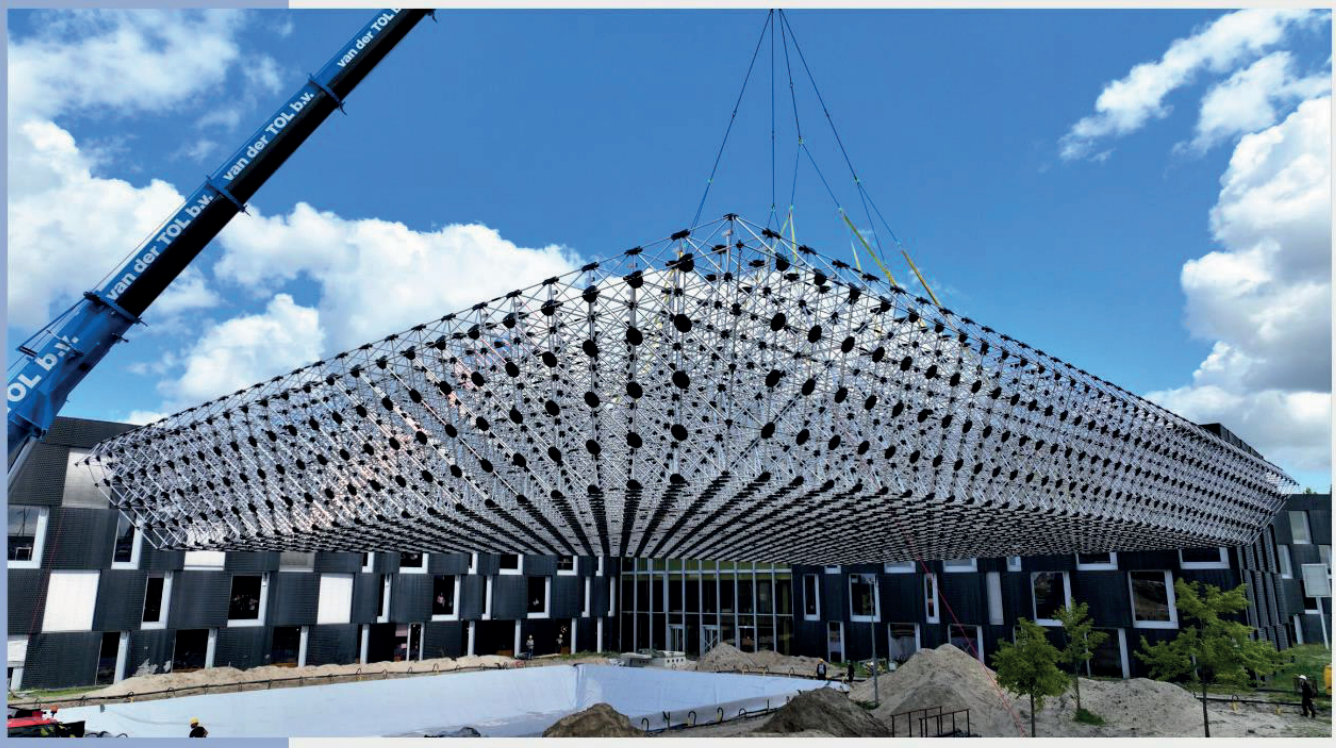
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HEAT BATTERY FOR ENERGY HUB IN ROOSENDAAL

PROJECT SUSTAINABLE ENERGY AND RESOURCE RECOVERY



2026

Authors:

Nilasree Bhattacharya, Julia Urbańska, Hannia Ríos Reyes, Zoè Correia Nunes

Cover Page Figure shows HoCoSto Heat Storage in the Groenpoort
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Summary

The Energy Trading Platform Roosendaal (ETPR) is researching the application of a thermal energy storage system in the industrial area Majoppeveld to conserve surplus energy and reduce grid congestion within the energy hub. To attain this, this study investigates the feasibility of Thermal Energy Storage (TES) systems with a capacity of 0.5 MW and 25 MWh.

First, a broad assessment of available TES was performed, including four technologies: Sensible heat storage, Latent/Phase change material. Thermochemical storage and Aquifer storage. Technical data was gathered through a literature review, combined with consultations with technology suppliers and calculations. The Multi-Criteria Analysis served as a framework to compare technologies in a structured way. Their performance over technical, environmental, spatial, operational, risk and social criteria determined a final score of performance.

The MCA scores indicate that Hocosto's underground sensible system using water is the best-fit solution for Majoppeveld. The technology combines a variety of advantages, including its high round-trip efficiency (99%), low thermal losses (0.1-0.4%/day), long storage duration (seasonal), and high technology readiness (TRL 9). Additionally, Hocosto's system has low environmental risks and a high social acceptance. Other technologies, like the thermochemical storage systems, have high energy density and long storage duration, but their suitability is limited by the lower market maturity and the complexity of implementation.

An important nuance within this study is the lack of a financial assessment in the final score. The limited economic data (CAPEX, OPEX, maintenance costs) that could be disclosed made it difficult to assess the financial feasibility. As a result of that, this study should be utilized mainly as a preliminary assessment/screening rather than a business case.

Based on the findings of the study, a recommendation to ETPR is to investigate the site-specific, geological and financial details for Hocosto's solution. Subsequently, the market development of thermochemical storage systems should be monitored, considering their attractive high energy density and negligible storage losses.

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1. Introduction

1.1 General background

The global energy system is undergoing a shift as society is moving away from the usage of fossil fuels toward the usage of renewable energy sources. This change is made to stop rising atmospheric carbon dioxide levels[1] .

The Intergovernmental Panel on Climate Change (IPCC) identifies rising CO^2 concentrations as a primary driver of global warming and climate change. To mitigate climate impact, energy systems are shifting to renewable energy sources like solar or wind power [2], [3]. However, integrating these renewables introduces two distinct challenges: energy mismatch and grid congestion. The mismatch problem arises because renewable generation is inherently weather-dependent and seasonal, creating a gap between when energy is produced and when consumers demand it. For instance, solar panels generate peak output during summer days, whereas industrial and heating demand often peak during winter months or at night. Grid congestion, on the other hand, is a localized infrastructural constraint that occurs when too many producers try to feed electricity into the network, or too many consumers draw from it, at the exact same moment, exceeding the physical capacity of the power lines. This grid overloading has become a critical bottleneck in countries with rapidly expanding renewable capacity, such as the Netherlands [4].

To address these infrastructural and timing constraints, the concept of local energy hubs has emerged, allowing producers and consumers within a specific geographic area to collaborate and manage their energy generation, consumption, and storage locally [4]. By balancing energy flows internally, these hubs can significantly reduce the peak demands placed on the national infrastructure, thereby alleviating grid congestion. A real-world example of this approach is the Majoppeveld industrial site in Roosendaal, which operates as an energy hub where manufacturing and agricultural enterprises utilize the Energy Trading Platform Roosendaal to optimize their collective energy use. In this ecosystem, the agricultural sector plays a unique role in driving energy fluctuations [5] Many of these local agricultural businesses rely heavily on intensive automated processes and seasonal activities, such as greenhouse climate control and harvest processing. This creates intense, concentrated periods of high electricity consumption, but also moments of massive excess electricity when their large-scale rooftop solar panels produce peak power during clear days when local industrial demand is low. Because the local grid cannot absorb these sudden spikes of excess agricultural generation, localized congestion occurs.

To solve these interconnected challenges, the client behind this initiative seeks to implement a robust energy management strategy that optimizes the hub's self-sufficiency. A critical question remaining for the Majoppeveld hub is how to effectively store surplus energy to solve both the seasonal mismatch and daily congestion issues. While the hub primarily generates and trades electricity, energy can also be stored in the form of heat, which aligns perfectly with the high thermal demands of both manufacturing and agricultural processes. A modular heat battery with a capacity of 0.5 MW / 25 MWh offers a compelling solution by converting excess electrical energy into thermal energy during periods of high agricultural solar production or low grid capacity. Theoretically, a thermal storage capacity of 25MWh can continuously supply a 0.5 MW heat demand for about 50 hours (approximately two days). An average Dutch household

consumes approximately 7 kWh of electricity per day (based on an average annual electricity supply of 2550 kWh)[6]. The size of the required heat battery could therefore be expressed as the equivalent of the daily energy use of 3100 to 3300 households. This stored heat can later be used directly by the industrial and agricultural processes on-site, effectively shifting the energy load away from peak times and reducing the need to draw electricity from an overloaded grid. By determining the viability of this setup, the client aims to establish a scalable model for localized grid relief. However, the technical suitability and economic feasibility of integrating such a thermal storage system within this specific hub are not yet fully understood. Consequently, this report evaluates various heat battery technologies available on the market to determine how they can best address local grid congestion and energy imbalances for the Energy Trading Platform Roosendaal.

1.2 Client

This feasibility study is conducted for the Energy Trading Platform Roosendaal (ETPR), in close collaboration with MNEXT and the municipality of Roosendaal. The EHPR functions as a localized energy community designed for the shared utilization, trading, and storage of sustainable energy at the Majoppeveld industrial estate. The platform accommodates roughly forty local manufacturing enterprises and agricultural businesses, allowing them to trade green energy directly with each other while ensuring that financial value stays within the Roosendaal region. To optimize this network, the platform utilizes a real-time monitoring system that balances local energy supply and consumer demand.

To strategically manage its ecosystem, the EHPR highlights three core goals: utilizing a local energy network to prevent regional grid congestion, aligning shifting solar production with business demand, and implementing reliable energy storage. MNEXT, acting as the Centre of Expertise for the materials and energy transition, has been tasked with evaluating whether a Thermal Energy Storage (TES) system can contribute to these goals. To deliver this technical expertise, MNEXT collaborates with the Sustainable Energy and Resource Recovery (SERR) project group, comprised of students from Avans University of Applied Sciences, who have executed this comprehensive technical and economic evaluation.

1.3 Goal

The goal of this project is to conduct comprehensive feasibility research within 20 weeks, culminating in a report. This report will evaluate the different heat battery technologies with a capacity of 0.5MW/25MWh. Additionally, the report will assess the technical, economic, environmental and social viability of implementing such a modular seasonal thermal energy storage system at the Majoppeveld Industrial Estate in Roosendaal.

1.3.1 Sub-goals

To achieve the primary goal, the project is divided into four sequential sub-goals:

- Conducting a thorough literature review of the different thermal technologies, organizing interviews with different technology suppliers, and assessing their operating mechanisms, heat sources, insulation methods, and general operational advantages or limitations.
- Conducting a technology screening phase to filter out only the viable options by directly consulting with commercial suppliers and calculating technical parameters.
- Designing a Multi-Criteria Analysis (MCA) framework to systematically rate and compare the technologies on their technical, economic, environmental, operational, risk, and social performance for the specific 0.5 MW / 25 MWh Majoppeveld installation.
- Deciding on a final operational advice and feasibility overview for the client, detailing the optimal heat battery configurations to address local energy imbalances.

1.4 Project Boundaries

This project will operate according to the defined boundaries:

This project focuses on assessing the technical and economic viability of the implementation of a heat battery at Majoppeveld Industrial Estate within the framework of the Energy Trading Platform Roosendaal (ETPR).

The scope of this project is limited to evaluating the operational efficiency of the proposed heat battery within the system.

This project does not extend to other industrial areas aside from Majoppeveld Industrial Estate and will merely focus on Thermal Energy Storage (TES) systems.

All proposed solutions must be technically applicable under the conditions of the area. This project will exclusively look at technologies that are currently available or expected to become available in the market with a high technology readiness level (TRL).

The feasibility assessment will solely rely on the data and resources available from MNEXT and suppliers.

The team will provide recommendations based on technical and economic analysis; however, the final decision regarding adoption and implementation rests with the client.

1.5 Reading Guide

This report is structured to systematically guide the reader through the development and findings of the feasibility study. Chapter 1 provides the foundational context, the client profile, the primary goals, and the established project boundaries. Chapter 2 presents a detailed technical review of the working principles, operational variations, and commercial suppliers for the four main categories of thermal energy storage: sensible, latent, thermochemical, and underground systems.

Chapter 3 describes the methodology, detailing the data collection, technology screening process, and the specific design of the 19 criteria used in the multi-criteria Analysis. Chapter 4 delivers the concrete results of the MCA, presenting the raw data, the weighting metrics, and the final scoring overview. Chapter 5 interprets these findings in the discussion, analysing the benefits, downsides, and real-world implementation constraints. Finally, Chapter 6 outlines the conclusions, followed by Chapter 7, which provides the definitive advice and long-term recommendations for the client. Supporting materials, supplier contact logs, and full calculations are compiled in the Appendix.

1. Principles of the different heat batteries and their suppliers

2.1 Sensible heat storage in Solids and Water

Sensible heat storage is an easy and economical thermal energy storage system that stores energy by raising the temperature of solid or liquid materials without changing their initial phase. The amount of thermal energy stored is determined by the material's mass, specific heat capacity, and temperature change. While liquid systems are most common in low- to medium-temperature applications such as district heating, domestic hot water, and seasonal solar thermal storage, solid systems are preferred for high-temperature applications [7], [8].

2.1.1 Principles of Operation and Commercial Suppliers

The principle of sensible heat storage in materials can be described using the fundamental heat equation:

$$Q = mC_p\Delta T$$

where

Q =stored heat energy (J)
m =mass of the storage material (Kg)
C_p =specific heat capacity of the substance (J/(kg·K)
ΔT =temperature difference (K)

This general principle applies to both solid and liquid systems, where the temperature difference directly determines how much heat is stored by the materials[7].

2.1.2 Heatwacht Heat battery

The Heatwacht system is an above-ground heat storage system (also called a powerstove) that works by converting generated renewable electrical energy into thermal energy, storing it in magnetite (a type of iron ore). The system works by using electrical energy generated by renewable sources to heat up thermal oil up to 360°C, which is then distributed with the help of integrated heat exchangers to heat up the magnetite, which stores this thermal energy for later use [9]. Additionally, the Heatwacht batteries work with storage modules. The number of storage modules is determined by the required storage capacity, the required charging and discharging power, and the connected process. For this project, the system would need only one storage module based on the 25 MWh capacity. Further information on the mass of magnetite required, along with the specific energy density per mass and volume, can be found in Table 1 below.

Table 1: Technical information about Heatwacht's heat battery

Parameter	Description	Formula	Input values	Calculated value
Total mass of magnetite required (m)	The total mass of magnetite required to store 25 MWh Thermal energy	$m = Q/(C_p \times \Delta T)$	Power/capacity(Q) = 25 MWh Specific Heat Capacity of magnetite (C_p) = 860 J/(kg·K) Temperature difference (ΔT) = 330 Kelvin (K)	317,125 kg of magnetite
Storage volume (V)	The physical volume occupied by magnetite at maximum temperature	$V = \frac{m}{\rho}$	Mass of magnetite(kg) Density of magnetite= 5170 kg/m^3	= 61.34 m^3
Specific Energy (E)	The amount of thermal energy stored per unit mass of the magnetite.	$E = \frac{Q}{m}$	Q= Stored energy (J) m = Mass of magnetite (kg)	283,800 J/kg of energy per kilogram of magnetite
Volumetric Energy Density (U_v)	The amount of thermal energy stored per unit volume of the core storage material	$U_v = \frac{E}{V}$	E = Stored energy (kWh) V = Volume of the magnetite (m³)	410 kWh/m³.

