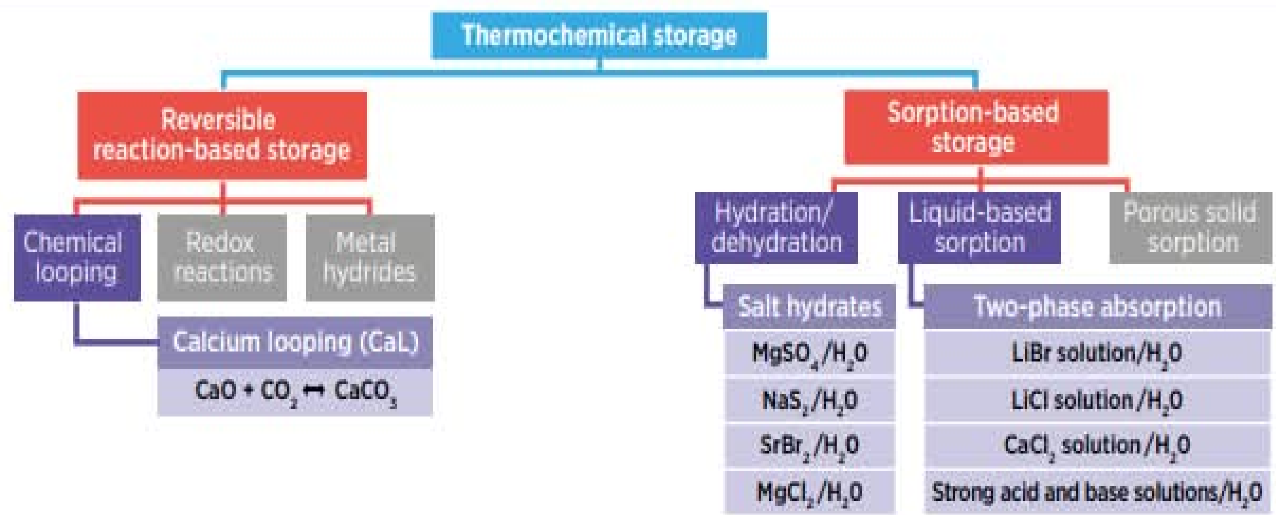


Figure 13 Overview of major thermochemical storage systems [8]

3.3.1 Reversible Reaction-based storage

Reversible chemical reactions store energy through a cycle of endo- and exothermic reactions. The concept can be understood using the general formula below, which is visualized in Figure 14.

Charging: [Energy Input] + AB = A + B
Discharging: A + B = AB + [Energy Out]

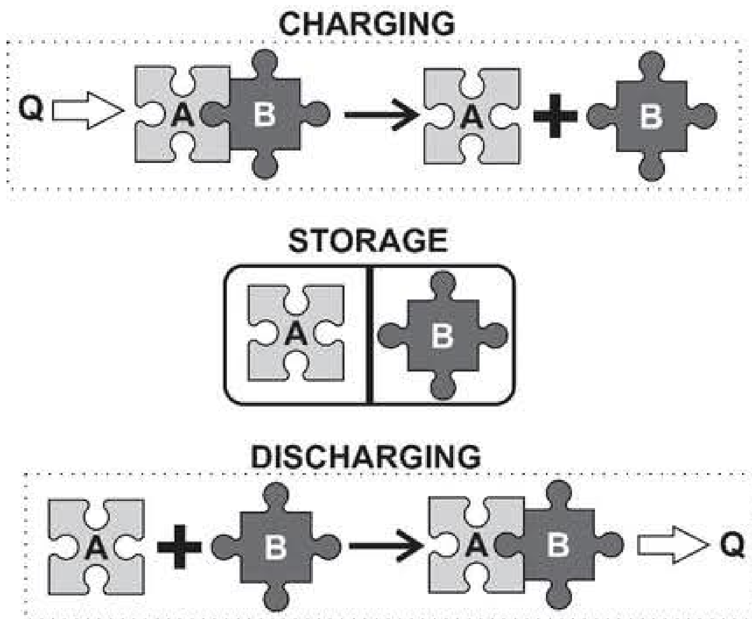


Figure 14 Generalized thermochemical heat storage cycle [14]

As seen in Figure 14, reversible TCTES systems often input energy in order to break a chemical structure into component reagents. These reagents are then stored separately to avoid unwanted reaction. In this state, the system stores the energy which was input by the system operator.

When the system operator would like to discharge to draw upon energy reserves, these reagents are brought back into contact, resulting in an exothermic reaction (energy output). This energy is then captured and used by the system operators. Table 3 shows a range of charging and discharging temperatures of several reversible chemical reactions [14]. As expected, there is some heat loss in this equation, leading to discharge temperatures being slightly lower than charge temperatures.

3.3.2 Absorption based storage

Absorption refers to the process by which one substance uptakes another through pores (solid) or between molecules (liquid, gas). Two common Absorption systems, namely Salt hydrate and concentrated refrigerants systems are commonly used as a case-study of absorption used in TCTES.

Salt Hydration/Dehydration

This technology relies on hydration and dehydration of hygroscopic salts. At rest, the system stores the salt in a hydrated form. When charging heat is added to the system, removing water molecules (which are then stored separately). When there is a demand for heat, water is added to the salt, releasing the stored heat energy. [8]

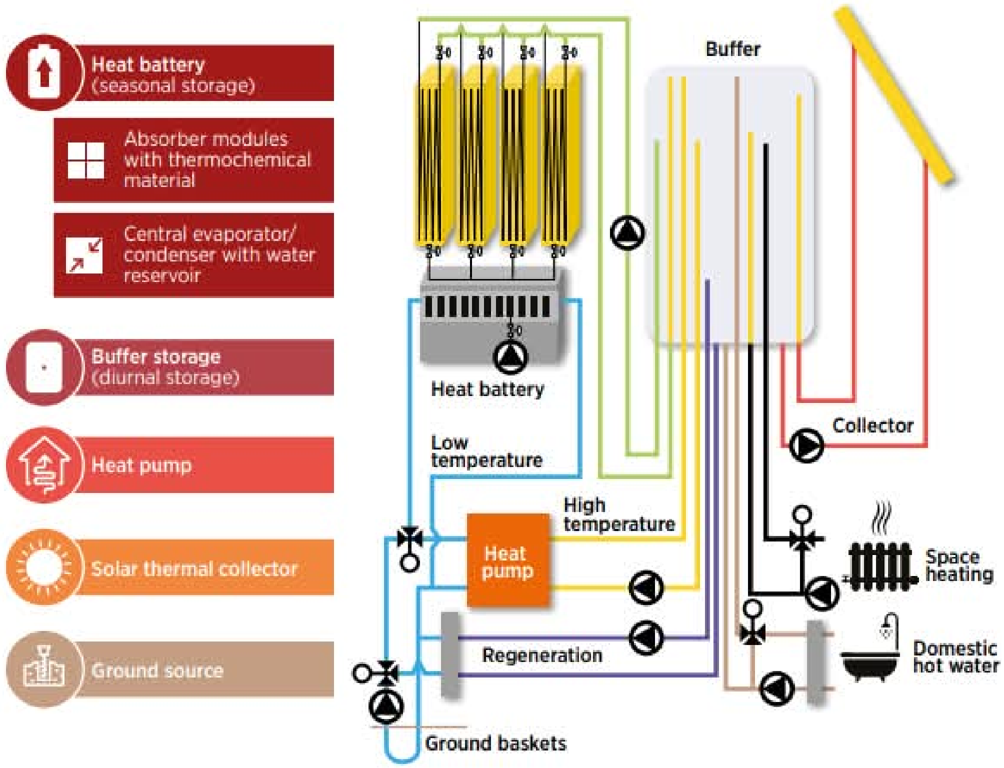


Figure 15 System diagram of CREATE demonstration salt hydrate system [8]

Liquid-Based Absorption

This grouping of technologies uses the concept of concentrated refrigerant solutions (i.e., aqueous salt solutions) in a close-looped system with separate reactors. Figure 10 shows a general schematic for a lithium-bromide absorption system.

The system is charged by inputting energy, heating a concentrated refrigerant solution. As heat is added, water is released from the solution – taking with it energy. The water and concentrated refrigerant is stored separately. During discharging operations, the water is added back to the concentrated refrigerant, releasing the stored heat of sorption for use by system operators [8, 13]

3.3.3 Adsorption based storage

Adsorption describes a process where atoms, ions or molecules from a gas or liquid dissolve on the surface of a solid. These compounds can be bound by physiosorption (physical bonds, van der Wall forces) or chemisorption (covalent bonds). [9]

There is an abundance of material science research on Adsoprtion based TCTES systems, but again, a lack of demonstration sites, or commercially ready systems.

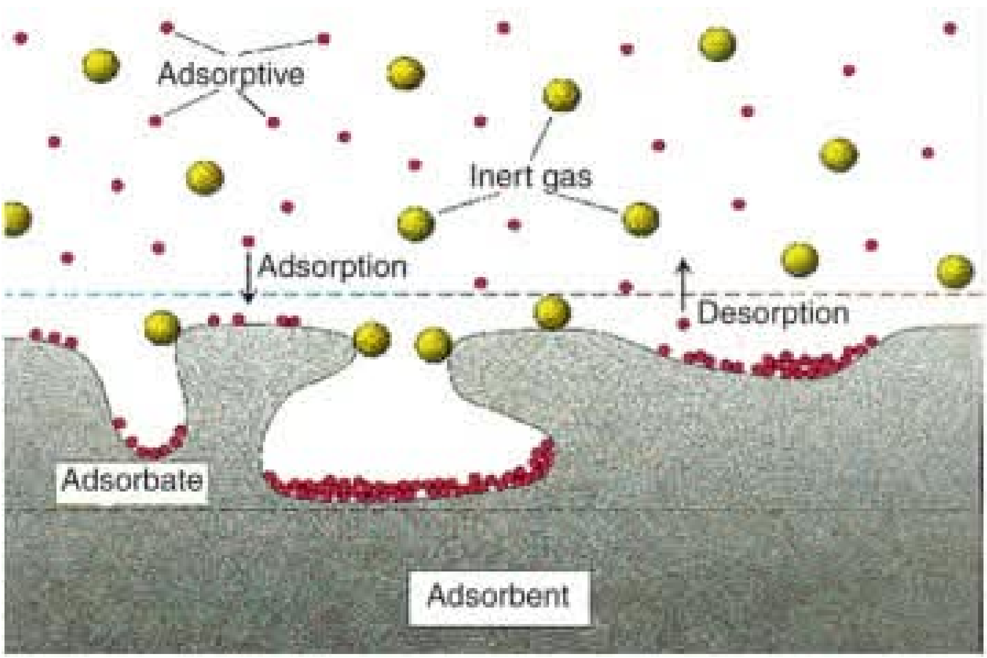


Figure 16 General visualization of gas-solid adsorption [9]

It is however, worth noting that Zeolites – a porous family of minerals comprised of aluminum, oxygen and silicon - have a large body of research, and promising experimental results. Table 3 shows the energy density of a variety of zeolite compounds, however more research and development of zeolite storage systems is required.

Table 3 Properties of materials used in thermochemical storage studies [14]

Phenomena	Sorbent	Sorbate	Charging temperature (°C)	Discharging temperature (°C)	Energy density (kWh/m³)
Adsorption					
	silica gel	H_2O	88	32	50–125
	zeolite 13X	H_2O	160–180	20–40	97–160.5
	zeolite 4A	H_2O	180	65	130–148
	zeolite 5A	H_2O	80–120	20–30	83
	zeolite MSX	H_2O	230		154
	APO-n	H_2O	95–140	40	240
	SAPO-n	H_2O	95–140	40	–
	MeAPO-n	H_2O	95–140	40	–
Absorption					
	$CaCl_2$	H_2O	45–138	21	120–381
	LiCl	H_2O	66–87	30	253–400
	$LiCl_2$	H_2O	46–87	30	253
	LiBr	H_2O	40–90	30	252–313
	NaOH	H_2O	50–95	70	154–250
	$SrBr_2$	H_2O	80	–	60–321
Chem. react.					
	$BaCl_2$	NH_3	56–70	40	787
	$CaCl_2$	NH_3	95–99	–	673
	$CaSO_4$	H_2O	–	89	390
	$CuSO_4$	H_2O	92	–	575
	Li_2SO_4	H_2O	103	–	255
	$MgCl_2$	H_2O	130–150	30–50	556–695
	$MgSO_4$	H_2O	122–150	120	420–924
	$MnCl_2$	NH_3	152	–	624
	Na_2S	H_2O	80–95	80–110	780

Table 3 sourced from Stritih & Mlakar (2018) shows the thermal properties of a variety of thermochemical storage materials.

3.3.4 Key Findings Thermochemical TES Systems

Research indicates that TCTES systems show:

- Highest equipment and material cost across all TES systems
- Requires complex operations and control systems
- Have the highest energy storage density of any TES system
- Have the lowest commercial readiness of any TES system
- Further research is required into the use of salt hydrates within district heating systems

3.4 Key Findings: TES Technology Overview

Key findings from the TES technology overview include:

- High alignment with water-based storage technologies and a low temperature supply scenario.
- Magaldi's MGTES fluidized sand bed storage is the only solid state system which showed alignment with low temperature waste heat supply.
- There is a lack of commercially available PCM and TCM technologies for low and mid temperature ranges.

Please see Appendix I for an overview of TES system parameters, technology readiness level, and suitable storage duration.