Based on Table 1 for a 25 MWh capacity, this battery would require a mass of approximately 317,125 kg (317 tonnes) of magnetite. Furthermore, the system can store about 283,800 J/kg (0.079 kWh/kg) of energy per kilogram of magnetite and has an energy density of approximately 410 kWh/m³**.** Furthermore, insulation and structural components increase the overall volume of a viable installation beyond that of the storage material itself. Based on a system surface area of 140 m² and insulation thickness of 0.1 m (rock wool equivalent), the entire system volume is anticipated to be between 80 and 120 m³, depending on the modular design of the battery.
Additionally, the insulating material (rock wool) used for the system was assumed, and the thermal performance was hypothetically calculated using the Heat Flux Conduction Formula (q):

$$Q = U \cdot \Delta T \quad \text{or} \quad Q = \frac{\Delta T}{R}$$

Where:

Q (heat loss) = Heat flux (W/m^2)
U = Overall heat transfer coefficient (W/m^2.K), which is simply U = $\frac{1}{R}$
ΔT= Temperature difference between the inside and outside (K)

The thermal resistance formula:

$$R = \frac{d}{k}$$

Where:

R = Thermal Resistance (5 m²/K/W)
d = Thickness (m)
k = Thermal Conductivity (W/m.K)

Additionally, the total heat loss of the system can be calculated. All calculations have been described in Table 2 below.

Table 2: Technical information about Heatwacht's heat battery

Parameter / Layer	Thickness d (m)	Thermal Conductivity *k* (W/m.K)	Formula	Calculated value
Rock Wool (R_{wool})	0.1	0.04	$R = \frac{d}{k}$	R_{wool} = 0.1 m/0.04 W/m. K = 2.5 m²/K/W
Stainless Steel (Inner)	0.025	14.4	$R = \frac{d}{k}$	Rst1 =0.0017 m²/K/W
Stainless Steel (Outer)	0.025	14.4	$R = \frac{d}{k}$	Rst2= 0.0017 m²/K/W
Total System Resistance (R_{total})	-	-	$R_{total} = R_{wool} + Rst_1 + Rst_2$	R_{total} = 2.50 m²/K/W
Heat Transfer Coefficient (U)	-	-	$U = \frac{1}{R}$	U = 0.4 W/ m².K
Heat Loss per Unit Area	-	-	$Q = U \cdot \Delta T$	Q = 131.9 W/m²
Heat loss per day	-	-	$Q = A *$ Loss Rate Area of the system (A)	= 443.21 kWh/day = 1.77 % /day
System efficiency (round trip)	-	-	$\eta = \left(1 - \frac{\text{Heat Loss}}{q}\right) * 100$ System Capacity (q)	η = 98.23%

Based on Table 2, the system results in an anticipated heat loss of around 443 kWh per day for the entire system. This equates to around 1.77% daily energy loss, or an efficiency of around 98.23% per day.
Overall, sensible heat storage in solids is a commercially established technology with a Technology Readiness Level (TRL) of 8 to 9. Magnetite is plentiful, non-toxic, and thermally stable, which contributes to the Heatwacht system's durability, cheap material cost, and operating safety [5] [10]. Other benefits include high efficiency, long cycle life, and modular scalability for varied applications [9]. The system has its limitations, such as moderate energy density, which leads to a relatively large physical size. It also experiences heat losses over time, meaning it is not suitable for seasonal energy storage and is instead best used for short- to medium-term cycling [9].

2.1.2.1 Existing reference project for Heatwacht

An existing project reference would be Nij Smellinghe Hospital in Drachten, which is the first hospital in the Netherlands to install two large-scale, container-sized battery units (each 8m long x 3.5m high x 3m wide) to fully replace natural gas-fired steam boilers and save approximately 285,000 m^3 of natural gas annually however, a small portion still comes from natural gas. The battery works by using electrical energy generated by installed solar panels to heat up thermal oil up to 360°C, which then distributes the high-temperature energy through integrated heat exchangers to 300 tonnes of magnetite. The system can deliver about 25 MWh of thermal storage and can store energy for days to weeks with minimum loss. At Nij Smellinghe, the stored energy is discharged as needed over an average of 3 to 4 days to supply high-temperature steam for critical hospital activities like sterilisation, in the pharmacy, kitchens, air humidification, and peak domestic hot water demands [10]. All supplier-related information can be found in Appendix 4.

2.1.3 Hocosto water Heat Battery

The Hocosto system follows the same principle as the Heatwacht's heat battery. This system is an underground thermal heat storage technology that works by storing thermal energy in water. This system has strong insulation provided by Polyisocyanurate (PIR); therefore, it is possible to store heat for long periods of time at temperatures up to 80°C. The total size of this system is decided by the energy consumption of the building or region where the battery is installed. The system is modular in design and is built with an aluminium internal structure. A key advantage of this subsurface structure is its structural integrity, where the ground layer above the battery (approximately 80cm of dirt) allows the surface area to be repurposed for alternative infrastructure, such as parking spaces or playgrounds [11].

Furthermore, a closed hydraulic circuit powers the heat battery. The water inside the storage module remains contained within the storage unit, while external heat exchangers manage the addition and removal of thermal energy. Charging the thermal storage can be fully integrated into clean energy systems, including solar collectors, industrial waste heat, photovoltaic (PV) arrays, wind energy, and heat pumps. Depending on whether the battery is set up for long-term seasonal storage or short-term daily operation, different physical dimensions, spatial footprints, and buffer capacity requirements apply[11]. Further information on technical specifications for a 25 MWh Capacity can be found in Table 3 below.

Table 3: Technical information about Hocostos's heat battery

Parameter	Calculated Value
The total mass of water required (m)	307,293 kg of water
Storage volume (V)/ Buffer Volume	320.63 m^3
Specific Energy (E)	292,880 J/kg (0.0813 kWh/kg) of energy per kilogram of water
Volumetric Energy Density (U_v)	77.97 kWh/m^3

Based on Table 3, when this system is used as a Long-Duration Energy Storage (LDES) system for seasonal cycles, the energy capacity is 77.97 kWh/m^3. This effectively reduces the required buffer volume to 320.63 m^3 and reduces the surface area footprint to 171m^2.

Table 4: Technical information about Hocostos's heat battery

Parameter	Calculated Value
Daily Energy Loss Percentage	Expected energy loss 0.1-0.4% per day
Heat Loss per Day	100 kWh/day
System Efficiency	99.6 % daily efficiency (assuming the highest value of 0.4% loss per day)

Based on Table 4, the system's thermal degradation is minimal to almost negligible. Each day, the battery loses between 0.1-0.4% of its thermal energy, so the daily efficiency of the system is 99.6%. To increase system efficiency, a portion of this heat loss can be recovered using an integrated capitation net, which is a secondary network of flowing water pipes that intercepts and retrieves escaping heat [12]. Additionally, relatively small secondary thermal losses occur during charging and discharging cycles, though these remain lower than the daily losses.

Overall, sensible heat storage in water is a commercially established technology with a Technology Readiness Level (TRL) of 8 to 9. The system uses pure water rather than synthetic chemical media, eliminating any risks related to toxic chemical leaks or groundwater contamination. Furthermore, its construction completely avoids the heavy use of concrete, and all primary building components, such as the internal aluminium framing, are fully recyclable at the end of the system's 25-year operational lifespan [11].

2.1.3.1 Existing reference project for Hocosto

Hocosto's modular subsurface seasonal storage (STES) and peak-shaving technologies are used in community grids, sports facilities, and commercial real estate.

Groenpoort District, Veenendaal-Oost (NL): Use for Smart-grid neighbourhood district heating. In cooperation with DEVO and Linthorst, Hocosto installed a major underground seasonal thermal buffer to act as a peak-shaving system for roughly 930 to 1,000 newly built homes. It functions within a localised smart-grid system to balance thermal demand, mitigate electrical net congestion, and shift solar/heat pump yields dynamically.

The Meer&Deel Eindhoven Project, Vredeoord (Eindhoven, NL): The Meer&Deel Project, in Eindhoven's Vredeoord area, is a prominent sustainable housing complex that makes use of HoCoSto's seasonal heat storage technology. The project comprises of 40 sustainable housing units linked by a common communal energy infrastructure. The system contains an 800 m^3 subsurface thermal storage unit with a capacity of around 81.2 MWh. Solar thermal collectors and photovoltaic panels mounted on rooftops provide renewable energy, which is stored during periods of excess production and then used to meet heating demand.

More such reference projects can be found on the Hocosto website, which is provided in Appendix 4, along with contact information of the supplier

2.2 Latent heat storage

Latent heat storage utilizing Phase Change Materials (PCMs) is an advanced thermal energy storage (TES) technology. It is based on the temporary storage of high-density thermal energy by utilizing the chemical material's transition between solid and liquid states [13], [14]. The technology absorbs energy during melting and releases it during solidification at a nearly constant temperature, making it possible to store large amounts of heat within a highly compact physical footprint for domestic or industrial use.

2.2.1 Principles of Operation

The phase change material heat battery works by absorbing thermal energy from an external source—such as heat pumps, solar photovoltaics, or industrial waste heat—and storing it primarily as latent heat of fusion. Unlike sensible heat systems that rely on a large temperature rise, this system stores energy as the internal PCM melts from a solid to a liquid. During discharge, cold water or a heat transfer fluid pass through the internal heat exchanger, causing the PCM to solidify and release its stored latent heat back into the system at a consistent, stable delivery temperature [15].

The modular design of these batteries allows the system configuration to be tailored to specific power and capacity requirements. To determine the performance and spatial requirements of these configurations, the core material behaviour can be quantified using the fundamental thermal storage equation:

$$Q = m \times H_l$$

Where Q represents the stored thermal energy *(J)*, m is the mass of the phase change material (kg), and H_l represents the latent heat of fusion *(J/kg)*. Based on the chemical composition of the core storage medium, the operational properties scale according to the parameters outlined in Table 5 below.

Table 5: Technical and Operational Parameters of PCM Storage Systems

Parameter	Lower Limit	Upper Limit	Unit
Specific Energy Density	144,000	324,000	J/kg
Specific Energy Density	0.04	0.09	kWh/kg
Volumetric Energy Density	60	120	kWh/m^3
Operational Lifespan	50	40,000+	Cycles/Years
Technology Readiness Level (TRL)	5 (Industrial)	9(Domestic)	Level

This dense storage mechanism allows the core material to occupy roughly one-quarter to one-third of the space required by traditional water-based storage systems. Insulation layers, structural housing, and the internal heat exchange matrices increase the overall volume of a viable installation beyond that of the storage material itself, resulting in total system footprints that remain highly compact and suitable for space-constrained installations.

Modern commercial units utilize high-performance insulation, such as vacuum insulation panels (VIPs), to minimize standing thermal losses. Because the system operates and stores energy at the specific melting point of the material rather than escalating to extreme temperatures, the thermal gradient with the surrounding environment is minimized. This targeted thermal management results in a low daily energy loss, providing high standing efficiency and making the system an exceptional solution for short- to medium-term cycling[14].

Latent heat storage in PCMs is a commercially viable technology with a Technology Readiness Level (TRL) of 8 to 9 for building climate control and domestic hot water applications, while high-temperature industrial variants sit between TRL 5 and 7. The system offers distinct advantages, including exceptional volumetric compactness, minimal standing thermal losses, a stable discharge temperature profile, and an operational lifespan exceeding 40,000 cycles (equivalent to 40 to 50 years). The system has its limitations, such as the low essential thermal conductivity of most PCMs, which requires extensive internal heat exchanger networks or graphite matrices to achieve high charge and discharge rates. It also carries a higher upfront capital cost compared to standard sensible water tanks and can suffer from subcooling or phase segregation if the material for

mulation is not properly stabilize.

2.2.2 Commercial Suppliers and Technological Variations

The exact performance of a latent heat battery depends heavily on the chemical approach chosen by the manufacturer.

Phase Change Solutions, based in Greensboro, North Carolina, focuses on fully bio-based, plant-derived fatty acids and oils under their BioPCM brand. They specialize in passive and semi-active building insulation fabrics and structural thermal mass buffers, such as their ENRG Blanket line. Their bio-based materials are non-toxic, non-corrosive, and carry an estimated 100-year operational life, eliminating the leakage risks and environmental concerns that are used to plague older organic storage mediums. [16].

Rubitherm Technologies GmbH, operating out of Berlin, Germany, provides a highly adaptable selection of macro-encapsulated components. They offer both organic paraffins, known as their RT series, and engineered inorganic salt hydrates, sold as their SP series. Rubitherm's paraffin systems are chemically inert against metal containers and demonstrate exceptional cyclic stability. While these paraffins have lower volumetric densities and need fire-retardant engineering to manage flammability risks, Rubitherm balances this by offering their inorganic SP salt series, which is completely non-flammable and provides higher volumetric capacities.[17].

Sunamp Ltd, headquartered near Edinburgh, Scotland, manufactures active domestic and commercial hot water batteries through their Thermino series. Their system relies on an inorganic salt hydrate formulation centered on Sodium Acetate Trihydrate, which they market as Plentigrade. Sunamp solves the classic degradation problems of salt hydrates by mixing a patented chemical nucleating agent into the formula, which permanently stops subcooling and phase segregation. This chemical breakthrough delivers a dense volumetric storage capacity, offering space savings up to four times greater than standard hot water cylinders while requiring zero internal maintenance over a 50-year operational life. Sunamp coordinates commercial installations and residential retrofits directly through their Scottish headquarters and global subsidiary branches[18].

All technologies suppliers contact information’s can be found in Appendix 4.

2.2.3 Existing Projects

Real-world operations demonstrate how these different material choices play out in practice.

Looking at Phase Change Solutions, their primary commercial success involves integrating ENRG Blanket systems into corporate offices across the United States. These passive installations sit quietly inside ceiling and wall cavities, acting as a thermal buffer to absorb excess heat during the day and lower HVAC energy use without relying on moving parts or liquid metals. Beyond buildings, their BioPCM transport containers are used across global pharmaceutical logistics networks to keep sensitive medication at steady ambient or sub-ambient temperatures during international transit.

Rubitherm's technology stands out in heavy industry and transport cooling. Their macro-encapsulated RT paraffin and SP salt hydrate modules are used globally in decentralized thermal storage tanks. These tanks capture low-temperature waste heat from manufacturing lines during working shifts and save it to heat the buildings overnight or during off-shift hours. In Western Europe, Rubitherm's active cooling and heating modules are built right into transport vehicles, providing precise climate control for temperature-sensitive medical and chemical deliveries.

Sunamp has focused heavily on active residential and commercial systems. Their Thermino hot water batteries are currently deployed at scale in thousands of social housing retrofits and residential developments across the United Kingdom and Europe. These compact batteries connect directly with air-

source heat pumps or local solar arrays, storing peak daytime energy so tenants can use it for space heating and hot water later in the evening. On a larger scale, Sunamp has rolled out active macro-scale modules across European commercial agriculture projects. These systems store solar photovoltaic energy during peak afternoon hours, providing immediate thermal balancing for space-constrained greenhouse and agri-business operations.

2.3 Thermochemical storage

Thermochemical energy storage (TCES) makes use of a reversible reaction in which energy is stored in the chemical bonds of a thermochemical material[19]. The endothermic reaction allows for heat to be stored, and under the right conditions the exothermic reaction releases heat again.

$$A + Energy\ (Heat) \rightleftharpoons B + C$$

The TCES system can be depicted by the equation above, in which A is the thermochemical material. The combination of the material with heat results in the splitting of the material into two components. When stored separately, heat is stored as long as needed, without any heat losses.

2.3.1 Salt hydrates in sorption-based TCES

Salt hydrate technologies in TCES has been led by Dutch spin-off Cellcius, in collaboration with the Technical University of Eindhoven (TU/E) . Cellcius utilizes potassium carbonate (K_2CO_3) and water to store heat. The salt takes part in a reversible reaction of hydration and dehydration, where salt 'hydrates' are formed, such as $K_2CO_3 \cdot 1.5H_2O$. [20]

$$K_2CO_3 + 3\ H_2O + Energy\ (Heat) \rightleftharpoons 2\ K_2CO_3 \cdot 3H_2O$$

Potassium carbonate offers a variety of advantages

- A moderate temperature is required to initiate the dehydration process. Temperatures around and below 120 °C. This implies that the drying of potassium carbonate is compatible with inputs of solar panels. Hydration processes occur at 50-70 °C, making it suitable for space heating.[21]
- Good thermal and chemical stability. Potassium carbonate shows a lower risk of unwanted liquefaction during the hydration process. The material remains solid after addition of water, which is important for effective mass-transfer (low deliquescence tendency). Delinquency is the amount of water that is absorbed by a solid material, until it actually dissolves into a liquid. Subsequently, this also reduces risks of caking, clogging or corrosion.
- This salt does not fall under rare-earth salts, and has low costs, and wide availability.
- A material energy density of 1.3-1.5 GJ/m³[20] or about 360 kWh/m³. This is generally lower than other salt hydrates, but has lower costs, and deliquescence, and higher stability and safety. The material energy density is significantly higher than that of water, about five to six times.

Table 5 illustrates the specific characteristics and performance of the salt sorption system of Cellcius. These details were obtained through an interview with Joey Aarts, postdoctoral researcher specializing in TCES, involved in the Cellcius project[21]. This data is important for interpreting the suitability of the technology for seasonal TES.

Table 5: Main Characteristics and Performance of the Celsius Salt Sorption Storage System

Characteristic	Value
Temperature of release	60-70 °C
Thermal losses due to efficiency of peripheral equipment	5%
Expected lifetime of material	20-25 years
TRL	7-8

Cellcius' system releases heat at temperatures of 60-70 °C, making it ideal for space heating. Because energy is stored chemically, there are no thermal losses due to storage, making it suitable for storage over months or years. The only loss of energy is due to conversion of heat exchangers and transport, accounting for roughly 5% of total stored energy. The salt has an expected lifetime of 20-25 years. Degradation is attributed to the salt tablets accumulating mechanic stress from water absorption and

secretion. This causes the pellets to slowly break down. The material stays usable after this, as it can be crushed and remoulded.[21]

To calculate the volumetric requirements for this system, the information of energy density is utilized in combination with formula to calculate required storage volume, in Table 6.

Table 6: Calculation of storage material volume and mass requirements for a 25 MWh K_2CO_3-based TCES system[21]

Parameter	Formula	Value
Volumetric energy density: U_v $(\frac{KWh}{m^3})$	-	**360 KWh/m³[21]**
Gravimetric/specific energy density: U_m $(\frac{KWh}{kg})$	$U_m = U_v(\frac{KWh}{m^3}) \div \rho\ (\frac{m}{V})$	360 KWh/m³ ÷ 2430 kg/m³[22] = **0.148 kWh/kg**
Required storage volume for K_2CO_3: $A_{K_2CO_3}$ (m^3)	$A_{K_2CO_3} = E\ (KWh) \div U_v\ (\frac{KWh}{m^3})$	25 000 KWh ÷ 360 KWh/m³= **69.4 m³**
Estimated required volume for complete system: A_{system} (m^3)	$A_{system} = A_{K^2CO^3}(m^3) * 2$	69.4 m³ * 2= **138.9 m³**
Required mass of medium	$m_{K_2CO_3} = A_{K^2CO^3}(m^3) * \rho\ (\frac{m}{V})$	69.4 m³ * 2430 kg/m³= **168 642 kg**

Potassium carbonate has an energy density of 360 kWh/m³ material, based on information from supplier Cellcius. a 25-MWh system would require 69.4 m³ for storage material (about the size of six sea containers). For the inclusion of peripheral equipment, approximately double that area is required, resulting in an estimated required volume of 138.9 m³ for the entire system. [21] The required mass of medium comes out to 168 tones.

Cellcius' system applies these principles, using the following technique. To charge the TCES, heat (from a heat exchanger) and dry air are combined to produce dry, hot air. This air is ventilated over the hydrated salt ($K_2CO_3 \cdot 1.5H_2O$) in the reactor. This warm air evaporates the water of the salt, drying it out, resulting in dry K_2CO_3. Lastly as byproduct, cold, wet air leaves the reactor. The charging process is schematically depicted in Figure 2**Error! Reference source not found.**.
When heat is required, the discharging process is initiated by a ventilator that blows damp air from the water reservoir into the salt reactor. As the water comes in contact with the energy-dense salt, the inverse reaction is initiated. Heat is released from the salt, into the air, which is led to houses or intended space for heating. See Figure 21 for mechanisms of discharging.



Figure 1: Charging Cellcius' TCES



Figure 2: Discharging Cellcius' TCES [33]

The technology has proven to work successfully in three demonstration projects of 70 kWh systems in Poland, France and Eindhoven. The technology currently resides at a TRL of 7 to 8. Cellcius has since March 2025 ceased business operations. The discontinuation was not caused by technical inability, but is

related to scaling issues. Scaling the current demonstration scale to a commercial scale requires investments that are currently not available.

2.3.2 Iron oxide in fuel cycle

Iron powder can be used in a fuel cycle, as applied by RIFT (Renewable Iron Fuel Technology). The circular fuel cycle is based on the combustion of iron powder to produce heat, and regeneration iron oxide inro iron using hydrogen.

To discharge the system, and release heat, iron powder is combusted in the presence of oxygen in a fluidized reactor. This yields in iron oxide and heat. This is a strongly exothermic oxidation reaction: $4Fe + 3O_2 \rightarrow 2Fe_2O_3 + Energy\ (heat)$, that yields in high temperatures released up to 1600 °C After obtaining heat from the material, the generated iron oxide must be regenerated to be able to store heat again. This is done through the addition of hydrogen in an endothermic reduction processes: $2Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$. [23] [23] RIFT regenerates the iron oxide powder in a centralized plant in Antwerp. The resulting iron is then transported back to the location of storage and discharge. The regenerated iron powder can be reused by the customer for heat storage, and is fully circular. From this mechanism, it can be concluded that Because hydrogen is a source of energy that provides the energy required to reduce iron oxide back into iron. This makes the distinction between typical TES, and the fuel cell technology.

Parameter	Formula	Value
Volumetric energy density: $U_v\ (\frac{KWh}{m^3})$	-	**6670 KWh/m3**
Gravimetric/specific energy density: $U_m\ (\frac{KWh}{kg})$	$U_m = U_v(\frac{KWh}{m^3}) \div \rho\ (\frac{m}{V})$	6670 KWh/m3 ÷ 7800 kg/m3 **0.86 kWh/kg**
Required storage volume for K_2CO_3: $A_{K_2CO_3}\ (m^3)$	$A_{K_2CO_3} = E\ (KWh) \div U_v\ (\frac{KWh}{m^3})$	25 000 KWh ÷ 6670 KWh/m3= **3.7 m3**
Required mass of medium	$m_{K_2CO_3} = E\ (KWh) \div U_m\ (\frac{KWh}{kg})$	25 000 KWh ÷ 0.86 kWh/kg = **36 764 kg**

Iron has a high energy density of 6670 kWh/m3, and 0.86 kWh/kg[24]. This would lead to a technical required mass of 36 764 kg and low volume of 3.7 m3. Through consultation with RIFT, it was revealed that in practice one module provides 4 kWh, with each module taking up a plot of 160 m2. It is currently uncertain how much space is needed for upscaling. It is important to note the difference of space requirement based on the calculations and information of supplier. The onsite system requires additional space for other reactor components, and does not account for the extremely high theoretical energy density of pure iron powder.

Table 7 depicts the values of performance, specifically for RIFT's iron technology. This information was obtained through an interview with Timo van der Laar[25]. Through this, values of material properties, temperatures and efficiencies were retrieved.

Parameter	Formula	Value
Volumetric energy density: $U_v\ (\frac{KWh}{m^3})$	-	**6670 KWh/m³**
Gravimetric/specific energy density: $U_m\ (\frac{KWh}{kg})$	$U_m = U_v(\frac{KWh}{m^3}) \div \rho\ (\frac{m}{V})$	6670 KWh/m³ ÷ 7800 kg/m³ **0.86 kWh/kg**
Required storage volume for K_2CO_3: $A_{K_2CO_3}\ (m^3)$	$A_{K_2CO_3} = E\ (KWh) \div U_v\ (\frac{KWh}{m^3})$	25 000 KWh ÷ 6670 KWh/m³= **3.7 m³**

Required mass of medium	$m_{K_2CO_3} = E\ (KWh) \div U_m\ (\frac{KWh}{kg})$	25 000 KWh ÷ 0.86 kWh/kg = **36 764 kg**

Iron has a high energy density of 6670 kWh/m^3, and 0.86 kWh/kg[24]. This would lead to a technical required mass of 36 764 kg and low volume of 3.7 m^3. Through consultation with RIFT, it was revealed that in practice one module provides 4 kWh, with each module taking up a plot of 160 m^2. It is currently uncertain how much space is needed for upscaling. It is important to note the difference of space requirement based on the calculations and information of supplier. The onsite system requires additional space for other reactor components, and does not account for the extremely high theoretical energy density of pure iron powder.

Table 7: Main Characteristics and Performance of the RIFT iron fuel cell.[24]

Characteristic	Value
Flame temperature within reactor	1400–1600 °C
Output temperature	220 °C saturated steam
Thermal losses due to efficiency of peripheral equipment per cycle	5-10%
Energy density of material	6670 KWh/m^3
Expected lifetime of material	15 years
TRL	7

RIFTs technology is currently classified at a TRL of 7[25]. The first commercially available boiler is expected to be released in 2029, raising the TRL to 9.
Challenges in the system are associated with slagging. Slagging happens when iron oxide particles melt and stick together or on surfaces. This precipitation causes blockages as well as poorer heat exchange and combustion. Practically this means the system isn't use at its full load hours, due to the risks.

2.3.3 Existing Projects

Potassium Carbonate (K_2CO_3): Cellcius

Cellcius has demonstrated the thermochemical storage technology in multiple pilot projects.

- In three locations in Eindhoven, France, and Poland, demonstration systems of approximately 70 kWh were installed. In these projects, the practical charging and discharging of potassium carbonate system was demonstrated. This demonstration showed that heat was indeed stored for long periods without thermal losses, and that heat is released at suitable temperatures for residential heating. These project also indicated. The three locations provided difference climate zones between −3 °C and 25 °C, to evaluate operation under different conditions. Subsequently, the project validate the durability of the system to a stability over 25 years. [26]
- Although the successful demonstration of the technology, since March 2025, Cellcius ceased operation. This was mainly due to financial and commercial challenges. The technology of the system did not contribute to the cease of operation.

Iron Fuel / Iron Powder: RIFT

The Iron Fuel technology has been demonstrated in multiple pilot and industrial projects. Below an overview of these projects

- In May 2023, a demonstration field was established in Helmond. This effort was realized in collaboration with Ennatuurlijk. The iron fuel boiler (1 MW) successfully supplied 500 residential homes through the local heating network. This demonstrated the reliable combustion and heat

production. The system subsequently prevented the emission of 5 tons of CO_2 emissions, a reduction of 66% compared to the previous heating system.[27]

- RIFT established a pilot regeneration plant in Arnhem, where the iron oxide powder is reduced back to iron powder, using green hydrogen.
- In March 2026, RIFT has secured a financing of €113.8 million to commercialize the technology. This funding originates from €83.1 million from PGGM fund (specifficaly the Series B investment round), and €30.7 million from the European Union Innovation Fund. RIFT will use this fund to set up the first commercial iron fuel production plant, and for the deployment of more industrial heat projects. [28]
- Moreover, the first commercial project has already been contracted with Kingspan Unidek, set for 2029. This installation will deliver 340 GWh of heat per year, reducing over one million tons of CO_2 emissions over its operational lifetime. This contract indicates the commercial implementation of RIFT's technology. [28]

2.4 Underground heat storage

2.4.1 Principle of Operation

The most prominent underground heat storage technology is Aquifer Thermal Energy Storage (ATES), which is an open natural underground technology that stores heat by circulating water between warm and cold wells within an aquifer. This technology is mainly divided into Low Temperature (LT) and High Temperature (HT) systems, where low temperature systems operate below 30ºC and are typically located in shallow aquifers, while high temperature systems operate above 50ºC.

In an ATES system, groundwater naturally has a temperature close to the outside air (around 12ºC). During the summer, cold groundwater is used to cool buildings, while extracted heat is stored through a heat exchanger for later use. During the winter, the heated groundwater (around 18ºC) can be used for heating, and as it releases heat, the groundwater cools off to around 6ºC. The cool water is then stored separately and reused for cooling during the following summer cycle. Over multiple years of operation, the aquifer gradually reaches thermal equilibrium between charging and discharging, allowing the system to achieve long term efficiency.

This seasonal cycle is enabled through a system of production and injection wells. Production wells are used to extract groundwater from either warm or cold zones depending on the seasonal demand, while injection wells return the groundwater back to the subsurface. The warm and cold wells continuously alternate between extraction and injection, facilitating an efficient seasonal cycle. In the Netherlands, ATES wells are typically installed at depths between 20 – 150 meters below surface, with the required distance between wells being determined by whether the system operates as a Low Temperature (LT) or High Temperature (HT) system. [29]

2.4.2 System Design Requirements & Feasibility

For the required 25MWh storage capacity, a series of calculations were carried out. These calculations were used to demonstrate the required aquifer volume, amount of groundwater and material involved for the size and flow rate needed to deliver 0.5MW. The formulas used, input parameters, and calculated results are shown in the following table.