Table 4 Summary of TES system characteristics [13]

	Sensible TES	Latent TES	Thermochemical TES
Fundamental principle	• Energy stored by raising temperature. • Depends on rise in temperature, ΔT, and material-specific heat capacity, C_p.	• Energy stored during phase change of material and constant temperature. • Depends on latent heat of material, L.	• Energy stored during reversible reaction. • Depends on reaction enthalpy, ΔH.
Amount of energy stored	$Q = mC_p\Delta T$	$Q = mL$	$Q = n_C\Delta H$
Energy density	Small (~50 kWh/m^3)	Medium (~100 kWh/m^3)	High (~500 kWh/m^3)
Storage temperature	Charging step temperature	Charging step temperature	Ambient temperature
Storage period	Limited (thermal losses)	Limited (thermal losses)	Theoretically unlimited
Technology	Simple	Medium	Complex
Pros/cons	Pros: • Low-cost materials • Reliable • Simple system Cons: • Low energy storage density • Higher thermal insulation and space requirements • Shorter storage duration	Pros: • Higher storage density compared to sensible • Compact system Cons: • Poor thermal conductivity • Higher thermal insulation requirements • Some materials are highly corrosive	Pros: • Highest storage density • Capable of long-term (seasonal) storage • Minor heat losses • Heat storage at ambient conditions Cons: • Expensive • Complex system • Limited heat and mass transfer

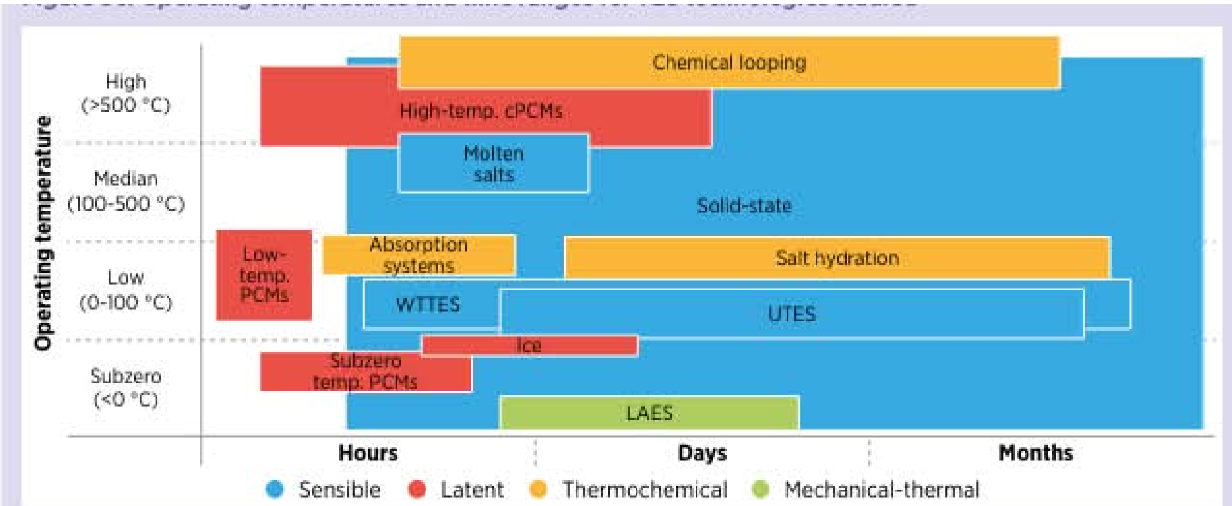


Figure 17 Operating temperature ranges across TES systems [8]

4 Techno-economic and Emission Reduction Analysis

The following section contains several analyses designed to assess the fitment and impact of TES options within HCE's proposed district heating scheme. This section is broken into two major parts;

- First, a ***technology fitment assessment*** which further examines TES systems identified in Section 2, and;
- Second, an ***economic and carbon reduction analysis*** of the impact of TES deployment across multiple demand thresholds, and supply scenarios.

4.1 Technology Fitment Assessment

The technology fitment assessment draws from the TES systems identified in Section 2. For the sake of brevity and providing applicable results, this analysis only considers TES systems with **1) *high-alignment with the district energy system parameters*** outlined in **Section 1.2** and **2) *high commercial readiness*.**

Therefore, this assessment ***excludes applications*** which:

- requires very high-grade heat to charge (>300°C),
- solely charge using electricity as an input,
- have a low TLR and/or are not commercially viable

The methodology used to assess technological fitment is adapted from Palomba & Frazzica (2019), whose work provided key performance indicators by which to assess TES systems across multiple categories.

A short list of high-alignment TES systems was developed for further examination in consultation with subject matter experts and the HCE core research team. The technology shortlist closely matches findings in industry-leading literature such as IRENA's Innovation Outlook, see Figures 18 and 19. [8]

Technology Shortlist

- Water Tank TES (TTES)
- Borehole Field (BTES)
- Pit Storage (PTES)
- Solid-state, fluidized bed [Magaldi – MGTES]
- PCM - Inorganic Salt (sodium acetate) [Sunamp – Central Bank]

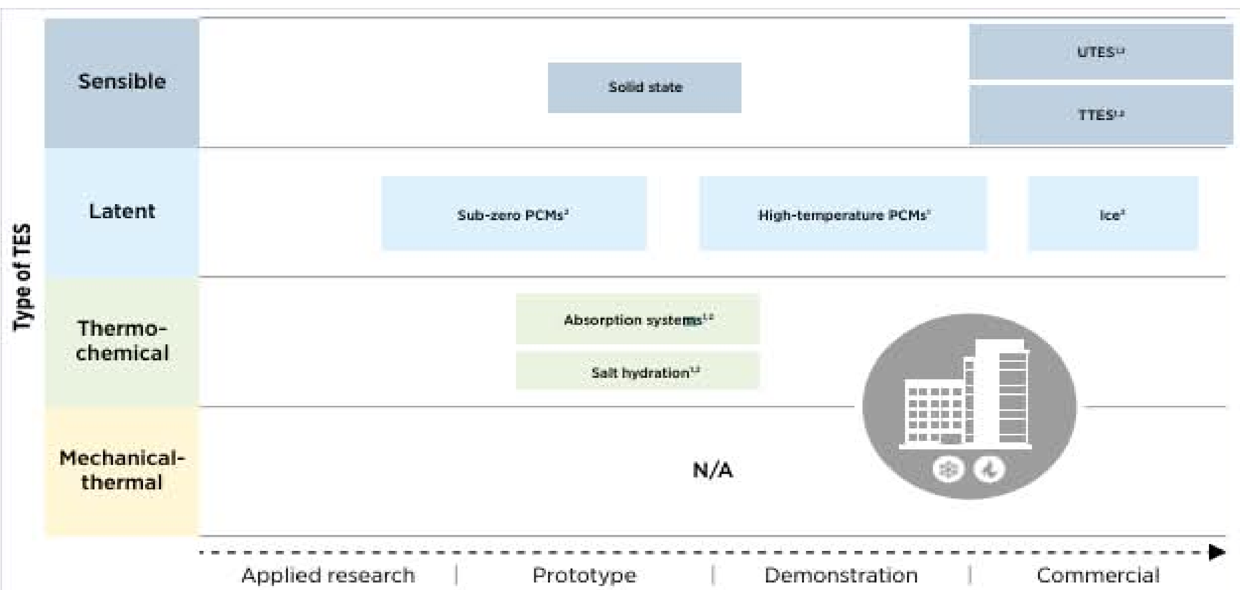


Figure 18 Commercial readiness of TES systems for district heating and cooling [8]

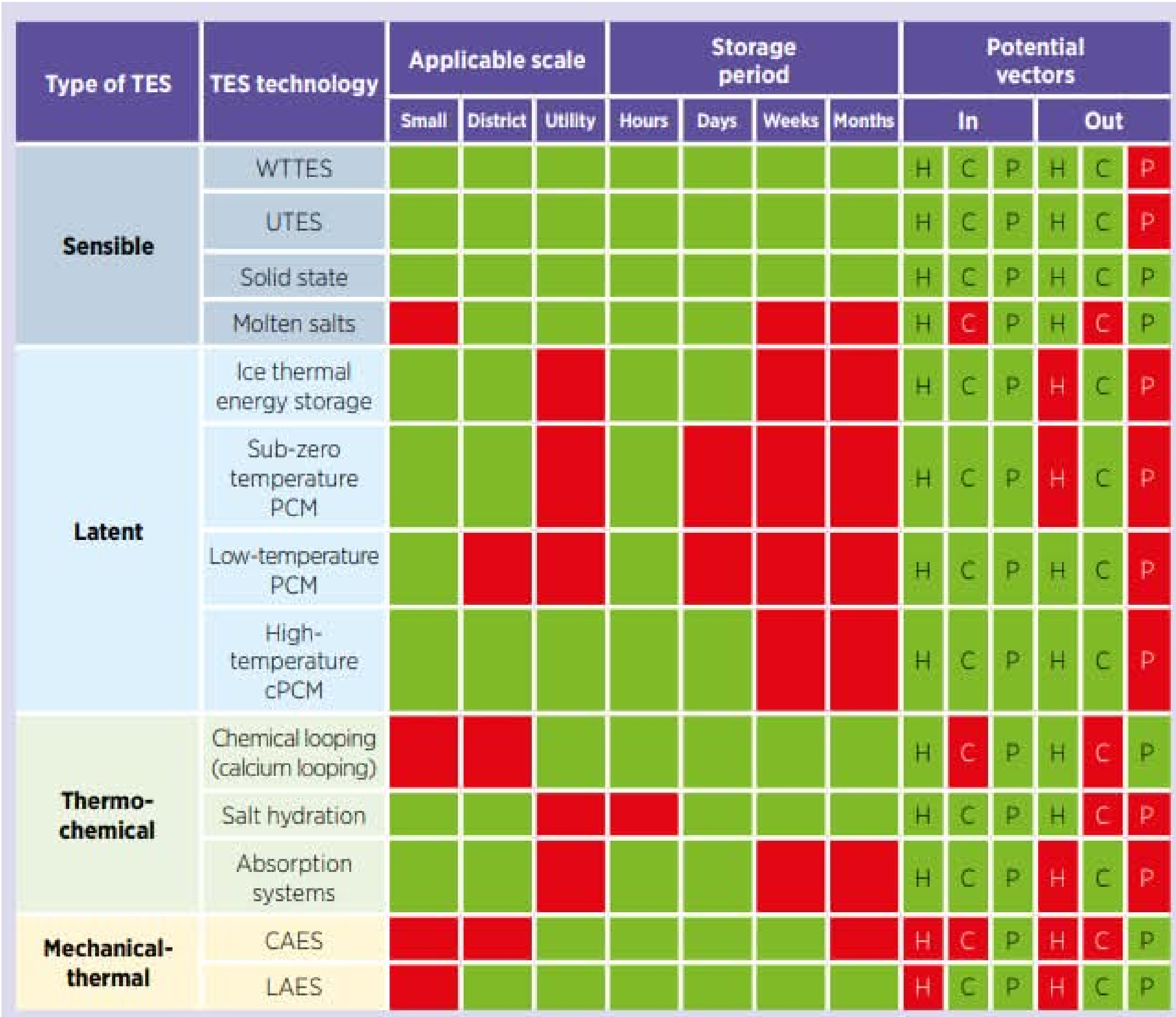
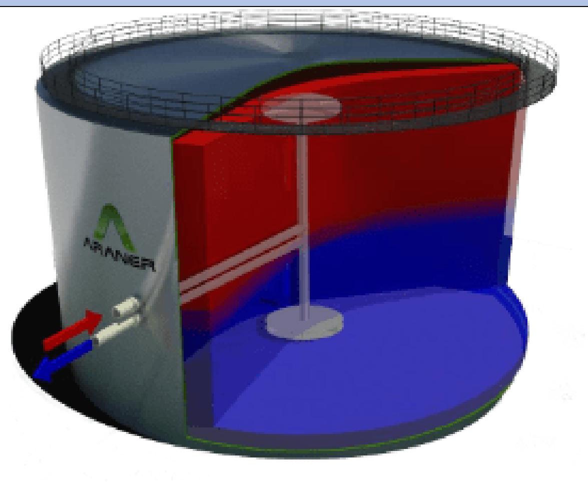


Figure 19 Description of TES fitment, storage period, and charge/discharge vectors [8]
Note: green denotes applicable, red denotes not applicable. C=cold, H=hot, P=power

4.1.1 Water Tank (TTES)



Key Performance Indicator (KPI)	Value	Fitment
Operating Temperature Range	10-90 °C	Good
Charge/Discharge Power [MW]	10 MW	Good
Energy Storage Capacity [kWh/m^3]	15-80	Good
Storage Duration	Hours – Weeks	Good
Highest Recovery Efficiency	90%	Good
Expected System Lifetime [y]	25	Good
Presence of Hazardous Goods	No	Good
Space Requirement	Medium	Challenging

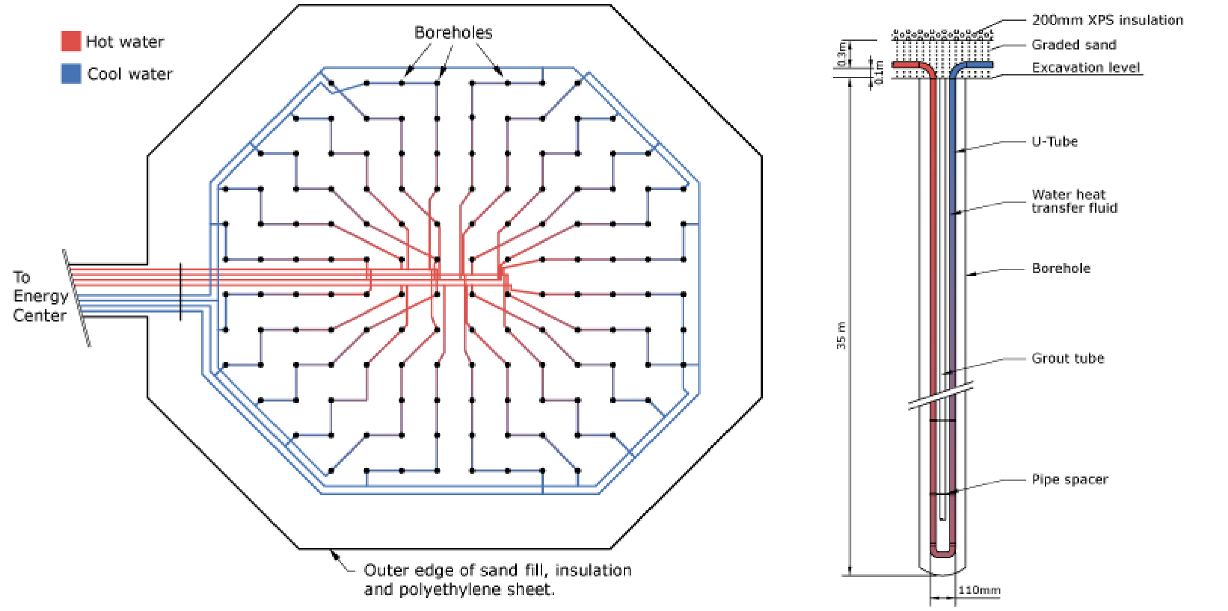
Image Source[9]

Water Tank (TTES) systems show the highest alignment with a peak-shaving scenario, and low alignment with a seasonal storage scenario. TTES systems are the most commonly deployed sensible storage system worldwide.