Table 7. Calculation Results of ATES System.

Parameter	Description	Formula	Input values	Calculated value
Volumetric Heat Capacity (Cvol)	Heat storage capacity of the aquifer per unit volume considering both groundwater and aquifer material. (J/ m^3 *K)	$C_{vol} = \eta \cdot p_w \cdot c_w + (1-\eta) \cdot \rho_s \cdot c_s$	n=0.3 pw= 1000 kg/m^3 cw= 4184 J/kg*K ps= 1741 kg/m^3 cs= 800 J/kg*K	2.23 x 10^6 J/ m^3 *K
Required Aquifer Volume (V)	Aquifer volume required to store 25 MWh of thermal energy. (m^3)	$V = \frac{Q}{C_{vol} \cdot \Delta T}$	Q= 9 x 10^{10} J Cvol= 2.23 x 10^6 J/*K Δ T= 52K	776.1 m^3
Groundwater Mass (mw)	Mass of groundwater contained in the aquifer volume. (t)	$m_w = n \cdot V \cdot p_w$	n=0.3 V= 776.1 m^3 pw= 1000 kg/m^3	232.8 t

Sand Mass (ms)	Total mass of aquifer material (sand). (t)	$m_s = (1-\eta) \cdot V \cdot p_s$	n=0.3 V= 776.1 m^3 ps= 1741 kg/m^3	945.1 t
Mass flow rate (ṁ)	Groundwater mass flow required to deliver 0.5 MW.	$\dot{m} = \frac{P}{c_w \cdot \Delta T}$	P=500,000 W cw= 4184 J/kg*K Δ T= 52K	2.3 kg/s
Volumetric flow rate (q)	Groundwater pumping rate.	$q = \frac{\dot{m}}{p_w} \cdot 3600$	ṁ= 2.3 kg/s pw= 1000 kg/m^3	8.27 m^3/h

As seen in Table 7, the results from the previously calculations show the system would require an aquifer volume of 776 m^3. This volume contains approximately 233 tons of water and 946 tons of sand. To provide an output of 0.5 MW, the system would require a groundwater flow of 8.27 m^3/h. These calculations provide an initial indication of storage capacity and flow requirements needed for the implementation of an ATES system at Majoppeveld Industrial Estate.

The efficiency of the system is influenced by the natural insulation of the aquifer, and the loss per unit of heat depends on the surface area to volume ratio of the stored hot water.
Some benefits of this thermal energy storage technology are its ability to provide seasonal heat storage, allowing heat to be stored for longer periods of time ranging from months to years. Additionally, due to the large natural mass of aquifers, the system can achieve significantly higher storage capacities compared to other thermal energy storage technologies. However, the implementation of this technology also presents several challenges, primarily related to geological and geochemical conditions. A suitable aquifer must have adequate permeability, groundwater flow, correct depth and storage volume. Geochemical factors are also considered for the development of the system. The chemical compositions within the aquifer (groundwater, sand, rocks) can be affected by temperature and pressure variations. During the system operation, pressure changes caused by pumps may release dissolved CO_2 leading to mineral precipitations and scale build-up within the system. These deposits commonly consist of calcium carbonate, silica, and metal sulfides, which can reduce system efficiency and increase maintenance requirements.[30]

Despite the challenges, the technology is considered a mature technology with a technological readiness level (TRL) of 9, and approximately 2,000 systems are currently operating in the Netherlands, most of them are Low Temperature (LT) systems. High Temperature (HT) systems have a lower market readiness level, due to demanding geological requirements, higher thermal losses, and limited operation for large scale implementation.
However, several HT-ATES pilot and demonstration projects have been successfully implemented in the Netherlands to evaluate the technical feasibility and long-term performance of storing heat at elevated temperatures.

2.4.3 Existing HT-ATES Projects in the Netherlands

The successfully implemented High Temperature (HT) systems implemented in the Netherlands are in Monster (Westland, South Holland). This ATES system was developed for Koppert-Cress Horticulture Company. The system has been operating since 2012, and it uses the stored heat for climate control throughout the greenhouse on-site and involves solar collectors for heat capture and storage. This system involves 4 warm wells and 4 cold wells and only stores heat of >30ºC. The company was provided with a provisional pilot permit, which is being studied to learn the behaviors of heat and groundwater at relatively high temperatures in shallow aquifers. The HT-ATES pilot at Koppert Cress was developed collaboratively,

with Vyverberg Advise B.V. acting as the engineering and consultancy partner for the greenhouse energy system and project development, while Bart van Meurs Projectontwikkeling was involved in the project development and system integration.

The other successful implemented High Temperature (HT) system in the Netherlands is in Agriport, Middenmeer, which is located at one of the largest greenhouses complexes in the country. The system involves 1 warm well and 1 cold well, and 1 monitoring well and has a temperature >25ºC up to 90ºC. The project was developed to study subsurface behavior with high temperature heat storage in deep aquifers (382 meters below surface), including groundwater interactions under elevated temperatures. The main supplier for this project was Dutch Thermal Energy Storage Solutions (DTESS), a consulting company specialized in HT-ATES focused on focused on system design[31] , feasibility assessment, and implementation support. [32]

2. Methodology

This section focuses on the methodological approach used to conduct research, identify, evaluate, and select feasible thermal (heat) storage technologies for the location of Majoppeveld Industrial Estate in Roosendaal. The project approach was divided into three phases: (1) literature review, (2) technology screening, and (3) multi-criteria analysis (MCA). The scheme can be found in Appendix 1 of this report. The next subsections address each phase individually and provide more thorough explanations of each step.

3.2 Technology Screening – Phase 2

After the literature review, the technology screening phase was conducted to identify the most suitable thermal energy storage (TES) technologies for further evaluation at Majoppeveld. To achieve this, technical, economic and operational information was collected beyond initial desk research to better understand each technology's characteristics, requirements and feasibility. During this phase, suppliers were contacted and consulted to provide practical insights regarding system design, material requirements, and scalability.

During this step, commercial providers were involved directly via formal email enquiries to obtain technology-specific information and operational boundary parameters. Following initial correspondence, technical consultation meetings were scheduled with companies and their representatives. These meetings gave them a chance to go in-depth about their respective technologies, confirm sizing estimates, assess material limitations, and acquire useful knowledge about modular system design and scalability.

Then, the technologies were assessed based on other important parameters such as storage efficiency, system performance, thermal losses, scalability, technological readiness level (TRL), and geological requirements. Based on these parameters, technologies that failed to meet the screening criteria were discarded, resulting in a final selection of the most promising TES technologies for further assessment through a multi-criteria analysis.

3.3 Multi-Criteria Analysis (MCA)- Phase 3

The multi-criteria analysis (MCA) was conducted as the last methodological phase of this analysis, following the technology screening phase. The primary goal of the MCA was to help determine the most feasible technology for the Majoppeveld (0.5 MW / 25 MWh), considering technical, environmental, operational, and social aspects.

The first step of the MCA was to establish a set of evaluation criteria to systematically compare the selected thermal energy storage technologies. Given that the MCA intended to recognise the most viable technology for the Majoppeveld, the criteria were developed to address all key factors affecting technology performance and implementation. Table 8 shows the criteria points for each category.

Table 8: Overview of MCA Categories and Evaluation Criteria

Category	*Criteria(s)*	*Range/scale*	*Unit/Type*
Technical performance	1. Efficiency of the system (Round trip)	High-Moderate-Low	Percentage (%)
	2. Heat Loss per day	High-Moderate-Low	Percentage (%)
	3. System's ability to meet 0.5 MW demand	Yes-No	N/A
	4. Heat storage duration (days-weeks-months)	Days-Weeks-Months	N/A
	5. Technology readiness level (TRL) of the system	Scale 1-9	Level (1-9)
	6. Lifespan of technology	Long-Medium-Short	Years
Environmental & Regulatory requirements	7. Material use/ Material sustainability	Yes-No	N/A
	8. Subsidy availability for the system	Yes-No	€/year
	9. System's alignment with Dutch regulations	High-Low	N/A
Spatial & Implementation requirements	10.Volumetric energy density	High-Moderate-Low	m3
	11. Uncomplicated/ Easy Installation of the technology	Yes-No	N/A
	12. Feasibility	High-Moderate-Low	N/A
Risks	13. Availability of system/ technology supplier	High-Moderate-Low	N/A
	14. Risk related to high temperature/chemical leak	High-Moderate-Low	N/A
Grid Integration & Integration in Energy Hub	15. Working/Coupling with renewable peaks (solar/wind)	Yes-No	N/A
Social performance	16. Social acceptance of the system (visual impacts on landscape)	Scale 1-10	N/A

After that, raw data for each technology was acquired through theoretical calculations, literature research, and information from suppliers. Both quantitative and qualitative data were included to ensure a balanced and fair comparison. Each technology was assessed against the given criteria using a standardized 1-5 scoring system, with 1 representing extremely poor performance and 5 representing exceptional performance. This scoring approach allows for consistent comparisons of technologies with varying data types and units.

Each evaluation category was analysed with a weighting factor based on its importance to the analysis. Technical Performance received the highest weight (40%), followed by Grid Integration (17%) and Spatial Requirements (12.5%). The remaining weight was allocated to environmental, risk, and social criteria to reflect regulatory compliance, safety, and community acceptance for the Majoppeveld installation. The final scores were determined by multiplying each criterion's weighting factor by its corresponding rating. The weighted ratings were then added to calculate the overall performance score for each technology. This method ensures that the most important factors have a proportionally bigger effect on the final evaluation outcome. A detailed overview can be found in Appendix 2.

3. Results of the Multi-Criteria Analysis

The final MCA scores obtained from the weighted assessment are summarised below in Table 9.

Table 9: Results of the Multi-Criteria Analysis (MCA): Ranking and Weighted Scores of Heat Storage Technologies.

Rank	Heat battery technology	Weighted score
1	Sensible heat storage: Underground Water Heat Storage (HoCoSto)	4.54
2	Sensible heat storage: Magnetite (Heatwacht)	3.90
	Phase change material: BioPCM Phase Change Material system	
3	Underground storage: Aquifer Thermal Energy Storage	3.82
4	Thermochemical storage: K_2CO_3 system (Cellcius)	3.79
	Thermochemical storage: Iron (Fe) based system (RIFT)	
5	Phase change material: Sodium Acetate Trihydrate system (Sunamp)	3.73
6	Phase change material: Paraffin PCM system (Rubitherm)	3.32

Table 9 demonstrates the scoring and ranking of all 8 investigated technologies, based on MCA. It can be concluded that the technology that performed best is Hocosto's underground water heat storage system, which received the highest score of 4.54, indicating that it outperformed the other assessed heat battery technologies. Following this, both the magnetite sensible heat storage (Heatwacht), and BioPCM phase change material systems received a score of 3.9, indicating good performance across the given assessment criteria. The Aquifer Thermal Energy Storage (ATES) also received a high score of 3.82. Both the iron (Fe)-based thermochemical storage (RIFT), and The K_2CO_3 thermochemical system (Cellcius) received a score of 3.79. The Sodium Acetate Trihydrate PCM (Sunamp) scored moderately (3.73), while the paraffin PCM (Rubitherm) system obtained the lowest score of 3.32. The following sub-chapters provide additional information on how each technology performed against the criteria, in descending order of their final MCA ranking.

3.1 Sensible heat storage (Hocosto's water-based thermal storage battery)

The Hocosto's underground thermal storage system performs the best among all other assessed technologies in the MCA, especially across significant technical criteria such as efficiency (scoring a 5) with 99% round trip system efficiency; has a TRL of 9 (score 5), and the capacity to satisfy the 0.5 MW heat demand in Majoppeveld. One significant advantage is its seasonal heat storage capacity (scoring 5), which makes it ideal for long-term surplus heat storage. The system also performs well in material sustainability (score 5), considering the use of water as a safe and ecologically neutral thermal storage medium, and it has a low-risk profile (scoring 5), with no concerns about chemical leakage. Due to its underground installation and little visible influence, it has a high social approval (score 5). Furthermore, in the context of its implementation, the system has good feasibility (score 4) and regulatory compliance (score 4), but groundwater permitting and geographical constraints must be considered (soil suitability). It also has a prominent supplier availability (scoring 4) and good integration with renewable energy peaks (scoring 5). However, the system scored poorly in subsidy availability (score 2). The system also has a moderate lifespan (score 3) due to long-term subsurface maintenance requirements and has a daily thermal loss of 0.4% (scoring 4). For a more detailed review of the results, please look at Appendix 3.

3.2 Sensible heat storage (Heatwacht's magnetite-based thermal storage battery)

This thermal storage system demonstrates strong technical performance in terms of round-trip system efficiency of 98% (a score of 5), and it can successfully deliver the required power output of 0.5MW (a score of 5). The system has a Technology Readiness Level (TRL) of 9 (a score of 5), proving that the technology has reached commercial maturity and has been demonstrated under operational conditions, explaining its implementation in existing projects within the Netherlands as described in Chapter 2. Furthermore, the system scores well in environmental and material sustainability criteria (a score of 5), due to the use of naturally occurring magnetite, which is abundant and non-toxic in nature and has a long operational lifetime of twenty-five years. Magnetite is a chemically stable element with a density of 5,170 kg/m³; subsequently, it has minimal danger of leakage, material degradation, or toxic chemical reactions. The system's volumetric energy density is about 410 kWh/m³, enabling a compact design with an active magnetite volume of 61.34 m³. The total estimated system volume is between 80 and 120 m³, including structural components and insulation, making it suitable for integration in Majoppeveld with a moderately easy installation process. However, it scored poorly in terms of storage duration. Thermal losses are estimated at 1.77% per day, depending on insulation design and operational circumstances. This system is best suited for daily to weekly thermal storage depending on the 3heat demand within Majoppeveld. It is less appropriate for long-term or seasonal heat storage spanning several months. For a more detailed review of the results, please look at Appendix 3.

3.3 Phase change material: BioPCM Phase Change Material system

BioPCM's phase change heat storage system, which uses plant-based phase-change material, earns an overall rating of 3.90, ranking it third among the heat storage options evaluated.

This system is fully capable of meeting the required power demand of 0.5 MW and has a Technology Readiness Level (TRL) of 9, confirming that it is a technology with high availability from suppliers. The system is assessed to have high overall feasibility and has an extremely low risk of accidents related to high temperatures or chemical leaks. From an environmental and regulatory perspective, this technology has a unique sustainability profile. The material used is fully bio-based, biodegradable and non-toxic. This close link with circular economy goals and Dutch certification requirements guarantees high compliance with national regulations. Additionally, it qualifies for excellent grant opportunities, mainly through green building programs. Due to its very low impact on aesthetics, it is very popular.