Real-world proposals provided to the CCCM showed a CAPEX for system design and installation ranging from 2.15-4.0 M ($CAD). TTES deployment would likely be limited to a low temperature scenario, as atmospheric tanks are held below 95°C to avoid steam formation. TTES systems are most effective when used to perform energy arbitrage (buying energy at a low off-peak price for use during peak demand periods).

[9] https://www.araner.com/blog/stratified-thermal-energy-storage-tanks#BENEFITS

4.1.2 Borehole Field (BTES)



Key Performance Indicator (KPI)	Value	Fitment
Operating Temperature Range	10-95°C	Good
Charge/Discharge Power [MW]	Dependant on system operations	Challenging
Energy Storage Capacity [kWh/m³]	15-30	Challenging
Storage Duration	Days - Months	Good
Highest Heat Recovery Efficiency	70-90%	Good
Expected System Lifetime [y]	50	Good
Presence of Hazardous Goods	No	Good
Space Requirement	Large	Barrier

Image Source[10]

Borehole thermal storage (BTES) systems show high alignment with a seasonal storage application, but further analysis is required as to the efficacy of BTES in a peak-shaving capacity. BTES allows for a high volume of waste heat to be stored, however in the absence of cooling operations, thermal balancing of the system poses a challenge.

BTES is highly dependant on the local geological and hydrogeological conditions. While BTES has a relatively low OPEX, CAPEX remains high due to the cost of land acquisition and drilling.

[10] https://www.dlsc.ca/borehole.htm#:~:text=A%20borehole%20thermal%20energy%20storage,boreholes%20resembling%20standard%20drilled%20wells.

BTES systems are best suited for low-grade heat storage (<90°C) as high-temperature heat inputs would suffer thermal losses to the surrounding soil. Due to the large size required to support seasonal storage, is unclear if investment could be recuperated using a BTES system.

Per conversations with the Energy Harvesting Study Task Team, optimization of geothermal systems is a field of research for McMaster University's Institute for Energy Studies. It is highly recommended that HCE continue to engage with researchers at McMaster University

4.1.3 Pit Storage

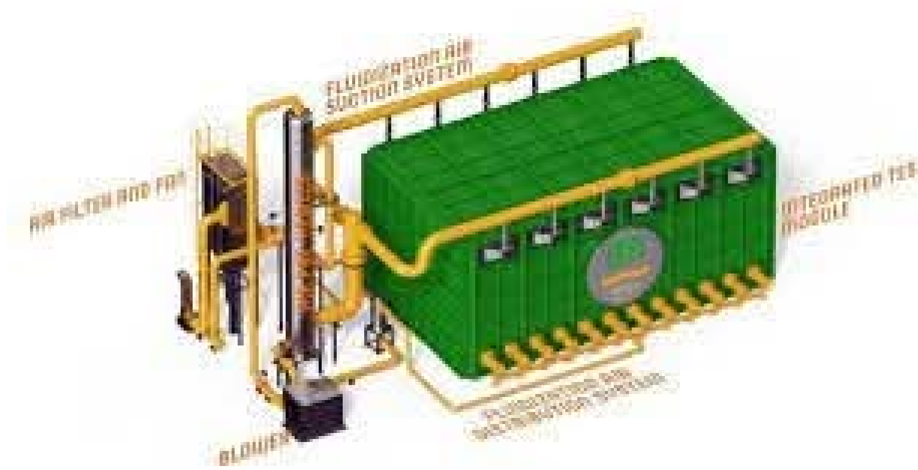
Key Performance Indicator (KPI)	Value	Fitment
Operating Temperature Range	>95°C	Good
Charge/Discharge Power [MW]	Dependant on system operations	Challenging
Energy Storage Capacity [kWh/m^3]	30-50	Good
Storage Duration	Days - Months	Good
Highest Heat Recovery Efficiency	50-90%	Good
Expected System Lifetime [y]	50-90%	Good
Presence of Hazardous Goods	No	Good
Space Requirement	Large	Barrier

Image Source[11]

[11] https://solarthermalworld.org/news/seasonal-pit-heat-storage-cost-benchmark-30-eurm3/

Pit thermal storage (PTES) was included due to the high alignment with both the system operating temperature, and the ability to store heat seasonally. PTES systems are commonly used to supplement district heating networks, however they often operate in a low temperature range, and are charged with low-cost solar thermal energy. PTES systems are hindered by high CAPEX relating to land acquisition and construction.

4.1.4 Fluidized Sand Bed – Magaldi MGTES



Key Performance Indicator (KPI)	Value	Fitment
Operating Temperature Range	Up to 1000°C	Good
Charge/Discharge Power [MW]	5 – 120	Good
Thermal Capacity [kJ/kg k]	1.0-1.1	Good
Storage Duration	Hours - Weeks	Good
Thermal Losses	~1.5% / day	Good
Expected System Lifetime [y]	30+	Good
Presence of Hazardous Goods	None	Good

Image Source[12]

Magaldi's MGTES technology is a modular, scalable system which utilizes a fluidized sand bed for thermal storage. The MGTES system shows good fitment across all categories in both low and high temperature heat supply scenarios, although a higher delta T is preferable for improved system economics.

[12] https://www.magaldi.com/en/applications/mgtes-green-thermal-energy-storage-system

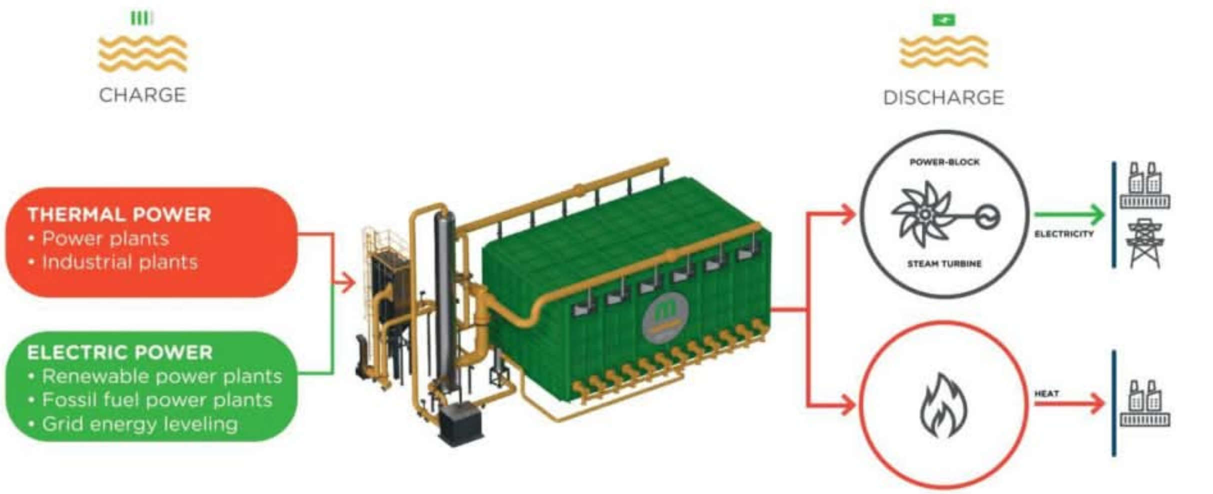


Figure 20 Magaldi MGTES charging and discharging scenario. Image Source[13]

The MGTES system operates up to 1000°C. Interestingly, the MGTES system has the ability to vary the output temperature affording district energy operators flexibility. MGTES is also capable of storing high-grade waste heat, allowing further system resilience.

The MGTES system can be charged with either electrical inputs (as is common with solid state TES systems) or thermal inputs from industrial processes using water as a heat transfer fluid. This is a notable contrast with other sensible heat systems which are typically charged by high temperature exhaust gases, or electrical resistance heaters

[13] https://www.magaldigreenenergy.com/en/thermal-energy-storage

4.1.5 PCM – Inorganic Salt (Sodium Acetate) Sunamp CentralBank

Key Performance Indicator (KPI)	Value	Fitment
Operating Temperature Range	58-120°C	Good
Charge/Discharge Power [MW]	Unknown	
Energy Storage Capacity [kWh/m^3]	Unknown, but likely ~200	Good
Storage Duration	Hours-Days	Good
Thermal Losses	Unknown	
Expected System Lifetime [y]	Unknown	
Presence of Hazardous Goods	Yes	Minor Challenge

Image Source[14]

Sunamp offers a suite of PCM thermal storage systems based on its proprietary sodium acetate based material, Plentigrade[15]. Plentigrade shows high alignment with the temperature range of the proposed district heating system. Unfortunately, at the time of reporting, specific information on operational behaviour and CAPEX could not be collected.

However, it is worth noting that Sunamp's CentralBank is being considered for a cutting edge initiative called the Thames Mobile Heat project, in London England. If successful, CentralBank systems would be used to capture waste heat at a waste facility, before being transported down the River Thames via

[14] https://sunamp.com/en-gb/heating-central-bank-overview/
[15] https://sunamp.com/en-gb/plentigrade/

barge for use within the Pimlico District Heating Network. This initiative has the potential to transport up to 240 MW_{th} per day.[16]

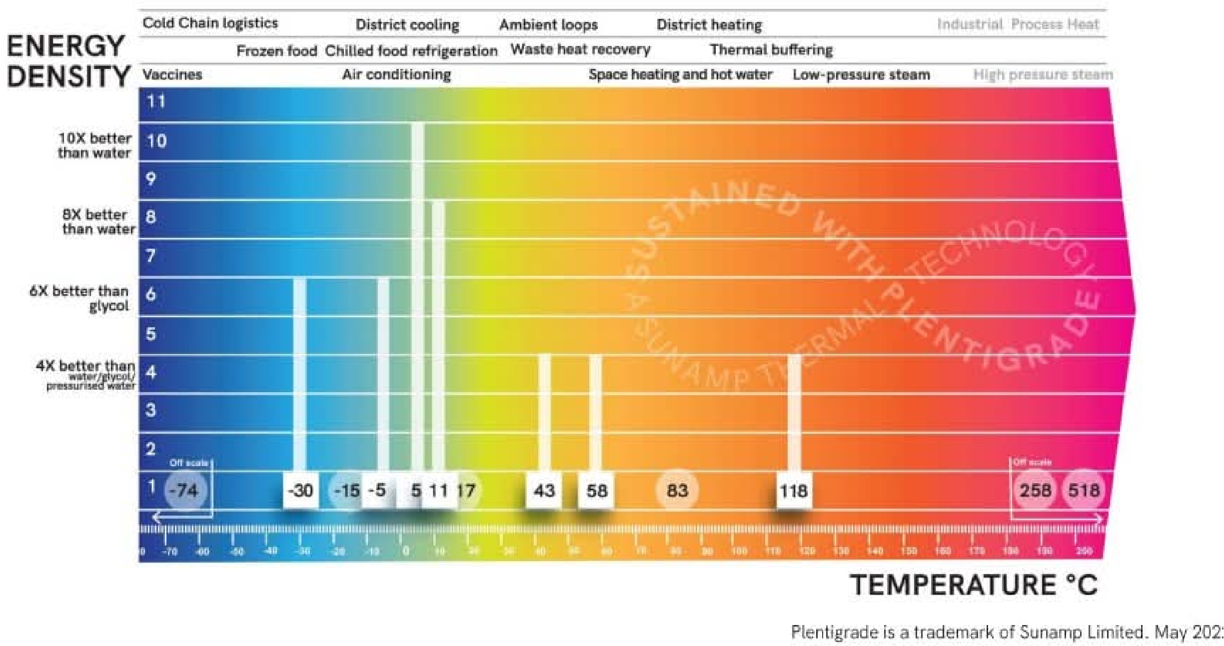


Figure 21 Energy density across various Plentigrade systems[17]

Sunamp reports that Plentigrade is four times more energy dense than water, placing a rough estimation of specific energy capacity at 200 kWh/m^3. Given the high storage capacity, and ability to store waste heat centrally, further investigation is warranted.