Excellent social acceptance. The system is also characterized by a service life exceeding twenty-five years. The main technical advantage of this system is its thermal retention, which achieves a rating of 5 thanks to an estimated energy loss of 0% per day under standard conditions.

However, this system faces certain limitations in terms of efficiency and integration. The round-trip efficiency of the system is slightly lower, ranging between 80% and 85%, and the system only allows passive coupling with renewable energy sources such as wind and solar. The installation process is relatively complicated as it requires a thorough initial assessment before configuration.

Furthermore, the system has limitations in terms of storage time and energy density. It is only suitable for daily heat storage, which makes it unsuitable for weekly or seasonal storage lasting several months. Since its volumetric energy density is relatively low at 35.4 kWh/m³, a large volume of material is required to meet performance needs. It is typically supplied in flexible sheets with a total volume of approximately 1,000 m³, although it has been designed to be integrated into building structures to minimize impact on usable space. A more detailed overview of these results is provided in Appendix 3.

3.4 Underground storage: Aquifer Thermal Energy Storage

The Aquifer Thermal Energy Storage System had a weighted score of 3.82, ranking it overall fourth in the heat battery technologies. As seen in Appendix 3, the technology is able to meet the required 0.5MW demand and provide seasonal heat storage capacity, it has a technological readiness (TRL) of 9, with several projects running in various parts of the Netherlands and Europe and an integration with renewable energy peaks, as well as a positive social acceptance. As a result, these criteria were given a result of 5. The system scored 4 for low energy losses per day (0.1 %-0.3 %), material sustainability, its availability in subsidies and overall feasibility, displaying strong technical and practical potential. Moderate scores of 5 were distributed in alignment with Dutch regulations, since the technology aligns with the required regulations, nonetheless the implementation of the system needs to oblige with environmental protection regulations due to underground infrastructure. Additionally, a moderate score was assigned mainly to operational risks, mainly through permitting requirements, limited specialized suppliers and proper design and maintenance system management, to prevent risks. The lowest scores in the analysis were to the complexity of the installation (score of 5), to round-trip efficiency and volumetric energy density (score of 5), these scores were given as ATES requires drilling and subsurface preliminary investigations to determine the feasibility of potential implementation. In terms of efficiency, the technology upon installation has low efficiency (70%) and needs years for the efficiency to stabilized. For volumetric energy density, ATES scores relatively low as the amount of energy that can be stored per cubic meter is limited by the temperature difference and properties of the groundwater, resulting in a need for large storage volumes.

3.5 Thermochemical storage: Potassium carbonate, by Cellcius

The potassium carbonate system by Cellcius has a weighted score of 3.79, ranking on a shared fifth place (out of 6). Appendix 3 shows an overview of Cellcius' performance over the set 16 criteria. The technology performs well in categories of Energy losses per day, Heat storage duration, TRL, and the volumetric energy density. In areas of Availability of suppliers, and lifespan perform lowest.
Because the heat is used in the endothermic process, energy is stored chemically, and can be retained for months or years without self-discharge. Moreover, the technology has a good technical performance, with a high reversibility and a TRL of 7-8. The system is characterized by a high volumetric density of 300-360 kWh/m³. Potassium carbonate is recyclable and reusable, which contributes to a positive material sustainability.Challenges associated with the salt hydrate system is the lack of supplier availability. This is because of the discontinuation of Cellcius' commercial activities, which affects the feasibility of implementing this system on the Majoppeveld site. Moreover, potassium carbonate has a relatively low volumetric energy density, positive material sustainability.
Challenges associated with the salt hydrate system is the lack of supplier availability. This is because of the discontinuation of Cellcius' commercial activities, which affects the feasibility of implementing this system on the Majoppeveld site. Moreover, potassium carbonate has a relatively low volumetric energy density, compared to alternatives.

3.6 Thermochemical storage: Iron based system, RIFT

Based on the MCA results, the iron-powder system of RIFT obtains a score of 3.79. This results in a shared fourth place. The system performs best in the technical performance category, with a score of 5/5 for round-trip efficiency, low material energy losses, long storage period, TRL of 7, and a remarkably high volumetric energy density (6670 kWh/m³).
Iron is an abundant and regenerable material, and scores a 4 on material sustainability. Similar to Cellcius, this TCES supports decarbonisation and energy transition, and is eligible for several subsidies (DEI+, EIA, VEKI, and SDE++).

There are however limitation that lower the overall performance. As RIFT uses iron in a 'fuel-cell' system, the input for the endothermic reaction is not heat but hydrogen. This is reflected in the low score of feasibility, and working with renewable peaks. Although the system work well, it is not suitable for heat as charging mechanism. Subsequently, the installation and regeneration is complex. The system requires combustion and storage units, transportation to central regeneration facility for the iron oxide powder. The availability of suppliers is also limited, with only two providers active in the Netherlands. For the full overview of scores, see .. in Appendix C.

3.7 Phase change material: Sodium Acetate Trihydrate, by Sunamp

System that uses sodium acetate trihydrate as a phase change material in heat storage system, commercially known as Sunamp, received an overall rating of 3.73.

This system is fully capable of meeting the required power demand of 0.5 MW and boasts Technology Readiness Level 9 (TRL), meaning it is fully operational. The system is highly feasible and features an uncomplicated, simple installation process. It also has unique capabilities for active coupling with renewable energy technologies from solar and wind, making it highly compatible with modern green energy systems. Moreover, the Sunamp system is fully compliant with Dutch regulations, as the company's technology is already fully available in the Netherlands, and its implementation may qualify for available subsidies related to heat pump integration. From an environmental and social point of view, this technology enjoys social recognition because its compact size and clean form have virtually no negative impact on the local landscape. The use of sodium acetate trihydrate ensures that the core material is non-toxic, recyclable and fully sustainable, creating very low operational risk in the event of high temperatures or chemical leaks.

However, the system faces some limitations in terms of energy retention and long-term storage capacity. Its round-trip efficiency is 90% and daily energy losses range from 1% to 1.5%. While the system is best suited for daily or weekly heat storage, it is less suitable for long-term or seasonal storage lasting several months. Furthermore, although the system has an impressive volumetric energy density of 114 kWh/m^3 and requires an extremely efficient space of approximately 40 m^3, its service life of over twenty years is slightly shorter than some alternative technologies. A more detailed overview of these results is provided in Appendix 3.

3.8 Phase change material: Paraffin PCM system (Rubitherm)

The phase change heat storage system from Rubitherm Technologies GmbH, using paraffin, receives an overall rating of 3.32.

The system is fully capable of meeting the required power demand of 0.5 MW and is characterized by a technology readiness level (TRL) of 9, which confirms that this technology is fully available on the market. The system is assessed as highly feasible, with high availability from the supplier, and the installation process is simple and easy to implement. From a structural and environmental point of view, this technology enjoys excellent public acceptance because it is typically incorporated directly into building materials such as plasterboard, ensuring no negative impact on the surrounding landscape. It uses phase change materials (PCMs) that are highly sustainable, and the system operates with a low risk of high temperatures or chemical leaks. In addition, it complies with Dutch regulations, although there is no detailed information on dedicated financial support, which means it may only qualify for basic grants.

However, the system has significant limitations in terms of energy retention, footprint and integration. Although it has a high efficiency of 95%, it has high energy losses ranging from 3% to 5% per day. The system is designed for daily or weekly heat storage, making it unsuitable for long-term or seasonal storage. Due to its relatively low bulk energy density of 35.4 kWh/m^3, it requires a large physical area of approximately 2,000 m^2 of building material to achieve the required performance, even though it is built

into the structure itself. Moreover, the system only allows for passive coupling with renewable peaks from solar and wind energy, and has a standard operating life of twenty years. A more detailed overview of results, including all criteria from Multi-Criteria Analysis, provided in Appendix 3.

4. Discussion and limitations

This analysis had some significant limitations in terms of data availability and accessibility. One of the crucial criteria that this project wanted to assess was the economic/financial feasibility of the heat batteries. However, this was not possible due to the limited availability of cost data, as most companies consider this information commercially sensitive and therefore do not disclose it immediately. Furthermore, since heat batteries are emerging, there are very limited designated subsidies or financial support mechanisms for these systems. Additionally, hypothetical calculations had to be made for all assessed technologies in this report to estimate and compare the heat loss per day and overall round-trip system efficiencies.

For sensible heat batteries, in the case of Heatwacht's magnetite-based storage systems, the assessment relied on the assumption that rock wool was used as the insulation material, as no specific insulation data was publicly available. Additionally, based on one-on-one discussions with Heatwacht's supplier, the system is recommended for applications where heat is generated and consumed within shorter intervals of time, such as daily or weekly. The provider stated that long-term seasonal storage would be less economically viable due to increased heat losses during longer storage periods, potentially resulting in greater operational expenses. It is worth noting that although Heatwacht scored a 3.9, Heatwacht may not be the best fit for Majoppeveld due to its short-term storage constraints. Conversely, Hocosto's water-based underground storage system is considered the most feasible technology for Majoppeveld due to its ability to store heat over seasonal periods while maintaining very low thermal losses. Considering this, it is especially useful for storing surplus heat and using it during periods of increasing heat demand. Even so, its implementation depends more on site-specific constraints, such as appropriate geological conditions and groundwater permits, which may have an impact on implementation feasibility.

For latent heat storage systems data collection faced commercial barriers, as suppliers refused to share information due to their reluctance to be involved in new research projects. Technology suppliers also reported that they treat exact production and installation prices as highly confidential. Therefore, daily heat loss profiles and return loop efficiency had to be modelled using idealized material constants for sodium acetate trihydrate, paraffins, and bio-based fatty acids, assuming optimal deployment of high-performance insulation such as vacuum insulation panels (VIPs). Although these calculations indicate a stable discharge temperature profile and exceptionally high volumetric compactness, actual performance remains sensitive to unspecified chemical hazards, such as subcooling and phase segregation over thousands of cycles. From an application perspective, PCM systems suffer from exactly the same critical drawback as the magnetite Heatwacht system when it comes to Majoppeveld requirements: they are physically and economically unsuitable for long-term, seasonal storage. Because PCMs have low intrinsic thermal conductivity, scaling these systems to handle seasonal power demands requires large, cost-prohibitive internal heat exchanger networks to maintain cost-effective heat transfer rates. As a result, the technology remains largely limited to short-term, modular peak-reduction cycles.

For the thermochemical storage systems, the reliability of data is influence by the limited amount of publicly available information, compared to more mature technologies. This means that the used data has been sourced from pilot projects with shorter-term deployments.
Factors making Cellcius' system more likely for implementation in Majoppeveld are its ability to store heat seasonally, and the high material energy density (reducing the required area). The fundamental

weaknesses for application is the uncertain commercial future of Cellcius, following the discontinuation of activities.
RIFT shows strengths in ultra-high energy density, and storage duration. However, fundamental technical criteria are not met. Although the system does discharge with heat, the charging of the iron powder is not carried out by heat, but hydrogen, and is therefore not directly couplable to the solar panels. Moreover, the installation and maintenance are considered complex, as combustion, transport to local plant, regeneration, and transport back is required.
The MCA demonstrates that the TCES systems offer great technologies, with high energy density and storage duration, but also have low market availability, complexity, and uncertainty on compatibility with current requirements in Majoppeveld. Therefore both systems reflect a moderate score (3.79 out of 5) and ranking (4th out of 6).

For Underground Storage, Aquifer Thermal Energy Storage proves to be a promising technology as it is capable of providing the require demand while supplying seasonal heat storage. The technology is a mature technology with around 2,000 operational systems in the Netherlands, suggesting a high level of technical reliability and acceptance within the market. However, the technology requires complex installation structure and a series of preliminary assessments for its potential implementation. The suitability of the system can only be confirmed through hydrological assessments, analysing aquifer permeability, groundwater flow, storage volume and the depth required of each well. Furthermore, continuous monitoring is needed as the system may face geochemical factors such as mineral precipitation and well scaling. Additionally, thermal losses within the system occur due to natural groundwater movement and heat transfer around the material surrounding the aquifer, resulting in a reduction of efficiency over time.

5. Conclusion

In conclusion, this analysis achieved the goal of selecting and assessing different thermal energy storage technologies to address grid congestion and energy imbalances for the industrial location of Majoppeveld, Roosendaal. This study successfully conducted a thorough literature review of the different thermal technologies, organized interviews with different technology suppliers, and assessed their operating principles and mechanisms, as well as the general operational advantages and limitations of the systems. Furthermore, according to the designed assessment framework of the multi-criteria analysis, the sensible underground thermal storage system of Hocosto performed the best, outperforming the other selected technologies and can be considered as a feasible choice for implementation at Majoppeveld.

However, the entire assessment was made without including the financial feasibility of the thermal storage systems since information on pricing is commercially sensitive and therefore, suppliers do not want to disclose it immediately. This lack of available cost data represents a notable gap in current evaluation, as initial upfront costs, system installation cost, and maintenance costs are important factors that will directly influence the commercial viability of the final implementation. Additionally, because such emerging thermal storage batteries are still developing in the Netherlands, the exact impact of regulatory and financial subsidies is not quantified. Consequently, while the multi-criteria analysis provides a ranking based on technical, environmental, spatial, and social performance, the selected final technology remains subject to subsequent economic confirmation. Bridging this data gap through formal commercial inquiries and targeted geological surveys will be necessary to establish a complete business case for the Majoppeveld energy hub.

6. Recommendation and Advice

7.1 Recommendation

Based on the Multi-Criteria analysis, Hocosto's underground water-based thermal storage technology is recommended as the most suitable thermal storage system for implementation in Majoppeveld. This technology achieved the highest score of 4.54 and performed well across all evaluated criteria, balancing between technical performance, system efficiency, feasibility, operational safety, environmental impact, and long-term storage capability. Hocosto has a high round-trip efficiency of 99%, minimal thermal losses of 0.1-0.4% per day, and the capacity to store heat for extended periods. In addition, the technology has a Technology Readiness Level of 9, indicating that it has already been commercially verified and can be deployed with little technical concerns. However, before implementation, it is important to conduct a thorough site investigation, to investigate the underground condition of the location, space availability and permitting requirements.

7.2 Advice

Although Hocosto outperformed the other thermal storage technologies by being the most suitable for the specific conditions of Majoppeveld, it is advised to keep an eye out for further developments in thermochemical technologies, such as potassium carbonate and iron fuel systems. As described in Chapter 2 of this report, these materials have very high energy densities and almost zero storage losses since the thermal energy is stored chemically in these materials. These technologies have the potential to become compelling options for large-scale seasonal heat storage once they have reached commercial maturity.

Further research should be performed to get a thorough financial assessment of the highest-ranking technologies. The MCA provides insight into technical and environmental performance, but economic aspects were not evaluated. Performances like investment costs, operational costs, maintenance costs, subsidy availability, and energy prices strengthen the decision whether Hocosto's TES remains the best solution in Majoppeveld.