4.1.6 Key insights: Technology Fitment Assessment

Technologies such as Molten Salt, High-temp PCM, TCM and others were excluded.

- Magaldi's MGTES system should be investigated further as there is high alignment in both a low and high temperature supply scenario. Further discussion on system sizing, system integration into the proposed hot water transmission system and CAPEX is recommended.

- Sunamp's CentralBank system should also be investigated further as there is high alignment with a low temperature supply scenario. The increased storage capacity (as compared to sensible systems) may

[16] https://sunamp.com/en-gb/thames-mobile-heat/
[17] https://sunamp.com/wp-content/uploads/2022/05/Sunamp-phase-change-material-Plentigrade-temperature-chart-May-2022.pdf

result in system economics which are not captured in Section 3.2. Further conversation and investigation is highly recommended.

- Pit Storage should likely be avoided. PTES shows high alignment with a seasonal storage scenario, but high CAPEX due to land acquisition, and construction costs is a significant barrier. Further, PTES systems show lower system efficiency than other water-based storage options. Last, system economics would likely by unfavourable as most PTES are charged by low-cost solar thermal.

- Borehole Storage shows highest alignment with a seasonal storage scenario, offering the largest storage capacity of any solution. However, high CAPEX due to land acquisition, and borehole drilling presents economic challenges. Further investigation into the economics of seasonal storage is required. Many BTES systems utilize low-cost solar thermal for charging, it is unclear if investment can be recuperated under a scenario where a dollar value is placed on waste heat.

- Water Tank (TTES) shows high alignment with a peak-shaving scenario under a low temperature heat supply scenario. Since the TTES system operates below the phase-change temperature of water, deployment of TTES under a high-heat scenario (120°+) is unlikely. TTES space requirements are moderate, and scales with capacity. Successful TTES deployment is dependant on the cost of input energy.

4.2 Economic & Carbon Reduction Analysis

The following section contains an economic and supplemental carbon analysis comparing the cost of meeting the system peak demand though a Business as Usual (BAU) Scenario vs deploying TES to meet network peaking. See Appendix II for carbon calculations.

4.2.1 Assumptions

The following assumptions were applied consistently across all economic and environmental analyses, including the base cases and various optimized scenarios. The CAPEX, in particular, was crucially influenced by manufacturers insights and scaled appropriately to match the required peak threshold.

- **Peak Threshold**: The work analyses operations of peak thresholds of both 24MW and 30MW based on the conceptual design suggestion[18] of four heat pumps total capacity (6MW each), the peaking equipment (natural gas boilers), and the highest demand expected (~50 MW).
- **CAPEX (Capital Expenditure)**: The capital expenditure was set to 2.15M $CAD based on manufacturer consultations for a water tank (TTES) system with 20MW discharge power output. The CAPEX was then approximated for a 26MW discharge power output to match the 24MW peak threshold scenario.
- **Heat Pump COP (Coefficient of Performance)**: A COP of 3.5 was assumed for the heat pumps used in scenarios where low-grade waste heat is supplied and needs to be upgraded for district energy. In the conceptual design, three heat pumps' COP were mentioned for different seasons. This analysis considers their average (COP = 3.5).
- **Fuel Costs**:
  - **Natural Gas Boiler Heating Cost**: CAD 0.036/kWh_{th}, this includes the embedded cost of carbon pollution.
  - **Electricity Cost for Heat Pumps**: Assumed CAD 0.10/kWh (Class A) as a baseline with variations for optimistic scenarios.
  - **Recovered Waste Heat Cost**: CAD 0.10/kWh for high-grade heat supply baseline scenarios and CAD 0.035/kWh_{th} for low-grade heat supply baseline scenarios, with potential for reduced costs in negotiated scenarios.
- **Emission Factors**:
  - **Natural Gas Emission Factor**: 0.178 kg CO_2e /kWh
  - **Electricity Emission Factor**: 0.038 kg CO_2e /kWh
- **Financial Metrics**:
  - **Discount Rate**: Set at 9%, reflecting typical rates used.
  - **Lifetime**: Based on water tanks manufacturers consultations a lifetime of 25 years is assumed for all scenarios, which applies to the calculations of the financial metrics (e.g., NPV and Payback periods).

4.2.2 Analysis Readouts

The following readouts are screenshots from a logic model built in Python which compared the cost of meeting the peak under a business as usual (BAU) scenario vs 20/26 MW storage scenario.

[18] Refer to Rathco's conceptual design report.

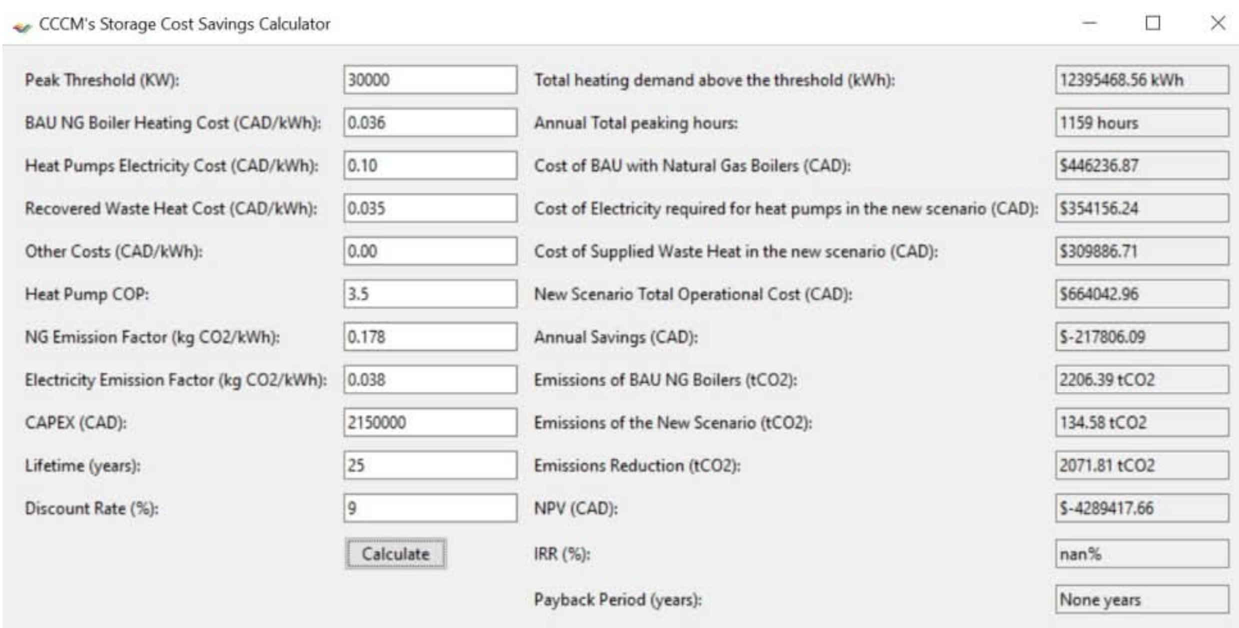


Figure 22 30MW Peaking Threshold Results - Low Temperature Scenario

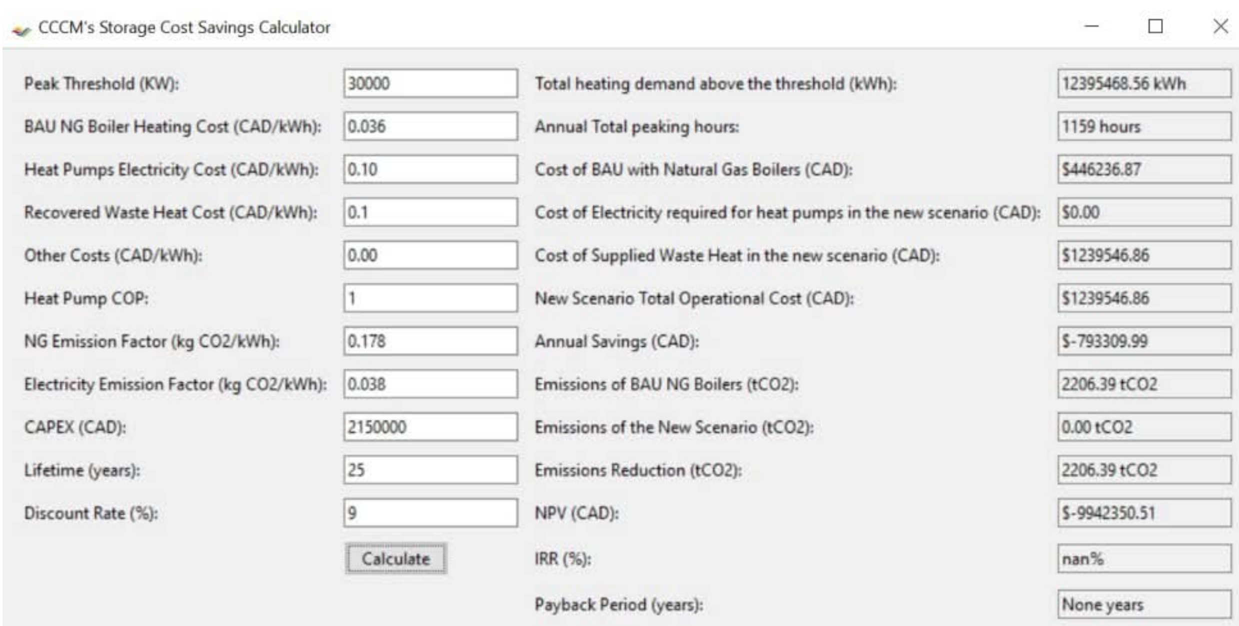


Figure 23 30MW Peaking Threshold Results - High Temperature Scenario

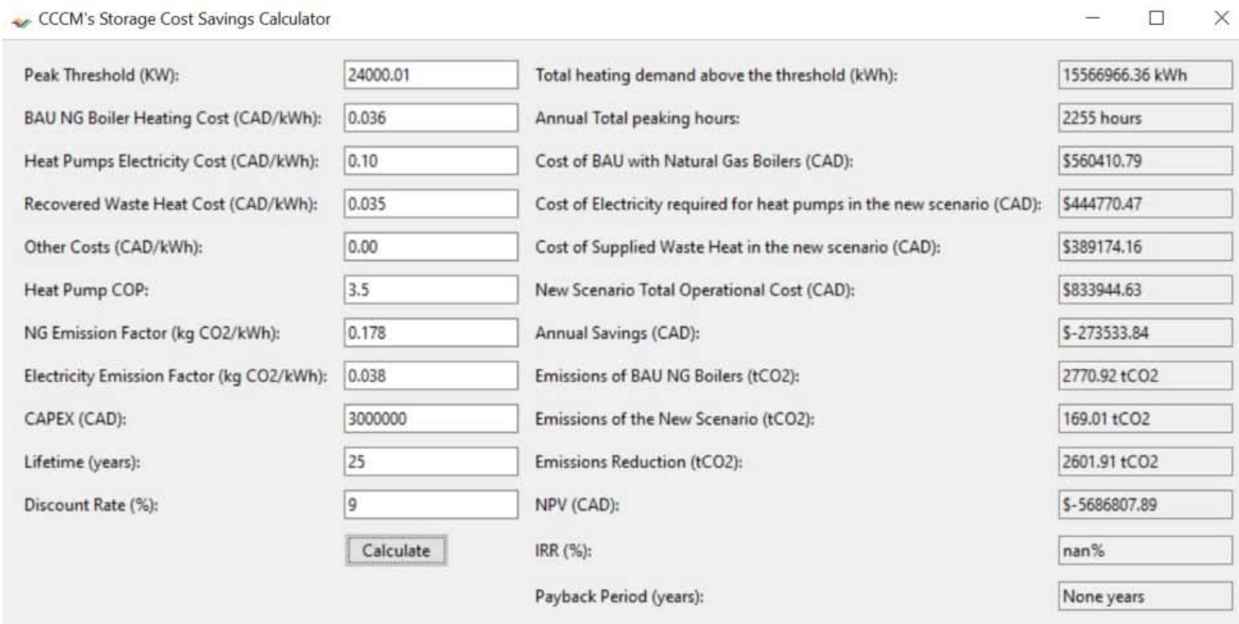


Figure 24 24MW Peaking Threshold Results - Low Temperature Scenario

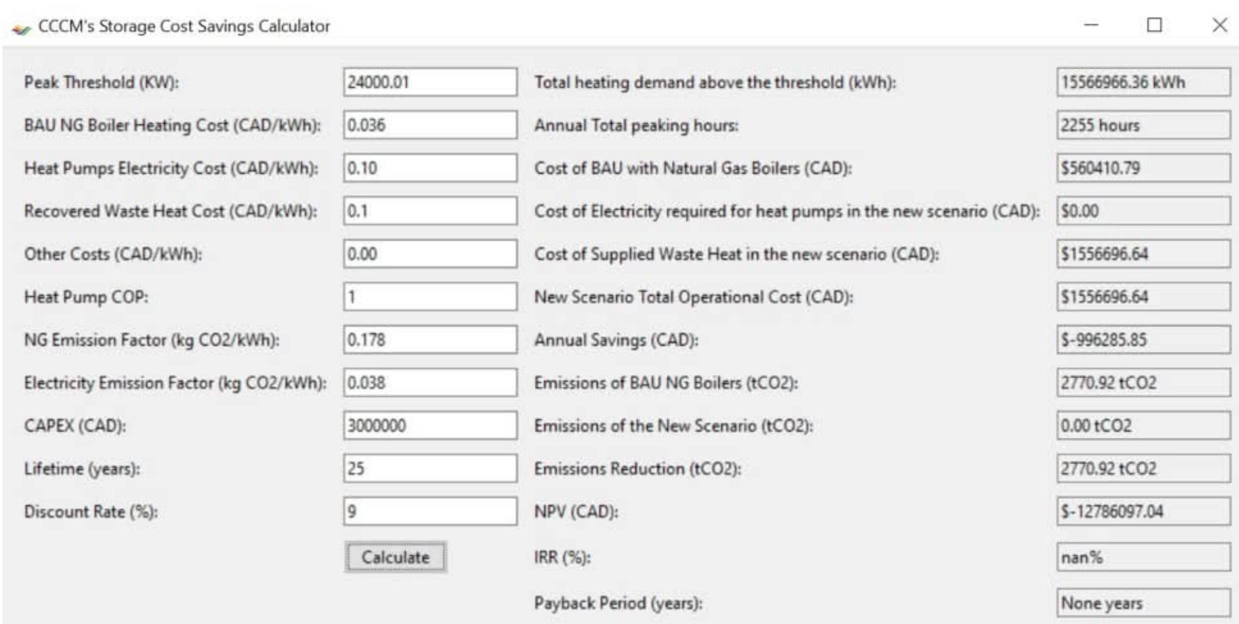


Figure 25 24MW Peaking Threshold Results - High Temperature Scenario

4.2.3 Annual Savings Comparison

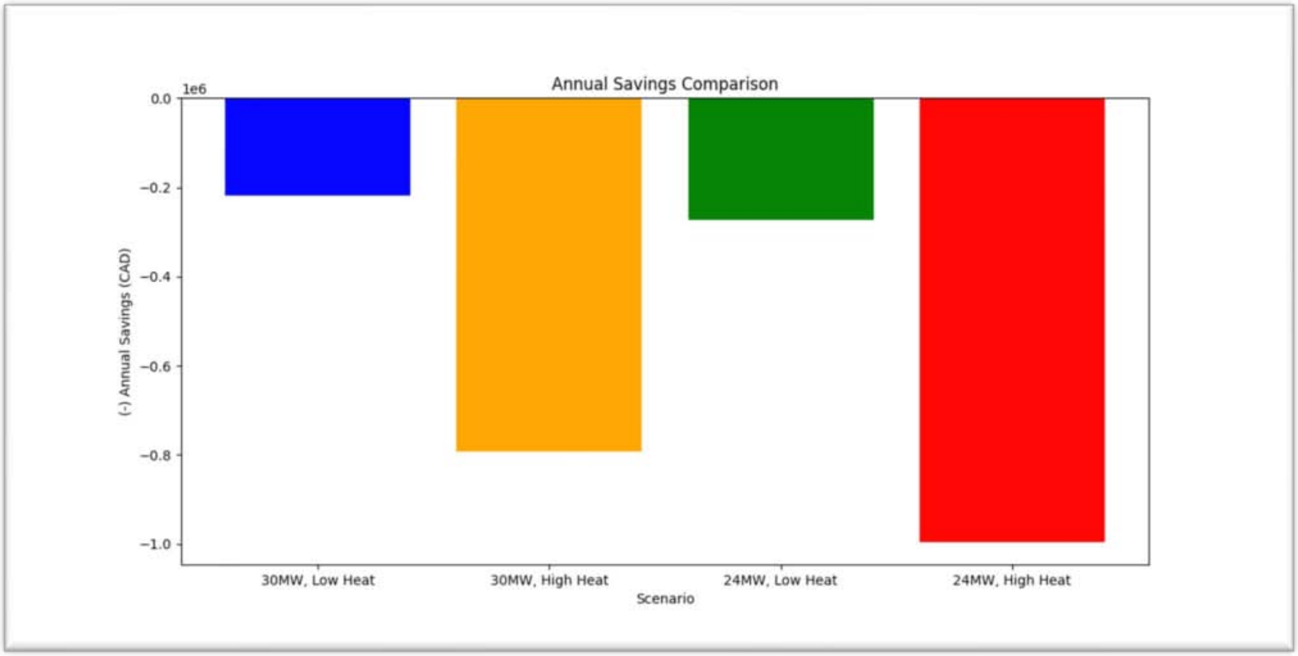


Figure 26 Annual Savings Comparison BAU vs TES

Figure 26 compares the annual savings (or losses) for the four scenarios:

- **30MW Low Temperature:** This scenario shows a moderate negative annual savings, meaning that the project is losing money annually. This is due to the significant operational costs of using electricity to power heat pumps (low heat scenario).
- **30MW High Temperature:** This scenario shows a slightly higher negative annual savings compared to the 30MW low heat scenario. This is because, despite not using heat pumps (thus no electricity costs), the higher cost of high-grade heat results in overall higher operational expenses.
- **24MW Low Temperature:** This scenario displays substantial negative annual savings. The combination of lower peak threshold and the need to use heat pumps results in a less favourable economic outcome.
- **24MW High Temperature:** This scenario has the worst annual savings, with the most significant negative value. The lower threshold for TES activation and high temperature combination are the least economically favourable, mainly due to high cost of acquisition associated with high temperature heat.

Key Insight: In all scenarios, the annual savings are negative, indicating that each configuration incurs more costs than it saves, with the 24MW High Heat scenario being the least favourable.

4.2.4 Net Present Value (NPV) Comparison

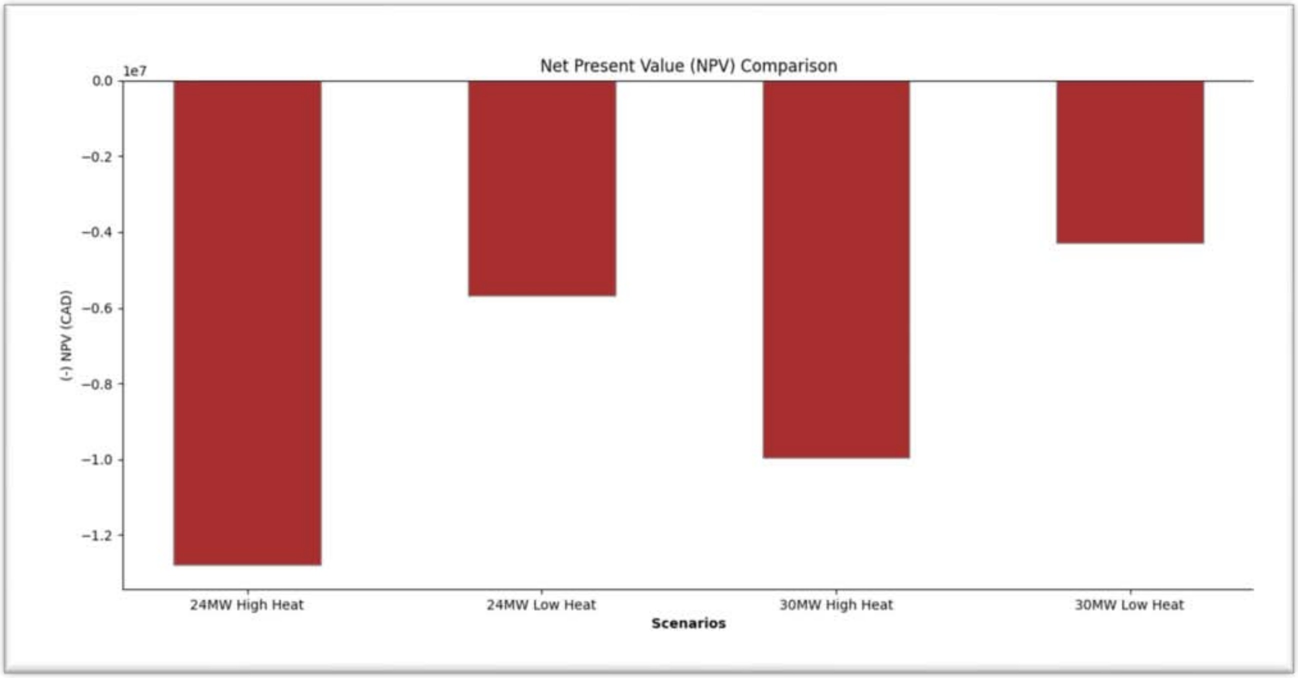


Figure 27 NPV Comparison BAU vs TES

Figure 27 compares the Net Present Value (NPV) of each scenario. NPV is a measure of the overall profitability of an investment, considering the time value of money.

- **24MW High Temperature:** This scenario shows the most negative NPV, indicating that it is the least economically viable. The high operational costs due to expensive high temperature heat combined with the lower peak threshold contribute to this result.
- **24MW Low Temperature:** While still negative, this scenario has a slightly less severe NPV compared to the 24MW High Heat scenario. The use of heat pumps (and associated electricity costs) is less expensive than purchasing the high temperature heat of amount that is equal to the peak demand, resulting in a somewhat better (but still negative) NPV.
- **30MW High Temperature:** This scenario shows an improved NPV relative to the 24MW scenarios. The higher threshold allows for more efficient operation, even with the increased cost of high-grade heat.
- **30MW Low Temperature:** This scenario has the least negative NPV, **making it the most economically viable of the four**. The

combination of higher threshold and low-grade heat results in reduced operational costs, albeit still not sufficient to generate a positive NPV.

Key Insight: None of the scenarios generate a positive NPV, meaning all are expected to incur a net loss over the project's lifetime. However, the 30MW Low Temperature Scenario is the least unprofitable, while the 24MW High Temperature Scenario is the most unprofitable.

4.2.5 Emissions Reduction Comparison

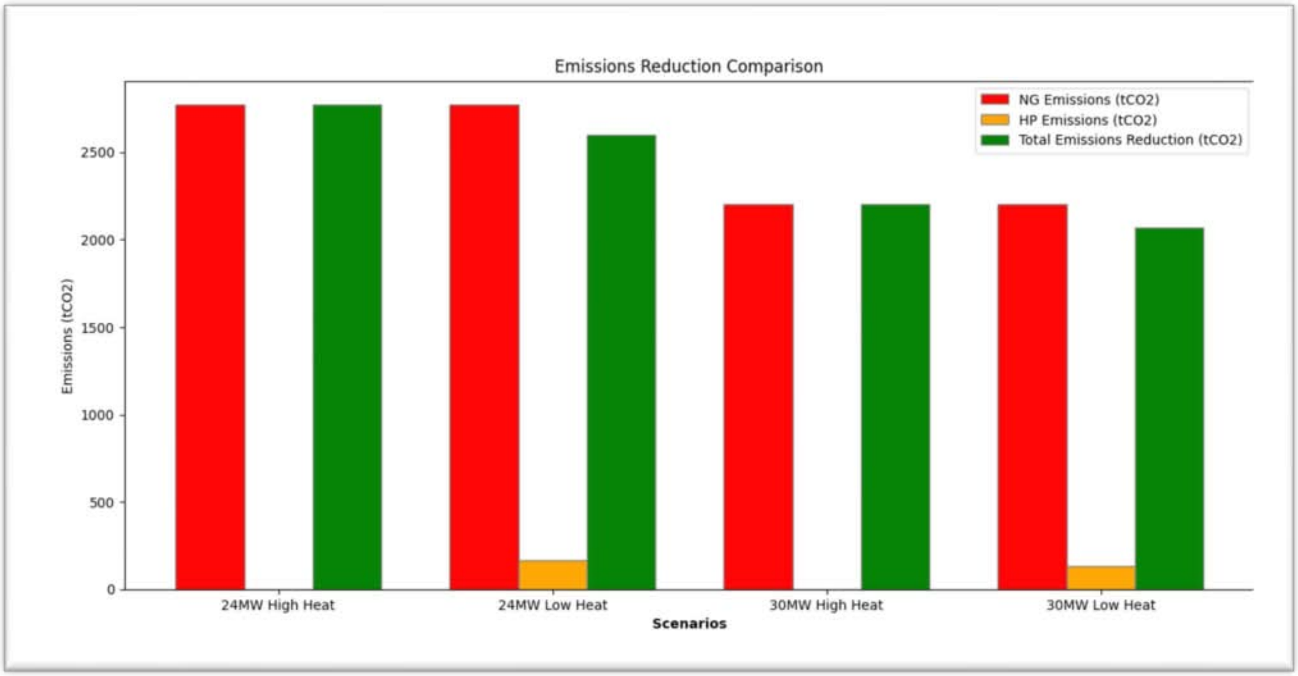


Figure 28 Emissions reductions across all TES scenarios

Figure 28 compares the emissions reduction for the mentioned scenarios. The emissions are broken down into contributions from natural gas (NG) boilers and heat pumps (HP) if applicable.

- **24MW High Temperature:** This scenario shows the highest total emissions reduction owing to the expected deferral of heat pump operations along the network, and reduced boiler operations. In a high temperature supply scenario, it is expected the network can directly source waste heat of a suitable temperature to directly deploy to the network. Despite high temperature heat costs, it provides the highest emissions reduction. However, further research into thermal losses along the route, and the impact of seasonal storage of high temperature waste heat is required.
- **24MW Low Temperature:** This scenario also achieves a high level of emissions reduction. However, it shows an additional contribution from heat pump electricity emissions (yellow bar). Although this reduces the

total emissions reduction slightly compared to the High Temperature scenario, it still performs well in terms of emissions reduction.