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Appendices

Appendix 1: Image of the methodological process

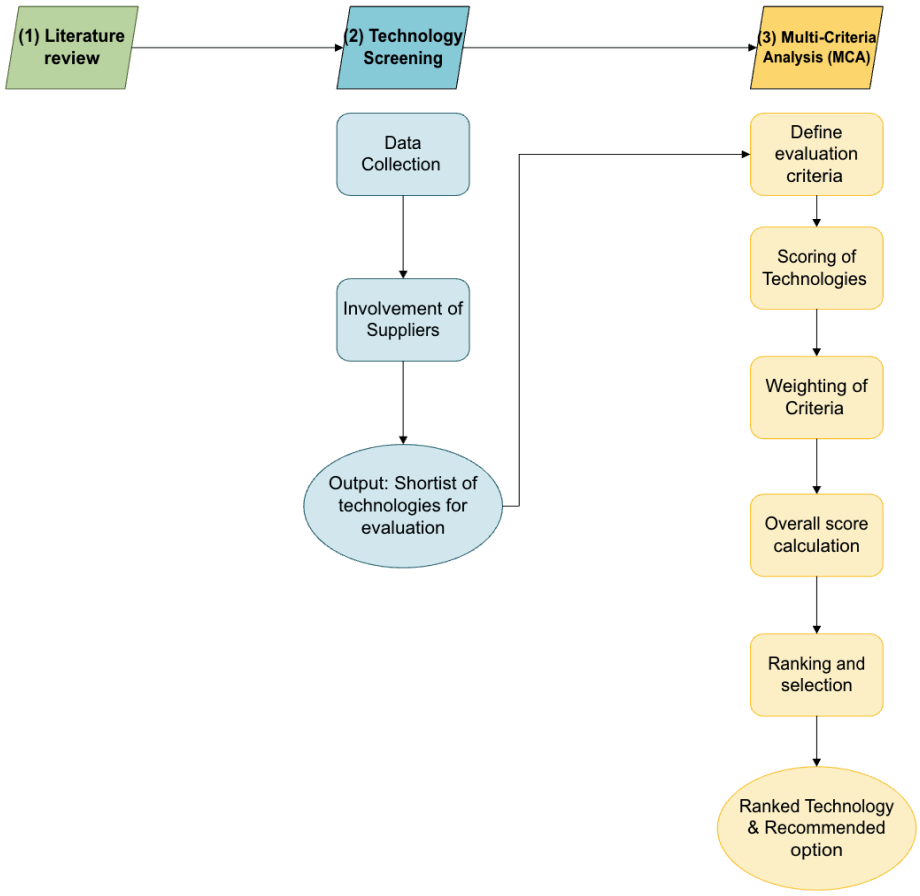


Figure 3: Visual demonstration of the methodology

Appendix 2: MCA Methodology and Calculations

Phase 1: Definition of Evaluation Criteria

The first phase of the Multi-Criteria Analysis (MCA) was to define the assessment criteria that would be utilised to determine the viability of the chosen thermal energy storage technologies for the Majoppeveld case study. The criteria were chosen to accurately reflect the project's technical, environmental, operational, economic, and social needs. To ensure a thorough evaluation, the criteria were divided into six categories: technical performance, environmental and regulatory requirements, spatial and implementation requirements, risks, grid integration and integration in energy hubs, and social performance. Each category was then broken down into criteria, yielding a total of 17 evaluation criteria. Refer to Figure 4.

Category	*Criteria(s)*	*Range/scale*	*Unit/Type*
Technical performance	1. Efficiency of the system (Round trip)	High-Moderate-Low	Percentage (%)
	2. Heat Loss per day	High-Moderate-Low	Percentage (%)
	3. System's ability to meet 0.5 MW demand	Yes-No	N/A
	4. Heat storage duration (days-weeks-months)	Days-Weeks-Months	N/A
	5. Technology readiness level (TRL) of the system	Scale 1-9	Level (1-9)
	6. Lifespan of technology	Long-Medium-Short	Years
Environmental & Regulatory requirements	7. Material use/ Material sustainability	Yes-No	N/A
	8. Subsidy availability for the system	Yes-No	€/year
	9. System's alignment with Dutch regulations	High-Low	N/A
Spatial & Implementation requirements	10.Volumetric energy density	High-Moderate-Low	m3
	11. Uncomplicated/ Easy Installation of the technology	Yes-No	N/A
	12. Feasibility	High-Moderate-Low	N/A
Risks	13. Availability of system/ technology supplier	High-Moderate-Low	N/A
	14. Risk related to high temperature/chemical leak	High-Moderate-Low	N/A
Grid Integration & Integration in Energy Hub	15. Working/Coupling with renewable peaks (solar/wind)	Yes-No	N/A
Social performance	16. Social acceptance of the system (visual impacts on landscape)	Scale 1-10	N/A

Figure 4: The formulated criteria's and their categories

Phase 2: Data Collection and Assessment

The second phase of the Multi-Criteria Analysis (MCA) was to collect data for each technology. The data was collected through a combination of literature reviews, scientific publications, supplier specifications, publicly available technical documentation, and hypothetical calculations. Quantitative data like round-trip efficiency, storage duration, space requirements, and technology lifetime were included in the analysis, followed by qualitative data, including parameters such as regulatory compliance, safety risks, and social acceptance. This method guaranteed that a consistent and balanced dataset was used to assess each technology. Refer to Figures 5,6 and 7.

Techniques	Sensible - Solid	Sensible - water	Thermochemical		PCM			Underground	Range/scale	Unit/Type
	Magnetite (Heatwacht)	Underground water heat storage (HoCoSto)	K2CO3 (Celcius)	Iron (RIFT)	Sodium acetate trihydrate (sunamp)	Rubitherm Technologirs GmbH (paraffin)	plant-based phase change material (BioPCM)	Aquifer Thermal Energy Storage		
Technical performance										
1. Efficiency of the system (system effieciency)	98%	99.6%, could be even lower due to a system that captures lost energy	efficiency of salt storage is 100. losses are due to conversion of heat exchanger and transport	90-95%	90% (high?)	95%	85-90%(High?)	70%	High-Moderate-Low	Percentage (%)
2. Energy losses per day (%)	1,77%	0,40%	0	0	~1-1.5%	3-5%	0	0.1-0.5%	High-Moderate-Low	Percentage (%)
2. System's ability to meet 0.5 MW demand	yes	Yes	Yes	yes	Yes	Yes	Yes	Yes	3	N/A
3. Heat storage duration (days-weeks-months)	daily to weekly	daily to months	months	months	daily to weekly	daily to weekly	daily	months	Days-Weeks-Months	N/A
4. Technology readiness level (TRL) of the system	9	8	7 8	7,00	9	9	9	9	Scale 1-9	Level (1-9)
5. Lifespan of technology	25+ years (long)	25 years	20-25 years	15	20+ years (long?)+	20 years	25+ years (long)	25-30 years	Long-Medium-Short	Years

Figure 5: Obtained raw data for each technology system

Environmental & Regulatory requirements										
6. Material use/ Material sustainability	Magnetite is non-toxic, abundant, recyclable steel	Uses fully recyclable materials	Circulair, after 20 yrs crushed and reused. Natural origin from mines (also poses a question about ethic sourcing)	repeatedly in a circular cycle, although some replenishment of virgin iron is required over time.	non-toxic and recyclable materials (fully sustainable)	Offers bio-based PCMs which are highly sustainable.	bio-based, biodegradable, and non-toxic material	Uses underground aquifers and groundwater (storage medium), needs additional infrestructure.	Yes-No	N/A
7. Subsidy availability for the system	ISDE DEI+ SDE++ Topsector Energie programs		Has worked with multipe big subsidies -> yielding in a high TRL. Demonstration phase is complete. Just commercial phase is difficult due to lack of investment money	multiple CAPEX subsidies (DEI, EIA, VEKI) and OPEX (SDE++)	subsidies for heat pump integration	No specific informatios, may qualify for basic subsidies	Excellent subsidy alignment, primarily through green building frameworks.	ISDE, SDE++, WIS, EIA	Yes-No	€/year
8. System's alignment with Dutch regulations	Aling with Dutch decarbonization and heat transition policies	Compliant with Dutch certification requirements	Low due to corrosive risk of material	schemes and can replace fossil-fuel-based heat generation. However, as an emerging	Fully compliant; Sunamp is active in the Dutch market,	Aligment with dutch regulations	High alignment with circular economy goals and Dutch certification requirements	Align with dutch climate goals, ATES systems require permit under Water Act or be registered in Activities Decree.	High-Low	N/A
Spacial & Implementation requirements										
9. Volumetric energy density	410 kwh/m3	77.97 kwh/m3	360 kwh/m3 (material density of) -> module 69 m3 for material, but an estimated double is needed including	6670 kwh/m3. one module of 4kwh takes up 80. 6 modules is 480m2, in case of no stacking...	114 kwh/m3. Extremly space efficient, around 40m3	35.4 kWh/m3. Low physical footprint, because it is typically embedded into building material wllboard. Requires	35.4 kWh/m3. Minimal impact on usable room space. It is usually supplied as a flexible sheet 1000m3	32.2 kWh/m3 .88.9 m2	High-Moderate-Low	m3
10. Uncomplicated/ Easy Installation of the technology	simple materials, modular construction, no underground caverns	Uses prefabricated materials so very easy installation	Moderately complex implementation due to required auxiliary systems (reactor, heat exchangers,	Installation is more complex than conventional heat storage systems due to the need for	straightforward for a professional tradesperson	Its quite difficult if is not build on prefabricated building components	Simple to install.	No, complicated installation due to premiliminary assessment	Yes-No	N/A
11. Feasibility	Technically feasible with growing commercial viability (Moderate)	High	moderate-high	still progressing towa	High	High	High	High	High-Moderate-Low	N/A

Figure 6: Obtained raw data for each technology system

Risks										
12. Availability of system/ technology supplier	High	High	Low	and also in other cou	High	High	High	High	High-Moderate-Low	N/A
13. Risk related to high temperature/chemical leak	Moderate high temperature risk but relatively low chemical/fire risk	Low	Potassiumcarbonate is corrosive in combination with water as it creates an alkaline solution, which affects metal.		Low operation Risk	Moderate risk	Extremely low risk	High, presents risk with groundwater contamination	High-Moderate-Low	N/A
Grid Integration & Integration in Energy Hub										
14. Working/Coupling with renewable peaks (solar/wind)	Highly compatible with renewable energy peak absorption (Yes)	Compatable with renewable energy peaks yes	take up depends on the heat converters. Strenght: cellcius works with modules.	suited for absorbing longer-duration renewable energy surpluses rather than short-term power fluctuations.	Exceptional active coupling	Passive coupling.	Passive coupling.	Yes	Yes-No	N/A
15. Ability to reduce heat demand in the area	Strong capability to reduce fossil-based heat demand				High impact on active grid peak reduction	Can reduce local heat demand and fossil-fuel consumption 10%-20%	Can reduce local heat demand and fossil-fuel consumption for 25%-35%	Can reduce local heat demand and fossil-fuel consumption	Scale 1-10	MWh/year
Social performance										
16. Social acceptance of the system (visual impacts on landscape)	Generally high social acceptance with limited visual and environmental impact	No visual impact on landscape after installation	just the containers		Excellent	Excellent	Excellent	High social impact due to limited visual impact	Scale 1-10	N/A

Figure 7:Obtained raw data for each technology system

Phase 3: Technology Scoring

The third phase of the Multi-Criteria Analysis (MCA) was to assess each technology against all criteria using a standardised scoring system ranging from 1 to 5. A score of 1 represented very poor performance relative to the criterion, whereas a score of 5 represented excellent performance. The relative performance of each technology in relation to the available alternatives was used to assign intermediate ratings. It was possible to evaluate many criteria, including both quantitative and qualitative indicators, inside a unified evaluation framework by using a standard scoring scale. The resulting scores formed the basis for the weighted assessment. Refer to Figures 8 and 9

	Techniques	Rating Categories	Sensible - Solid	Sensible - water	Thermochemical		PCM			Underground
			Magnetite (Heatwacht)	*Underground water heat storage (HoCoSto)*	*KCO3 (based on Cellcius)*	*Fe (based on RIFT)*	*Sodium acetate trihydrate (Sunamp)*	*paraffin (Rubitherm Technologirs GmbH)*	*plant-based phase change material (BioPCM)*	*Aquifer Thermal Energy Storage*
Technical performance	1. Efficiency of the system (round-trip)	1= <80%, 2= 80–85%, 3= 85–90%, 4= 90–95%, 5= >95%	5	5	4	5	3	4	3	1
	2. Energy losses per day (%)	5 = 0% 4= 0-0,5% 3 0,5-1,5% 2= 1,5-3 % 1=>3,0%	2	4	5	5	3	1	5	4
	3. System's ability to meet 0.5 MW demand	1= Cannot meet demand, 2= Meets <0.25 MW, 3= ~0.25 MW, 4= 0.25–0.5 MW, 5= ≥0.5 MW	5	5	4	4	5	5	5	5
	4. Heat storage duration (days-weeks-months)	1= Days, 2= Several days, 3= Weeks, 4= Several weeks, 5= Months/Seasonal	2	5	5	5	2	2	1	5
	5. Technology readiness level (TRL) of the system	1= TRL 1–2, 2= TRL 3–4 , 3= TRL 5–6, 4= TRL 7–8, 5= TRL 9	5	5	4	4	5	5	5	5
	6. Lifespan of technology	1= <=20 years, 2= 21-24 years, 3= 25–27 years, 4= 28–39 years, 5 = 30 years	3	3	2	1	2	1	4	3
Environmental & Regulatory requirements	7. Material use/ Material sustainability	1= Non-sustainable (high impact), 2=Mostly non-sustainable, 3=Moderate sustainability, 4=Mostly sustainable, 5= Sustainable (low impact)	5	5	4	4	4	4	5	4
	8. Subsidy availability for the system	1= No subsidy, 2= Very limited support, 3= Partial subsidy, 4= Moderate subsidy, 5= Strong subsidy	3	2	3	4	4	2	2	4
	9. System's alignment with Dutch regulations	1= Difficult Alignment, 2= Low alignment, 3= Moderate alignment, 4= Good alignment, 5= Strong alignment	4	4	3	4	4	3	4	3
Spatial & Implementation requirements	10. Volumetric energy density (kWh/m³)	1= < 50 2= 50 – 150, 3=150 – 350 4=350 – 1000 5= > 1000	4	3	4	5	2	1	1	1
	11. Uncomplicated/ Easy Installation of the technology	1= Highly complex, 2= complex, 3= moderate complexity, 4=relatively easy, 5= Easy/simple installation	4	5	3	2	4	2	3	2
	12. Feasibility	1= Very low feasibility, 2=Low feasibility, 3= Moderate feasability, 4= Good feasibility, 5= High feasibility	4	4	3	1	4	5	5	4

Figure 8: A score of 1-5 was assigned to each technologies

Risks	13. Availability of system/ technology supplier	1= Very limited suppliers, 2= Few suppliers, 3= Some suppliers, 4= Several suppliers, 5= Many established suppliers	4	4	2	3	3	5	5	3
	14. Risk related to high temperature/chemical leak	1=Very high risk, 2=High risk, 3= Moderate risk, 4= Low risk. 5= Very low risk	5	5	4	4	4	5	5	3
Grid Integration & Integration in Energy Hub	15. Working/Coupling with renewable peaks (solar/wind)		4	5	4	1	4	3	3	5
Social performance	16. Social acceptance of the system (visual impacts on landscape)	1 = Very low acceptance / major visual impact, 2 = Low acceptance / noticeable visual impact, 3 = Moderate acceptance / moderate visual impact,4 = Good acceptance / limited visual impact,5 = High acceptance / minimal visual impact	4	5	5	4	5	5	5	5
		Total	63,0	69,0	59,0	56,0	58,0	53,0	61,0	57,0

Figure 9: assigned to each technologies

Phase 4: Assignment of Weighting Factors

Each assessment criterion was given a weighting factor since not all of them were deemed equally significant for the Majoppeveld project. The relative significance of the criteria in accomplishing the project's goals is reflected in these weighting variables. Technical performance received the highest rating (40%), emphasising the need for dependable and effective thermal energy storage operation. The necessity of sustainability and regulatory compliance was reflected in the 15% emphasis given to Environmental and Regulatory Requirements. Spatial and Implementation Requirements accounted for 12% of the total weighting, recognising the importance of available space and installation feasibility. Risks were assigned a weighting of 10% to address operational and safety concerns. Grid Integration and Integration in Energy Hubs received 17% of the weighting due to the importance of renewable energy utilisation and heat demand balancing. Finally, Social Performance was given a 5% weighting to account for stakeholder acceptability and visual impact concerns. Individual criterion weights were dispersed within each category so that the overall weighting was 100%.