- **30MW High Temperature:** The emissions reduction in this scenario is lower compared to the 24MW scenarios. The lower peak threshold of 30MW results in reduced operational hours, hence lesser emissions reduced from the BAU natural gas boilers operation.
- **30MW Low Temperature:** This scenario shows the lowest emissions reduction among the four scenarios. The combination of the lower peak threshold and efficiencies gained from heat pump operations results in reduced overall emissions reduction.

4.2.6 Marginal Abatement Cost Curve (MACC)

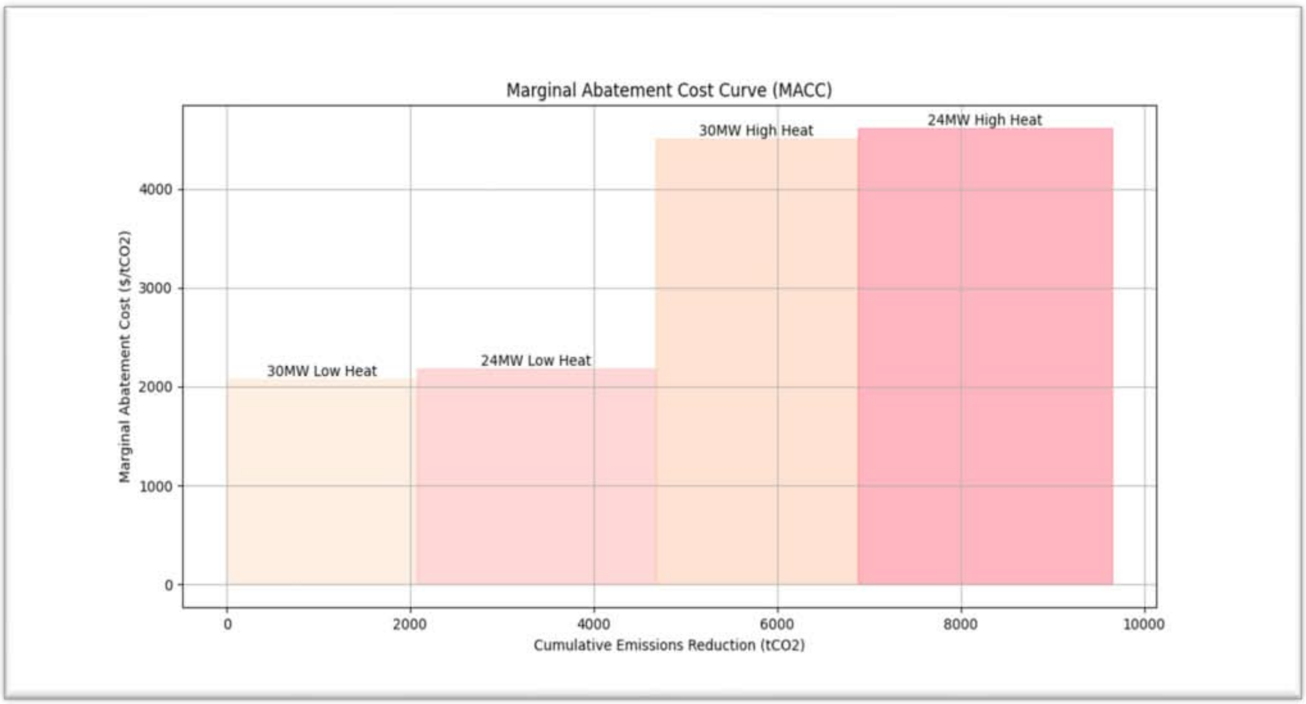


Figure 29 MACC Curve across TES scenarios

Figure 29 depicts a Marginal Abatement Cost Curve showing the cost in dollars per ton of avoided carbon emissions.

- It helps prioritizing the scenarios based on cost-effectiveness and emissions reduction goals. If the goal is to maximize carbon emission (CO_2e) reductions at the lowest cost, focusing on the **30MW Low Temperature Scenario** would be the most strategic approach, while the **24MW High Temperature Scenario** would be the least preferred due to its higher costs.

- In the context of the project, **Low Temperature Scenarios** exhibit more cost-effective for emissions reduction compared to High Heat scenarios.
- In **High Temperature Scenarios**, although elimination of heat pumps reduces operational costs related to electricity, the significantly higher cost of the high-grade heat, compared to both low-grade heat price (0.035/kWh_{th}) and BAU NG price (0.036/kWh_{th}), increases the cost of carbon reductions, leading to a substantial price increase.
- **30MW Low Temperature**: This scenario has the lowest marginal abatement cost (MAC) at approximately $2000 per ton of CO_2e reduced. It results in an annual emissions reduction of 2071.81 t CO_2e. This makes it the most cost-effective option for reducing emissions, despite the operational costs associated with running heat pumps.
- **24MW Low Temperature**: Following the 30MW Low Temperature scenario, the 24MW Low Temperature scenario shows a slightly higher MAC of about $2600 per ton of CO_2e reduced. It achieves an annual emissions reduction of 2601.91 t CO_2e. Although it's more expensive than the 30MW Low Temperature scenario, it remains relatively cost-effective.
- **30MW High Temperature**: This scenario shows a significant increase in abatement costs, with a MAC of around $3500 per ton of CO_2e reduced. It achieves an annual emissions reduction of 2206.39 t CO_2e. The lack of heat pump costs is outweighed by the higher price of high-grade heat, making this scenario less cost-effective.
- **24MW High Temperature**: Finally, the 24MW High Temperature scenario has the highest MAC at approximately $4500 per ton of CO_2e reduced. It achieves the largest annual emissions reduction of 2770.92 t CO_2e, but at the highest cost. This scenario reflects the increased operational expenses due to the high cost of high-grade heat (compared to the low-grade heat) and the lowered peaking threshold of 24MW.

4.2.7 Optimistic Scenarios

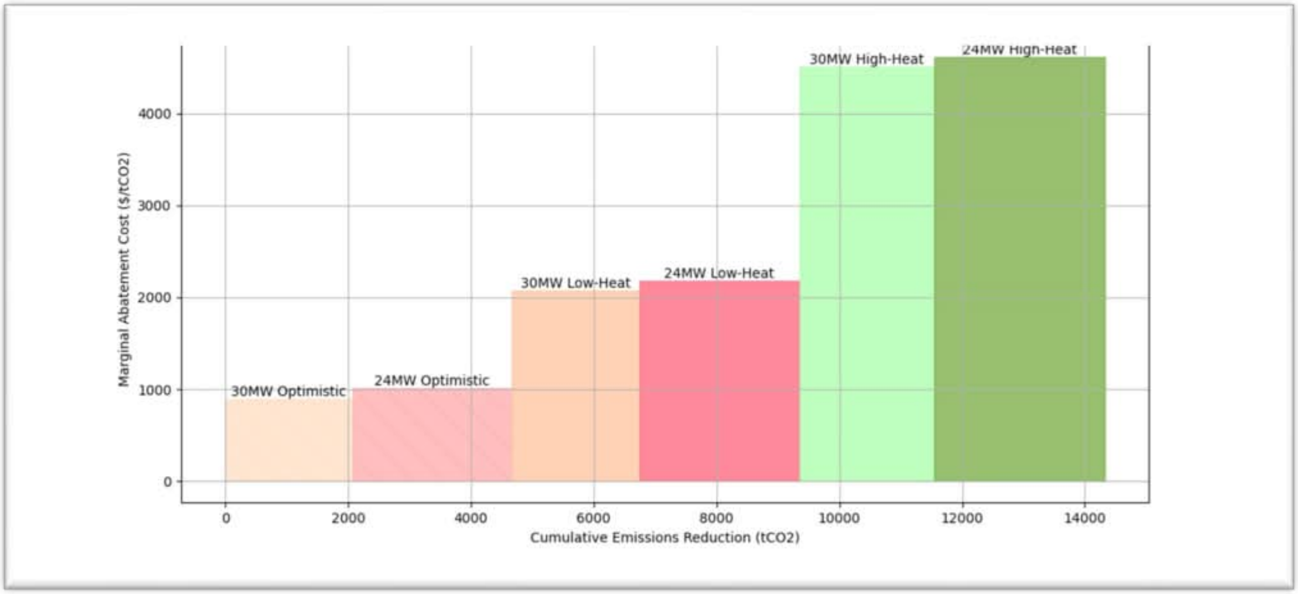


Figure 30 MACC using ultra-low electricity rate, $0.03/kWh

Figure 30 compares four scenarios which manipulate fuel input, and operational conditions. Included in this analysis is an optimistic scenario where the price of electricity is fixed at $0.03 per kWh in the low temperature heat supply case. This is achieved under a scenario where HCE successfully shaves each peak throughout the year. This ultra-low rate significantly impacts the economics of using heat pumps to boost the temperature level. Both thresholds in this, 24MW and 30MW, have been tested in this scenario and found to be the most cost-effective options in the graph. This highlights the significant cost benefits of lowering electricity prices, which reduces the operational costs of heat pumps and thus lowers the cost per ton of CO_2e abated.

4.2.8 Optimistic Scenarios Continued: Impact of Electricity and Waste Heat Price Decrease

This analysis examines the effect of different electricity prices and negotiated waste heat prices on the financial viability of two district energy scenarios where TES would activate above 30MW and 24MW peaking thresholds. The scenarios consider different combinations of electricity and waste heat pricing, assessing their impact on key financial metrics such as Net Present Value (NPV), Payback Period, and Internal Rate of Return (IRR), as well as the associated emissions reductions.

Scenario 1: Impact of Reduced Electricity Prices

The table below summarizes the financial and environmental outcomes when the electricity price drops to 1 cent/kWh and the price of waste heat price is fixed at 3.5 cents/kWh_{th}.

Table 5 Scenario with Reduced Electricity Price

Scenario	Electricity Price (cent/kWh)	NPV ($CAD)	Payback Period (years)	Emissions Reduction (tCO_2)
30MW Peaking Threshold	1	-1,158,562.55	22	2,071.81
24MW Peaking Threshold	1	-1,754,893.90	24	2,601.91
30MW Peaking Threshold (Free Electricity, e.g., using owned solar energy plant of 3MW that increases the total CAPEX to ~ 5M dollar without considering land acquisition cost)[19]	0	-3,660,689.76	Can't recover within lifetime of equipment.	2,071.81

Key Insights:

- Despite a significant reduction in electricity prices, the NPV remains negative for both 30MW and 24MW thresholds, indicating that even at a price as low as 1 cent/kWh, the implementation of storage in these scenarios is not financially viable.
- The payback periods remain long (22 and 24 years), further highlighting the challenge of achieving a positive financial outcome under these conditions.
- A rough analysis considering "free" electricity sourced through a wholly owned a solar energy plant, also fails to yield a positive NPV, with a negative IRR of 2.75% and expected inability to recover CAPEX.

Scenario 2: Optimistic Scenario with Reduced Waste Heat Price

The second table, below, outlines the results of a scenario where the recovered waste heat price is negotiated to 1 cent/kWh, combined with an electricity price of 3 cents/kWh. This scenario is considered attractive due to the favourable pricing conditions.

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[19] It is worth noting that the average capital expenditure for utility-scale solar energy projects in Canada currently ranges from approximately 1.43 to 1.56 CAD per watt, according to recent studies. Integrating an owned 3 MW solar energy plant, excluding land acquisition costs, could increase the total CAPEX to around 5 million CAD (NREL ATB) (Lawrence Berkeley National Laboratory, 2022).

Table 6 Scenario with reduced Waste Heat Price

Scenario	Annual Savings ($CAD)	NPV ($CAD)	IRR (%)	Payback Period (years)	Emissions Reduction (tCO_2e)
30MW Peaking Threshold	251,450.93	319,896.81	10.79	9	2,071.81
24MW Peaking Threshold	315,787.03	101,843.26	9.42	10	2,601.91

Key Insights:

- The combination of a low electricity price (3 cents/kWh) and a negotiated waste heat price (1 cent/kWh) significantly improves the financial viability of the projects.
- The 30MW Peaking Threshold scenario under these conditions achieves a positive NPV of $319,896.81, with an IRR of 10.79% and a payback period of 9 years. This makes it an attractive investment compared to other scenarios.
- The 24MW Peaking Threshold scenario also shows improved metrics, although the NPV is lower ($101,843.26), with an IRR of 9.42% and a payback period of 10 years. This scenario is slightly less favorable financially but still viable.

4.2.9 Breakeven Conditions

In another scenario, we assume the price of supplied low grade waste heat from industrial partners is set to zero. This assumes that the heat supply is cost-neutral with connections charges and bypasses[20]. Under these conditions, the breakeven point, where the Net Present Value (NPV) becomes zero, is achieved at specific electricity prices for Class A consumers (large-scale heat pumps). The results are as follows:

Table 7 Breakeven Scenarios

Peaking Threshold	Net Present Value (NPV)	Emissions Reduction (t CO_2e annually)	Breakeven Electricity Price ($/kWh)
30MW	$0	2,071.81	$0.064/kWh
24MW	$0	2,601.91	$0.057/kWh

This highlights the necessary electricity prices to achieve financial breakeven in scenarios where the waste heat is supplied at no cost.

4.3 Economic and Carbon Analysis Conclusion

[20] Inspired from the first Urban Equation's Commercial Model Report which assumes cost-neutral waste heat supply.