Phase 5: Calculation of Weighted Scores

After determining the ratings and weighting factors, a weighted score was determined for each criterion. This was done by multiplying the rating given to a technology by the weighting factor associated with that criterion. Consequently, factors with higher relevance had a greater impact on the final score than those with lower importance.

The weighted score for each criterion was obtained as follows:

$$\text{Weighted Score} = \text{Rating} * \text{Criterion Weight.}$$

For example, Magnetite (Heatwacht) technology achieved a 5 grade for system efficiency. Since these criteria had an 11% weighting, the weighted contribution to the final MCA score was computed as follows:

$$5 * 0.11 = 0.55$$

Similarly, the technology received a rating of 2 for daily energy loss(%). With a weighting of 11%, this criterion contributed:

$$2 * 0.11 = 0.22$$

This calculation was repeated for every criterion in the assessment matrix. The final MCA score for each technology was determined by summing all weighted criterion scores. The resulting value represents the overall performance of the technology while accounting for the relative importance of each evaluation criterion, refer to Figure 10

For example, the final score for the Magnetite (Heatwacht) technology was determined by summing all individual weighted criterion scores. Refer to Figure 10 The same procedure was applied to all other technologies included in the assessment.

Category	Criteria	*Assigned weight per category*	Weight	Sensible - Solid	Sensible - water
				Magnetite (Heatwacht)	*Underground water heat storage (HoCoSto)*
Technical performance	1. Efficiency of the system (round trip efficiency %)	50%	11,0%	0,55	0,55
	2. Energy losses per day (%)		11,0%	0,22	0,44
	3. System's ability to meet 0.5 MW demand		7,0%	0,35	0,35
	4. Heat storage duration (days-weeks-months)		8,0%	0,16	0,40
	5. Technology readiness level (TRL) of the system		7,0%	0,35	0,35
	6. Lifespan of technology		6,0%	0,18	0,18
	7. Material use/ Material sustainability	16,0%	8,0%	0,40	0,40
	8. Subsidy availability for the system		4,0%	0,12	0,08
	9. System's alignment with Dutch regulations		4,0%	0,16	0,16
Spatial & Implementation requirements	10. Volumetric energy density (kWh/m³)	12,0%	7,0%	0,28	0,35
	11. Uncomplicated/ Easy Installation of the technology		3,0%	0,12	0,15
	12. Feasibility		2,0%	0,08	0,08
Risks	13. Availability of system/ technology supplier	10%	5,0%	0,20	0,20
	14. Risk related to high temperature/chemical leak		5,0%	0,25	0,25
Grid Integration & Integration in Energy Hub	15. Working/Coupling with renewable peaks (solar/wind)	7%	7,0%	0,28	0,35
Social performance	16. Social acceptance of the system (visual impacts on landscape)	5%	5,0%	0,20	0,25
Total score		100%	100%	3,90	4,54

Figure 10: Weighting of the criterias

Phase 7: Technology Ranking

After calculating the final MCA scores, the technologies were ranked from highest to lowest score. The technology with the highest overall score was deemed the most suitable option for the Majoppeveld application based on the selected criteria and weighting factors. Based on the results, Underground Water Heat Storage (HoCoSto) achieved the highest score of 4.5, followed by Magnetite (Heatwacht) with 3.9 and Aquifer Thermal Energy Storage with 3.8. These technologies demonstrated the best overall balance between technical performance, environmental considerations, implementation feasibility, risk profile, grid integration potential, and social acceptance. Refer to Figure 11 for all the individual values.

Criteria	*Assigned weight per category*	Weight	Sensible - Solid	Sensible - water	Thermochemical		PCM			Underground
			Magnetite (Heatwacht)	*Underground water heat storage (HoCoSto)*	*CaCO3*	*Fe (based on RIFT)*	*Sodium acetate trihydrate (Sunamp)*	*paraffin (Rubitherm Technologirs GmbH)*	*plant-based phase change material (BioPCM)*	*Aquifer Thermal Energy Storage*
1. Efficiency of the system (round trip efficiency %)	50%	11,0%	0,55	0,55	0,44	0,55	0,33	0,44	0,33	0,11
2. Energy losses per day (%)		11,0%	0,22	0,44	0,55	0,55	0,33	0,11	0,55	0,44
3. System's ability to meet 0.5 MW demand		7,0%	0,35	0,35	0,28	0,28	0,35	0,35	0,35	0,35
4. Heat storage duration (days-weeks-months)		8,0%	0,16	0,40	0,40	0,40	0,16	0,16	0,08	0,40
5. Technology readiness level (TRL) of the system		7,0%	0,35	0,35	0,28	0,28	0,35	0,35	0,35	0,35
6. Lifespan of technology		6,0%	0,18	0,18	0,12	0,06	0,12	0,06	0,24	0,18
7. Material use/ Material sustainability	16,0%	8,0%	0,40	0,40	0,32	0,32	0,32	0,32	0,40	0,32
8. Subsidy availability for the system		4,0%	0,12	0,08	0,12	0,16	0,16	0,08	0,08	0,16
9. System's alignment with Dutch regulations		4,0%	0,16	0,16	0,12	0,16	0,16	0,12	0,16	0,12
10. Volumetric energy density (kWh/m³)	12,0%	7,0%	0,28	0,35	0,12	0,35	0,35	0,21	0,21	0,35
11. Uncomplicated/ Easy Installation of the technology		3,0%	0,12	0,15	0,06	0,06	0,12	0,06	0,09	0,06
12. Feasibility		2,0%	0,08	0,08	0,15	0,02	0,10	0,10	0,10	0,08
13. Availability of system/ technology supplier	10%	5,0%	0,20	0,20	0,10	0,15	0,15	0,25	0,25	0,15
14. Risk related to high temperature/chemical leak		5,0%	0,25	0,25	0,20	0,20	0,20	0,25	0,25	0,15
15. Working/Coupling with renewable peaks (solar/wind)	7%	7,0%	0,28	0,35	0,28	0,07	0,28	0,21	0,21	0,35
16. Social acceptance of the system (visual impacts on landscape)	5%	5,0%	0,20	0,25	0,25	0,20	0,25	0,25	0,25	0,25
Total score	100%	100%	3,90	4,54	3,79	3,81	3,73	3,32	3,90	3,82

Figure 11: Final results of weighting

Appendix 3: MCA results

Sensible heat – Underground Water storage, by HoCoSto Score: 4.54 Rank 1		
Score (high to low)	**Criteria in category**	**Explanation**
5	Technical performance: Efficiency of the system	This system has a high system efficiency at 99%, hence it scored a 5
	Technical performance: System's ability to meet 0.5 MW demand	This system can successfully deliver a heat output of 0.5 MW, hence it scored a 5
	Technical performance: Heat storage duration	The system can store thermal energy for months to seasonal timescales, hence it scored a 5
	Technical performance: Technology readiness level (TRL)	This battery is readily available in the market for use, therefore it has a high TRL level of 9, hence it scored a 5
	Spatial & Implementation requirements: Uncomplicated/Easy installation	Although subsurface conditions must be assessed, the system is based on known underground water storage techniques and drilling practice making installation easy, hence it scored a 5
	Risks: Risks related to high temperature/chemical leak	The system uses water to store heat, which is non-toxic and chemically stable, reducing risks with hazardous leaks or chemical degradation, hence it scored a 5
	Environmental & Regulatory requirements: Material use/ Material sustainability	Water is environmentally neutral resource, and the system has a low environmental footprint and is recyclable making it highly sustainable in material usage, hence it scored a 5
	Grid Integration & Integration in Energy Hub: Working/coupling with renewable peaks	The system is compatible with renewable energy integration, particularly for absorbing surplus wind and solar energy over seasonal cycles, supporting long-term energy balancing, , hence it scored a 5
	Social performance: Social acceptance of the system	Since its is an underground system, no infrastructure is visible, so system has minimal visual impact and therefore high social acceptance, hence it scored a 5
4	Technical performance: Energy losses per day (%)	The system has a heat loss of 0.4% per day but has a captivity net to recover some of the lost heat, hence it scored a 4
	Environmental & Regulatory requirements: System's alignment with Dutch regulations	Follows Dutch energy and environmental regulations, but requires permitting for groundwater use, subsurface installation, and spatial planning approval making regulation a bit complex, hence it scored a 4
	Risks: Availability of system/technology supplier	Hocosto is a well known thermal energy storage supplier within the Netherlands and can be easily contacted, hence it scored a 4
	Spatial & Implementation requirements: Feasibility	This system is highly feasible due to proven implementations in the Netherlands, but feasibility also depends on local geological conditions such as soil suitability, hence it scored a 4
3	Technical performance: Lifespan of the technology	This system has a operational lifespan of around 25 years, but ther e are long-term effects like material degradation and maintenance requirements especially because its is located underground, hence it scored a 3
	Spatial & Implementation requirements: Volumetric energy density	The system has a relatively low volumetric energy density (63 kWh/m^3), hence it scored a 3
2	Environmental & Regulatory requirements: Subsidy availability	No known subsidy availability, hence hence it scored a 2

Sensible heat – magnetite-based thermal storage (Heatwacht) Score: 3.90 Rank 2		
Score (high to low)	**Criteria in category**	**Explanation**
5	Technical performance: Efficiency of the system	Heatwacht's battery using magnetite for storing heat has a high system efficiency at 98%, hence it scored a 5
	Technical performance: Technology readiness level (TRL)	This battery is readily available in the market for use, therefore it has a high TRL level of 9, hence it scored a 5
	Technical performance: System's ability to meet 0.5 MW demand	Heatwacht's battery can successfully deliver a heat output of 0.5 MW, hence it scored a 5
	Environmental & Regulatory requirements: Material use/ Material sustainability	Magnetite is a naturally occuring, abundant, and environmentally sustainable material, hence it scored a 5
	Risks: Risks related to high temperature/chemical leak	Magnetite is a naturally occurring, abundant, non-toxic and environmentally sustainable material, hence it scored a 5.
4	Environmental & Regulatory requirements: System's alignment with Dutch regulations	The system shows good alignment with Dutch regulatory frameworks, although permitting and spatial planning requirements may still require moderate effort, hence it scored a 4.
	Spatial & Implementation requirements: Volumetric energy density	The system has a high energy density of 410 kWh/m^3, allowing compact storage design, hence it scored a 4.
	Spatial & Implementation requirements: Uncomplicated/Easy installation	Installation is relatively easy but requires monitoring and labour work , hence it scored a 4.
	Spatial & Implementation requirements: Feasibility	This system is technically and operationally feasible for installment in community heating applications, hence it scored a 4.
	Grid Integration & Integration in Energy Hub: Working/coupling with renewable peaks	This system is easily compatible with renewable energy sources, hence it scored a 4
	Risks: Availability of system/technology supplier	The supplier is available and is based in the Netherlnads, , hence it scored a 4
	Social performance: Social acceptance of the system	The system has limited visual impact and can be well accepted at Majoppeveld, hence it scored a 4
3	Technical performance: Lifespan of the battery	The lifespan of the technology is 25 years (considered excluding repair and replacement of individual elements of the battery), hence it scored a 3
	Environmental & Regulatory requirements: Subsidy availability	Subsidy support is moderate because it is a developing technology, hence it scored a 3
2	Technical performance: Heat storage duration (days-weeks-months)	The system can store heat from days to weeks. Storing heat for months is not advised, hence it scored a 2
	Technical performance: Energy losses per day (%)	This system has a 1.77% per day heat loss, hence it scored a 2

Phase Change Heat Storage – plant-based phase change material (BioPCM) Score: 3.90 Rank 2		
Score (high to low)	**Criteria in category**	**Explanation**
5	Energy losses per day (%)	Has energy loss of 0% per day
	System's ability to meet 0.5 MW demand	System meets the 0.5 MW demand
	Technology readiness level (TRL) of the system	Has TRL of 9
	Material use/ Material sustainability	Material is: bio-based, biodegradable, and non-toxic.
	Feasibility	Has high feasibility,
	Availability of system/ technology supplier	High availability of the system
	Risk related to high temperature/chemical leak	Extremely low risk
	Social acceptance of the system (visual impacts on landscape)	Good social acceptance due to low visual impact
4	Lifespan of technology	Lifespan of technology of 25+ years.
	Subsidy availability for the system	Excellent subsidy alignment, primarily through green building frameworks.
3	Efficiency of the system (round-trip)	Efficiency of 85-80%
	System's alignment with Dutch regulations	High alignment with circular economy goals and Dutch certification requirements
	Uncomplicated/ Easy Installation of the technology	Technology has complicated installation due to preliminary assessment
	Working/Coupling with renewable peaks (solar/wind)	Passive coupling with renewable energy sources (wind/solar energy)
1	Heat storage duration (days-weeks-months)	Heat can be stored daily.
	Volumetric energy density (kWh/m^3)	35.4 kWh/m3. Minimal impact on usable room space. It is usually supplied as a flexible sheet 1000m3