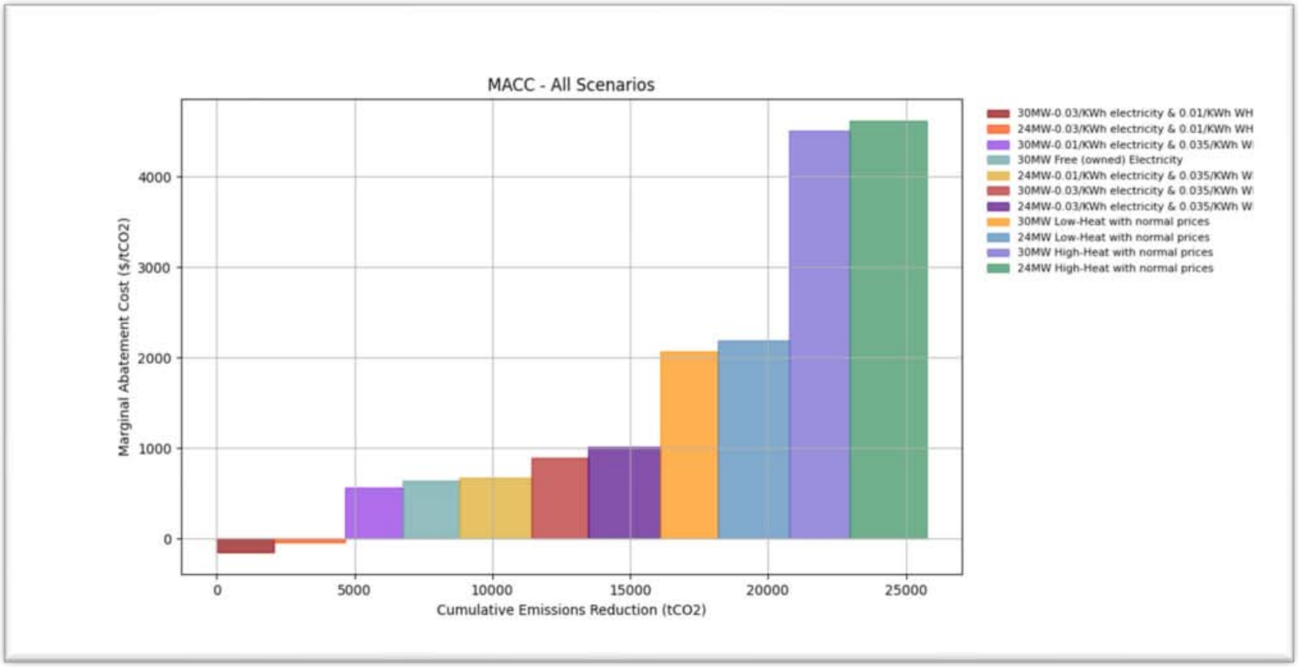

Figure 31 MACC comparison across all scenarios

Figure 31 shows a Marginal Abatement Cost Curve (MACC) depicting a comprehensive comparison across multiple scenarios, representing different combinations of electricity and waste heat prices. The analysis includes scenarios with regular market conditions as well as those assuming optimistic conditions, such as significantly reduced electricity costs and even free electricity (owned electricity plant).

4.4 Author’s Key Insights

1. **Lowest Marginal Abatement Costs:** The scenarios with the lowest marginal abatement costs are those where both the electricity price and waste heat cost are set to their optimistic minimums. Specifically, the within a 30MW storage scenario, \$0.03/KWh electricity & \$0.01/kWh$_{th}$ waste heat, and in a 24MW storage scenario, \$0.03/kWh electricity and \$0.01/KWh$_{th}$ waste heat, demonstrate the most cost-effective reductions in CO2 emissions. These scenarios achieve a marginal abatement cost of \$150/tCO_2e and \$35/tCO_2e respectively, which indicates that the emission reduction here actually saves money overall making them both financially viable and environmentally impactful.
2. **Standard Market Scenarios:** On the other end of the spectrum, the scenarios with regular market at prices ("24MW High-Heat with normal prices" and "30MW Low Temperature with normal prices") have the highest marginal abatement costs. These scenarios exhibit significantly less favourable economics, with much higher costs per tonne of CO_2e reduced and negative NPVs. The high marginal costs in these cases underscore the financial challenges of achieving emissions reductions under standard market conditions.
3. **Optimistic Scenarios:** Scenarios that involve optimistic but more realistic conditions, such as moderately reduced electricity costs or owned-plant electricity, occupy the middle of the curve. For instance, "30MW Free (owned) Electricity" is among the more favourable options, costing only \$640/tCO_2e reduced. These scenarios highlight the potential of favourable pricing agreements to improve the economic feasibility of significant CO_2e reductions.
4. **Cumulative Emissions Reduction:** The cumulative emissions reduction potential varies across scenarios. The highest emissions reduction is achieved in scenarios involving 24MW High Temperature with pricing of utility and waste heat inputs in-line with Rathco’s forecast (2770.92 tCO2 annually). However, in this scenario, we see a high cost per tonne of CO_2e reduced. This suggests that while larger reductions are possible, the associated costs are steep unless favourable pricing conditions are secured.

5 Research Conclusion & Future Outlook

The following major conclusions may be gleaned from this research:

- Under a low temperature supply scenario highest technical alignment for a peak-shaving scenario is seen with a water tank (TTES) system
- Under a high-temperature supply scenario, increased operational efficiencies may be realized through the higher energy storage capacity of Magaldi's MGTES or Sunamp's Plentigrade PCM system (further research required).
- Under all peak shaving scenarios grounded in the use of a 20MW water tank, a negative NPV is seen.
- Other capitally intensive systems show negative NPV.
- Seasonal storage (e.g. BTES) is assumed to have negative NPV due to the higher capital cost, thermal losses and challenge of achieving price parity in meeting peak demand with heat pumps vs natural gas boilers. However, optimization of geothermal systems is a field of study at McMaster University's Institute for Energy Studies. It is highly recommended HCE engage with McMaster researchers to both review this finding and stay abreast of emerging research findings.
- Under every TES deployment scenario, significant emissions reductions are realized are realized from avoided natural gas boiler operations (2600 – 2770 t CO_2e/ yr).
- The most favourable Marginal Abatement Carbon Cost ($2000/t$CO_2$e reduced) is found under a low-temperate supply scenario, with a 30MW demand threshold (20MW TES operation).
- A breakeven scenario is reached for TES deployment when the price on waste heat is set to zero, and the price of electricity is set to an ultra-low rate of $0.057-0.064/kWh. This highlights the importance of charging the system with both low-rate electricity, and low-rate thermal energy.

5.1 Recommendations and Future Work

Several key recommendations have arisen from this research:

1) Investigate new and emerging PCM and TCM system. Such systems offer higher storage densities than sensible solutions, potentially leading to better economics (i.e. CentralBank)

2) Reduce the cost of waste heat acquisition wherever possible

3) Peak shaving is required to access ultra-low electricity rates required to see positive returns

4) Wherever possible, utilize heat pumps to multiply the efficiency of the transmission system. When Heat Pumps are not used in a high-grade scenario, increased storage costs are seen as the energy is stored in a 1:1 ratio, rather than 1:3.5

5) Adapt the Storage Cost Calculator Model provided by the CCCM to reflect the carbon pricing scenarios as legislation evolves.

Future work may include:

- Further analysis of PCM and TCM systems as they become commercially available
- Further sensitivity analysis within the economic model
- Further analysis to confirm the research team's suspicion of negative NPV in seasonal storage scenario
- Future collaboration and investigation into financial feasibility, and operational optimization of geothermal storage systems.

For more insights into the future of TES in district heating system, please refer to Appendix IV.

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Appendix I: Thermal Energy Storage Systems Overview

Type of TES	TES technology	Range of capacities	Range of power	Operating temp-erature	Round-trip efficiency	Storage period	Energy density	Lifetime (years or no. of cycles)
Sensible	WTTES	kWh to 1 GWh	kW to 10 MW	10 to 90°C	50 to 90%	Hours to months	15-80 kWh/ m^3 (1)	15-40 years
	UTES	MWh to GWh	MW to 100 MW	5 to 95°C	up to 90%	Weeks to months	25-85 kWh/m^3	50 years
	Solid state	10 kWh to GWh	kW to 100 MW	-160 to 1 300°C	>90%	Hours to months	0.4-0.9 kWh/ $m^3 \cdot K$ (heat capacity) (2)	> 5 000 cycles
	Molten salts	MWh to 5 GWh	100 kW to 300 MW	265 to 565°C (4)	>98%	Hours to days	70-200 kWh/m^3	> 20 years
Latent	Ice thermal energy storage	kWh to 100 MWh	kW to 10 MW	-3 to 3°C	>95%	Hours to days	92 kWh/ m^3	> 20 years
	Sub-zero temperature PCM	kWh to 100 kWh	kW to 10 kW	down to -114°C	>90%	Hours	30-85 kWh/m^3	> 20 years
	Low-temperature PCM	kWh to 100 kWh	kW to 10 kW	up to 120°C	>90%	Hours	56-60 kWh/m^3	300-3 000 cycles
	High-temperature cPCM	10 kWh to GWh	10 kW to 100 MW	up to 1 000°C	>90%	Hours to days	30-85 kWh/m^3	> 5 000 cycles
Thermo-chemical	Chemical looping (calcium looping) (5)	MWh to 100 MWh	10 kW to 1 MW	500 to 900°C	45-63%	Months	800-1200 kWh/m^3	>30 years
	Salt hydration	10 kWh to 100 kWh	N/A	30 to 200°C	50% (open systems) 60% (closed systems)	Months	200-350 kWh/m^3	20 years
	Absorption Systems	10 kWh to 100 kWh	10 kW to 1 MW	5 to 165°C	COP: 0.7-1.7	Hours to days	180-310 kWh/m^3	50 years
Mechanical-thermal systems	CAES	10 to 1 000 MWh	10 to 1000 MW	up to 600°C	> 90% (thermal efficiency)	Hours to weeks	N/A	20-40 years
	LAES	MWh to GWh	10 to 300 MW	> 300°C (heat) -150°C (cold) -196°C (liquid air)	> 90% (thermal efficiency)	Hours to months	N/A	> 25 years

Notes: (1) The energy density of water TTES and UTES is based on a reference temperature at 20°C; sensible heat is not considered in the calculation of energy density of latent heat storage; (2) Energy density of solid state is determined by the operating temperature difference; energy density = heat capacity x temperature difference; (3) for "solar salt" (60% $NaNO_3$ and 40% KNO_3); (4) Only referring to calcium looping process (as opposed to other chemical looping examples); kW = kilowatt; MW = megawatt; MWh = megawatt hour; COP = coefficient of performance.

Note: N/A dennotes that no main needs were identified.

Figure I-A: Overview of TES System Parameters [8]

TES Technologies according to their categories	Technology Readiness Level		
	1-3	4-6	7-9
Most technologies already commercially available with track record of pilots and use cases:			
Sensible Heat			
Graphite			■
Ceramics, silica and sand			■
Molten Salts			■
Concrete			■
Rocks			■
Steel		■	
Underground water			■
Water			■
Large range of technical maturity, with some already commercially available and others in the R&D phase:			
Latent Heat			
Microencapsulated metals		■	
Inorganic salts and eutectic mixtures			■
Sodium		■	
Other liquid metals	■		
Molten aluminium alloy		■	
Paraffin waxes, fatty acids		■	
Salt hydrates			■
Salt-water mixtures			■
Ice			■
Liquid air		■	
Relatively nascent with most technologies in the R&D or pilot phase:			
Thermochemical Heat			
Chemical Reaction Storage		■	
Absorption		■	

Figure I-B Overview of TES Technology Readiness Level (TRL) [2]

TES Technologies according to their types	Storage duration use case			Current marketed power *
	Hours	Days	Week	MW
Most technologies able to serve intraday to multiday durations, with several able to serve up to months (e.g., water):				
Sensible Heat				
Graphite				
Ceramics, silica and sand				1-200
Molten Salts				1-300
Concrete				400
Rocks				>20
Steel				
Underground water				
Water				>100
Most technologies serve intraday to multiday durations:				
Latent Heat				
Microencapsulated metals				
Inorganic salts and eutectic mixtures				
Sodium				
Other liquid metals				
Molten aluminium alloy				0.1-300
Paraffin waxes, fatty acids				
Salt hydrates				
Salt-water mixtures				
Ice				
Liquid air				>100
Potential to serve intraday durations up to months:				
Thermochemical Heat				
Chemical Reaction Storage				
Absorption				

**The EASE Secretariat would like to highlight that the information within this table is based on preliminary research and is subject to further development.*

Figure I-C Storage durations of various TES systems [2]

Appendix II: Carbon Emission Reduction Calculations

Carbon emissions were calculated according to the following methodology and expressed in carbon dioxide equivalents.