Underground Storage: Aquifer Thermal Energy Storage Score: 3.82 Rank 3		
Score (high to low)	**Criteria in category**	**Explanation**
5	Technical Performance: 3. System's ability to meet 0.5MW demand	The technology can meet the 0.5MW demand and higher capacities
	Technical Performance: 4. Heat Storage Duration	The technology sustains a storage of several months (through seasons)
	Technical Performance: 5. TRL	Has a technological readiness of 9, several ATES systems are available in the market.
	Grid Integration and Integration in Energy Hub: 15. Working/Coupling with renewable peaks	The technology can store heat or cold during renewable energy peaks, help the demand while increase use of solar and wind energy.
	Social Performance: 16. Social acceptance of the system (visual impact on landscape)	It's highly accepted due to the main infrastructure of the system being underground, minimizing the visual impact.
4	Technical Performance: 2. Energy losses per day (%)	Has energy losses of 0.1% to 0.3% per day.
	Environmental and Regulatory Requirements: 7. Material Use/Material Sustainability	The technology relies mainly on natural underground aquifers, but well construction, pipes and heat pumps are required
	Environmental and Regulatory Requirements: 8. Subsidy availability for the system	The technology is supported by several Dutch sustainable incentives, although depends on project scale size and location.
	Spatial & Implementation Requirements: 12. Feasibility	The technology is relatively space efficient and can be implemented in industrial areas.
3	Technical Performance: 6. Lifespan of the Technology	The technology has a known lifespan to be around 20-25 years.
	Environmental and Regulatory Requirements: 9. System's alignment with Dutch regulations	Aligns with Dutch regulations, however implementation requires permits and compliance with groundwater protection regulations
	Risks: 13. Availability of system/ technology supplier	Suppliers are available in the Netherlands, but specialized companies are relatively limited.
	Risks: 14. Risk related to high temperature/chemical leak	The technology presents low safety risks, nonetheless groundwater contamination and system malfunction can occur if the system is not designed or managed properly
2	Spatial & Implementation Requirements: 11. Uncomplicated/ Easy Installation of the technology	Complex Installation due to required drilling and subsurface investigations.
1	Technical Performance: 1. Efficiency of the system (round-trip)	The technology has a initial efficiency of 70%, making it not sufficient. Throughout the years, the system stabilizes into higher efficiencies.
	Spatial & Implementation Requirements: 10. Volumetric energy density (kWh/m^3)	The technology has a low volumetric energy density compared to other technologies, requires large underground volumes to store significant amounts of thermal energy.

Thermochemical heat storage – Iron, by RIFT Score: 3.79 Rank 4		
Score (high to low)	**Criteria in category**	**Explanation**
5	1. Efficiency of the system (round-trip)	Thermal conversion efficiency of 90 to 95% per single round-trip.
	2. Energy losses per day (%)	Energy is stored chemically, in iron powder. Results in virtually no losses during long storage periods.
	4. Heat storage duration (days-weeks-months)	Due to high energy retention, suitable for seasonal storage without degradation.
	10. Volumetric energy density (kWh/m^3)	Very high energy density (6670 kWh/m^3), strongly reducing required storage area.
4	5. Technology readiness level (TRL) of the system	High TRL (7-8), as project has been successfully demonstrated.
	7. Material use/ Material sustainability	Iron is an abundant, regeneratable material. Requires hydrogen for regeneration.
	8. Subsidy availability for the system	Makes use of multiple Dutch subsidies, including DEI+, EIA, VEKI and SDE++.
	9. System's alignment with Dutch regulations	Aligns with, and support Durch goals of energy transition and decarbonisation.
	3. System's ability to meet 0.5 MW demand	Capable of delivering a heat output of 0.5 MW. Technology is traditionally designed for larger industrial application.
	14. Risk related to high temperature/chemical leak	High temperatures during incineration, but are contained under closed reactor system. No significant risks of chemical leakage.
	16. Social acceptance of the system (visual impacts on landscape)	Container modules, with limited visual impact. Intervention of trucks for transport of iron oxide powder.
2	11. Uncomplicated/ Easy Installation of the technology	Complication of installation is affected by the need for combustion units, storage units, transportation and regeneration of material.
	13. Availability of system/ technology supplier	Supplier availability is established, but still relatively limited, with approximately two suppliers in The Netherlands.
1	12. Feasibility	Technology is feasible, but the deployment of the system depends on the use of hydrogen, and not heat or electricity. Therefore not suitable for Majoppeveld.
	6. Lifespan of technology	Operational lifetime of approximately 15 years. Relatively low compared to other TES systems.
	15. Working/Coupling with renewable peaks (solar/wind)	System is not designed to work with excess electricity (or heat) from solar panels.

Thermochemical heat storage – Salt (calcium carbonate), by Cellcius Score: 3.79 Rank 4		
Score (high to low)	**Criteria in category**	**Explanation**
5	2. Energy losses per day (%)	As energy is stored in chemical bonds, and not in temperature, virtually no self-discharge or heat losses over time.
	4. Heat storage duration (days-weeks-months)	Suitable for storage over months, seasonally, or even years.
	16. Social acceptance of the system (visual impacts on landscape)	Container modules, with limited visual impact.
4	1. Efficiency of the system (round-trip)	Cellcius indicates that only efficiency losses are due to conversion of auxiliary equipment, and account for approximately 5% per round-trip.
	3. System's ability to meet 0.5 MW demand	Is a modular design that allows scaling, to meet a demand of 0.5 MW
	5. Technology readiness level (TRL) of the system	Technology has been demonstrated successfully in multiple pilot project,SSSS with a TRL of 7-8.
	7. Material use/ Material sustainability	Potassium carbonate is an abundant material, reusable, and can be reprocessed after degradation.
	10. Volumetric energy density (kWh/m^3)	A higher energy density compared to sensible and latent systems, approximately 300-360 kWh/m^3.
	15. Working/Coupling with renewable peaks (solar/wind)	Is well suited for storing surplus energy.
	14. Risk related to high temperature/chemical leak	Potassium carbonate can form a mildly corrosive alkaline solution when combined with water.
3	8. Subsidy availability for the system	Cellcius received support trough several innovation funds, but has now a lack of funding to launch to commercial scale.
	11. Uncomplicated/ Easy Installation of the technology	Moderate installation complexity: requires reactors, heat exchangers, vaporizers and controllers.
	9. System's alignment with Dutch regulations	Supports the Dutch goal towards heat transition. Requires
	12. Feasibility	Has technically been proven, and is suitable for space heating. Commercial application however remains limited.
2	6. Lifespan of technology	Material lifetime of 20 to 25 years.
	13. Availability of system/ technology supplier	Supplier availability is currently low, due to discontinuation of Cellcius' activity.

Phase Change Heat Storage – Sodium acetate trihydrate (Sunamp) Score: 3.73 Rank 5		
Score (high to low)	**Criteria in category**	**Explanation**
5	System's ability to meet 0.5 MW demand	Technology is fully able to meet demand of 0.5 MW
	Technology readiness level (TRL) of the system	Technologies Readiness level is 9. It's fully available on a market.
	Feasibility	Technology is assessed to have high feasibility.
	Social acceptance of the system (visual impacts on landscape)	Due to it's size and form, it is assessed to have excellent acceptance. It not affects landscape much.
4	Material use/ Material sustainability	Because it uses sodium acetate trihydrate it was assessed that material is non-toxic and recyclable, which also aligned that it's fully sustainable.
	Subsidy availability for the system	Available subsidies for heat pump integration
	System's alignment with Dutch regulations	Fully compliant; Sunamp is active in the Dutch market,
	Uncomplicated/ Easy Installation of the technology	Installation is straightforward for a professional tradesperson
	Risk related to high temperature/chemical leak	There is low operation risk
	Working/Coupling with renewable peaks (solar/wind)	Exceptional active coupling
3	Efficiency of the system (round-trip)	Efficiency is 90%.
	Energy losses per day (%)	Daily this system looses around 1-1.5% of energy
	Availability of system/ technology supplier	Readily available
2	Heat storage duration (days-weeks-months)	Stores heat daily to weekly.
	Lifespan of technology	Technologies lifespan is 20+ years
	Volumetric energy density (kWh/m^3)	114 kwh/m3. Extremely space efficient, around 40m3

Phase Change Heat Storage – paraffin (Rubitherm Technologirs GmbH) Score: 3.32 Rank 6		
Score (high to low)	**Criteria in category**	**Explanation**
5	System's ability to meet 0.5 MW demand	Meets dement for 0.5 MW
	Technology readiness level (TRL) of the system	Technologies Readiness level is 9. It's fully available on a market.
	Feasibility	Technology is assessed to have high feasibility.
	Risk related to high temperature/chemical leak	There is low operation risk
	Social acceptance of the system (visual impacts on landscape)	Technology is incorporated into building
4	Efficiency of the system (round-trip)	Has an efficiency of 95%
	Material use/ Material sustainability	Offers bio-based PCMs which are highly sustainable.
3	System's alignment with Dutch regulations	corresponds to the regulations in the Netherlands
	Availability of system/ technology supplier	High availability of the system
	Working/Coupling with renewable peaks (solar/wind)	Passive coupling.
2	Heat storage duration (days-weeks-months)	daily to weekly
	Subsidy availability for the system	No specific information, may qualify for basic subsidies
	Uncomplicated/ Easy Installation of the technology	simple to instal
1	Energy losses per day (%)	Loss of 3-5% of energy per day
	Lifespan of technology	20 years
	Volumetric energy density (kWh/m^3)	35.4 kWh/m3. Low physical footprint, because it is typically embedded into building material wllboard. Requires around 2000 m2

Appendix 4: Supplier Contact Information

1. Sensible Heat Storage

1.1 Supplier: Heatwacht

Heatwacht Holding B.V.: Industrial solid-medium (magnetite) thermal energy storage systems.

Address: Scholtensteeg 1, 8042 PS Zwolle, Netherlands
General Email: info@heatwacht.nl
Key Contact: Martin Rijnen (martin@heatwacht.nl)
Chamber of Commerce (KvK) Number: 78759285

1.2 Supplier: Hocosto

HoCoSto Renewables B.V.: Subsurface modular water-medium thermal storage and seasonal LDES systems.

Address: de Ambachten 14, 4881 XZ Zundert, Netherlands
Email: info@hocosto.com
Website: https://hocosto.com
Chamber of Commerce (KvK): 89068866
Main Products: Seasonal Thermal Energy Storage (STES), underground heat batteries, district heating storage systems, and thermal energy management solutions.

2. Thermochemical energy storage

2.1 Supplier: Cellcius

Former headquarters: Eindhoven, North-Brabant, Netherlands.
Website: https://www.cellcius.com
Key contact: Joey Aarts (PhD Researcher at TU/e, and involved in the Cellcius project)
Main applications/product: Seasonal Thermochemical Energy Storage for residential and district heating.
Current status: Cellcius had discontinued operation since March 2025, due to financial and scaling challenges. Technology remains technically validated.

2.2 Supplier: RIFT

Headquarter: Helmond, North-Brabant, Netherlands.
Website: https://www.ironfueltechnology.com
Key contact: Timo van der Laar
General contact: info@ironfueltechnology.com
Main applications/products: Iron fuel boilers, generators for decarbonized renewable heating (industrial, district).

3.Latent Heat Storage – Phase Change Materials

3.1 Supplier: BioPCM

This supplier specializes in plant-derived fatty acids and bio-based oil formulations intended for structural thermal mass buffers and building insulation.

Global Headquarters: 813 Winston St, Greensboro, North Carolina 27405, United States
Phone Number: +1 (336) 629-3000 / Toll-Free Sales: +1 (800) 283-7887
General Inquiry Email: info@phasechange.com

3.2 Supplier: Rubitherm Technologies GmbH

Rubitherm manufactures macro-encapsulated inorganic salt hydrates and organic paraffin components for highly customized industrial climate control and heat exchange networks.

Head Office Address: Sperenberger Str. 5A, 12277 Berlin, Germany
Phone Number: +49 (30) 7109622-0
General Inquiry Email: info@rubitherm.com

3.3 Supplier: Sunamp Ltd

Sunamp develops active high-density thermal hot water batteries utilizing their patented *Plentigrade* inorganic salt hydrate formulation (Sodium Acetate Trihydrate).

Global Headquarters: 1 Satellite Park, Macmerry, East Lothian, EH33 1RY, Scotland, United Kingdom
Dutch Branch (Local Presence): Sunamp Europe BV, Industrieplein 2, 7553 LL Hengelo, the Netherlands
Phone Number: +44 (0)1875 610001
General Inquiry Email: info@sunamp.com

4. Underground Thermal Energy Storage

4.1 Supplier: DTESS (Dutch Thermal Energy Storage Solutions)

DTESS is an Aquifer Thermal Energy Storage consultancy and design specifically for HT-ATES systems.

Headquarters Address: Zomertalinghof 29, 8043 JW Zwolle, the Netherlands.
General Email: bas.godschalk@dtess.com
Key Contact: Bas Godschalk
Phone Number: +31 6 3088 7473

kWa Advisor

KWa Advisor is a dutch engineering and consultancy firm that provides advice in regards of ATES systems.

Headquarters Address: Regentesselaan 2 3818 HJ Amersfoort
General Email: desk@kwa.nl
Key Contact: Joris Groot
Phone Number: 033 - 422 13 00

Appendix 5: Use of AI in this report

In this report, AI was used responsibly and ethically. The main purpose of using AI was to understand the complex technical concepts concerning the technical systems in the report, for brainstorming ideas, and to improve the overall structure of the report. AI tools such as ChatGPT, Grammarly, QuillBot, Gemini, and Copilot were used to support the extensive research and analyse scientific articles to help brainstorm criteria for the Multi-Criteria Analysis (MCA). AI was implemented solely as a support tool, not to replace independent research, critical thinking, or decision-making. The team evaluated and confirmed all AI-generated material together, making final judgments on content, analysis, and conclusions. The application of AI adhered to ethical criteria by ensuring transparency, maintaining academic integrity, and accurately analysing information derived from AI-generated outputs.

Medegefinancierd door de Europese Unie

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OPZUID
Europees programma voor transitiegedreven innovatie

FLECS wordt mede mogelijk gemaakt vanuit het Europese subsidieprogramma OPZuid en is medegefinancierd door de Europese Unie.

Binnen het project werken bedrijven, kennisinstellingen en energiepartners samen aan innovatieve oplossingen voor netcongestie, lokaal energiedelen en duurzame energievoorziening.

Projectnaam:
FLECS – Flexibel Lokaal Energie & Capaciteit Systeem

Looptijd:
april 2025 – april 2028

Locatie:
Roosendaal en bedrijventerrein Majoppeveld

Thema's
energiedelen, netcongestie, batterijopslag, slim energiemanagement en lokale energiegemeenschappen