This section draws information from The Government of Canada's Emission Factors and Reference Values and Global Warming Potentials [4, 5]

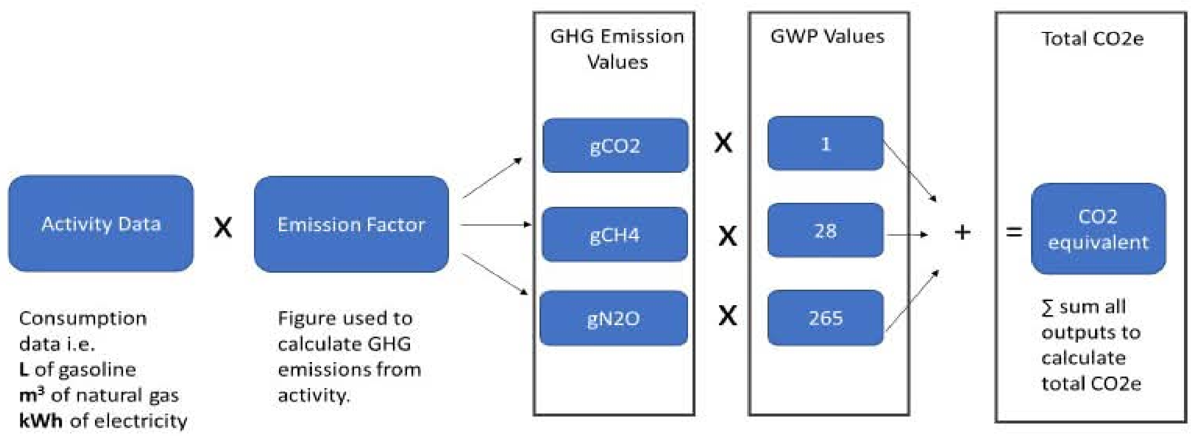

Figure 32 *General Carbon Dioxide Equivalent Calculation*

Carbon Emissions from Electricity

The carbon intensity of the 2025 grid was used for this calculation.

gCO2e from electricity (kWh) = 38 gCO_2/kWh x [Electricity Consumption (kWh)]

Carbon Emissions from Natural Gas

Part 1 – Calculating gCO2e per m^3 natural gas

First, we must calculate carbon dioxide equivalents for 1 cubic meter of natural gas

gCO_2e / m^3 natural gas = [gCO_2 /m^3 x GWP 1] + [gCH_4 /m^3 x GWP 28+ [gN_2O/m^3 x GWP 265]

= [1921 gCO_2 /m^3 x 1] + [0.037 gCH_4 /m^3 x 28] + [0.035 gN_2O/m^3 x 265]

= 1931.31 gCO_2e / m^3 natural gas

Part 2 – Calculating energy density of 1 m^3 in kWh

Now that we know the grams of carbon per m^3 of natural gas, we will calculate how many kWhs of energy is in 1 m^3 of natural gas based on the following formula:

$$\text{kWh/m}^3 \text{ natural gas} = \frac{[\text{nat. gas consumed (m}^3)] \times [\text{Calorific Value (MJ)}] \times \text{Gas Correction Factor}}{3.6 \text{ MJ/kWh}}$$

$$= \frac{1 \text{ m}^3 \times 38 \text{ MJ/m}^3 \times 1.02264}{3.6 \text{ MJ/kWh}}$$

$$= 10.79 \text{ kWh}$$

Part 3 – Calculating gCO2e per kWh of natural gas consumed

Since we know both the number of kWh and carbon emissions associated with 1 m^3 of natural gas, we can use a simple equivalency to calculate the amount of carbon emissions associated with consumption of 1 kWh of natural gas.

$$\frac{10.79 \text{ kwh}}{1 \text{ m}^3 \text{ nat gas}} = \frac{1931.31 \text{ gCO}_2\text{e}}{1 \text{ m}^3 \text{ nat gas}}$$

1 m^3 nat gas = (1931.31 gCO_2e) / 10.79 kwh

= 178.9 gCO_2e/kwh

These carbon intensities were then integrated into the *CCCM Waste Heat Storage Analysis* model, which multiplies these carbon intensities by utilities consumed by the peaking equipment (natural gas and electricity).

Carbon Emission Reduction Calculation

Emission Reductions = [CO2e Business as Usual Scenario] – [CO2e New Scenario]

Business as Usual (BAU) Scenario is defined emissions associated with the amount of energy in kWh required to meet the annual peak demand under the proposed operational standard operations. As designed, the proposed district heating network employs heat pumps with a capacity of 24MW, with about 27MW of peaking boilers. Therefore, it is assumed that under BAU, peaking demand is met by natural gas equipment. The BAU emissions are described by the following formula:

$$\text{CO2e BAU} = [\text{ kWh natural gas required } \; x\; 179\,\frac{\text{gCO2e}}{\text{kwh}}\;]$$

New Scenario describes a scenario where the peak demand (in kWh) above a threshold is met by a combination of thermal energy storage (TES) and peaking equipment. The new scenario assumes a system behaviour where a bulk of the peaking demand is met by a TES system. It is assumed that the system will be "charged" using electric heat pumps, and avoid the use of natural gas peaking boiler operation where possible. The new scenario emissions are described by the following formula:

$$\text{CO2e New Scenario} = \left[\left(\frac{\text{kWh electricity required}}{\text{COP Heat Pump}}\right) x\; 38\,\frac{\text{gCO2e}}{\text{kWh}}\right] + [\text{ kWh natural gas required (if any) x } 179\,\frac{\text{gCO2e}}{\text{kwh}}\;]$$

Appendix III: Summary Tables, Economic and Emissions Analysis

Savings Analysis

Scenario	Annual Savings (CAD)	Cost of BAU with NG Boilers (CAD)	New Scenario Total Operational Cost (CAD)
30MW, LH	-217,806.09	4,462,636.87	6,640,402.96
30MW, HH	-793,309.99	4,462,636.87	12,395,946.86
24MW, LH	-273,533.84	5,604,410.79	8,339,443.63
24MW, HH	-996,285.85	5,604,410.79	15,566,696.64

Emissions Analysis

Scenario	Emissions of NG Boilers (tCO2)	Emissions of Heat Pumps (tCO2)	Emissions Reduction (tCO2)
30MW, LT	2206.39	134.58	2071.81
30MW, HT	2206.39	0	2206.39
24MW, LT	2770.92	169.01	2601.91
24MW, HT	2770.92	0	2770.92

Financial Metrics Analysis

Scenario	NPV (CAD)	IRR (%)	Payback Period (years)
30MW, COP = 3.5	-4,287,417.66	NaN%	None
30MW, COP = 1	-9,942,350.51	NaN%	None
24MW, COP = 3.5	-5,686,807.89	NaN%	None
24MW, COP = 1	-12,786,097.04	NaN%	None

Appendix IV: Future Outlooks TES in District Heating

Future outlooks in TES development for District Heating include:

- Increased efficiency and reduced costs across all technology categories
- Increased commercial availability of low-grade PCM
- Increased research into TCM systems, with demonstration projects anticipated in the early 2030s
- Advancement in hybrid systems, such as PCM infused BTES and PTES

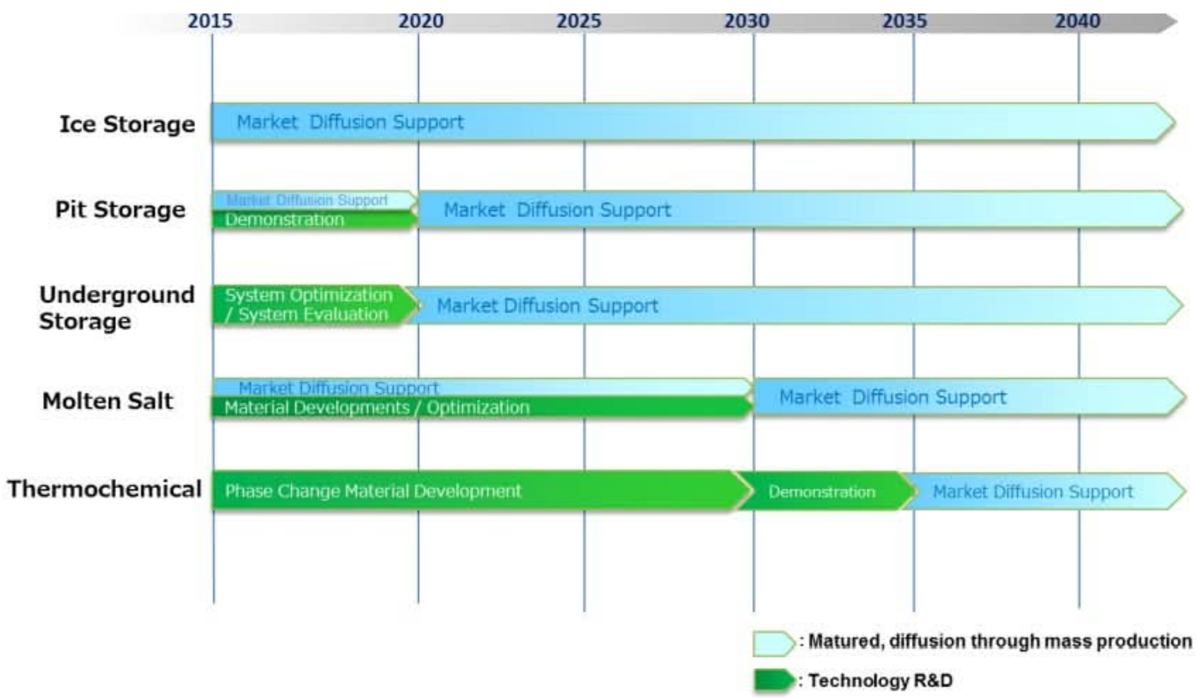

Figure IV-A ICEF Roadmap for next actions in TES development[21]

[21] Image sourced from Innovation for Cool Earth Forum: Energy Storage Roadmap (2017) https://www.icef.go.jp/wp-content/uploads/2024/02/icef2017_roadmap2.pdf

Attribute	Sensible			Latent			Thermochemical		
	2018	2030	2050	2018	2030	2050	2018	2030	2050
Cost (USD/kWh)	0.1-35	0.1-25	0.1-15	60-230	45-185	35-140	15-150	Pilot scale 15-120	Demon-stration 10-80
Efficiency (%)	55-90	65-90	75-90	> 90	> 92	> 95	50-65	(1)	
Energy density (kWh/m³)	15-80	(2)		30-90			120-250		
Lifetime (years or cycles)	10-30 years	20-30 years	> 30 years	10-20 years	> 25 years	> 30 years	15-20 years	20-25	> 30
Operating temperature (°C)	5-95	5 to > 95		0 to up to 750			15-150		

Figure IV-B Key objectives and benchmarks for innovation within TES systems for district heating [8]

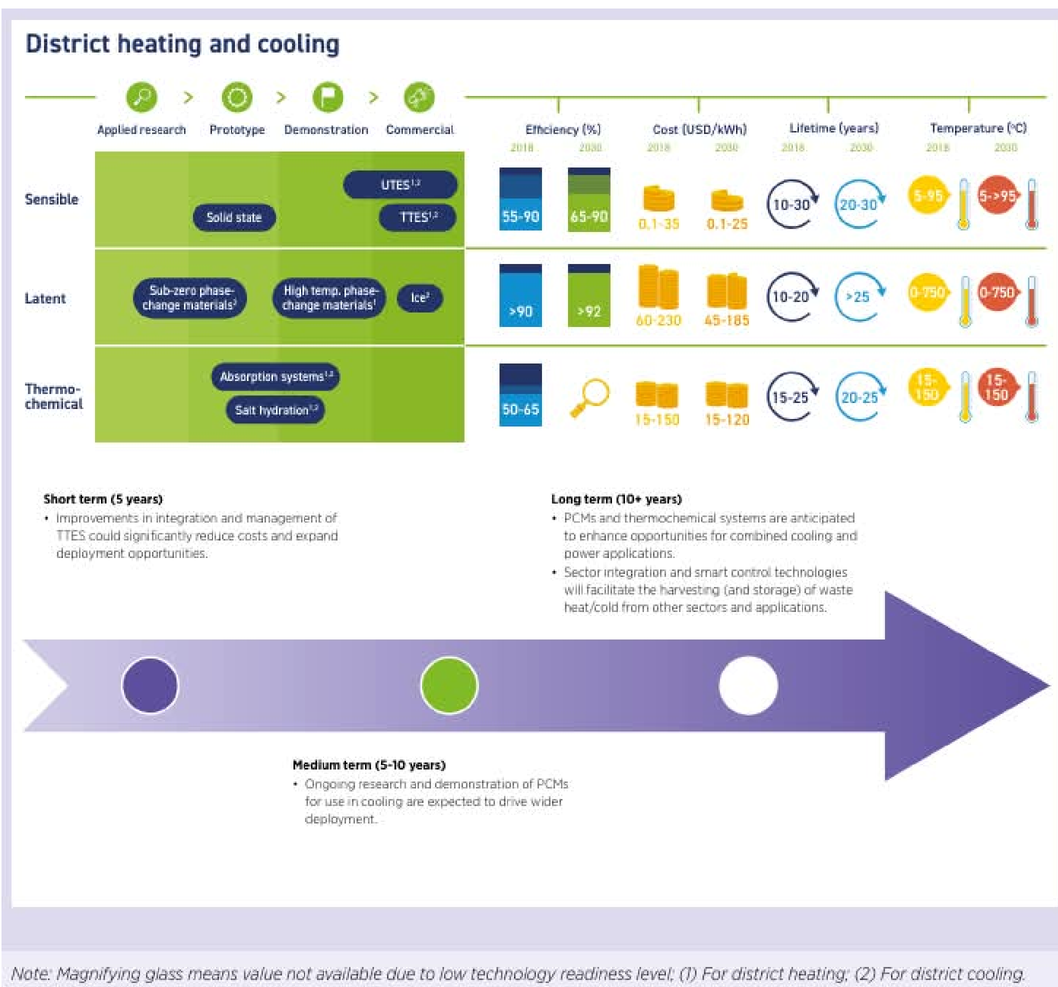

Figure IV-C Future outlooks for TES in district heating and cooling [8]