A review of thermal energy storage technologies for seasonal loops

Citation for published version:
Mahon, H, O'Connor, D, Friedrich, D & Hughes, BR 2022, 'A review of thermal energy storage technologies for seasonal loops', *Energy*, vol. 239, no. Part C, 122207. https://doi.org/10.1016/j.energy.2021.122207

Digital Object Identifier (DOI):
10.1016/j.energy.2021.122207

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Energy

A review of thermal energy storage technologies for seasonal loops

Authors: Mahon, H. [a, *], O'Connor, D. [b], Friedrich, D. [c], Hughes, B.R. [d]

Address:

a: School of Engineering, University of Edinburgh, Edinburgh, EH9 3DW, United Kingdom
Free Running Buildings, 18 Stalker Walk, Sheffield, S11 8NF, South Yorkshire, United Kingdom
b: Free Running Buildings, 18 Stalker Walk, Sheffield, S11 8NF, South Yorkshire, United Kingdom
c: School of Engineering, University of Edinburgh, Edinburgh, EH9 3DW, United Kingdom
d: Department of Engineering, University of Hull, Hull HU6 7RX, Yorkshire, United Kingdom

* = corresponding author details, harry.mahon@freerunningbuildings.com

Abstract:

As mitigating climate change becomes an increasing worldwide focus, it is vital to explore a diverse range of technologies for reducing emissions. Heating and cooling make up a significant proportion of energy demand, both domestically and in industry. An effective method of reducing this energy demand is the storage and use of waste heat through the application of seasonal thermal energy storage, used to address the mismatch between supply and demand and greatly increasing the efficiency of renewable resources. Four methods of sensible heat storage; Tank, pit, borehole, and aquifer thermal energy storage are at the time of writing at a more advanced stage of development when compared with other methods of thermal storage and are already being implemented within energy systems. This review aims to identify some of the barriers to development currently facing these methods of seasonal thermal energy storage, and subsequently some of the work being undertaken to address these barriers in order to facilitate wider levels of adoption throughout energy systems.

Highlights:

- Review of aquifer, borehole, tank, and pit seasonal thermal energy storage.
- Identifies barriers to the development of each technology.
- Advantages and disadvantages of each type of STES.
- Waste heat for seasonal thermal storage
- Common storage temperatures, recovery efficiencies, and uses for each technology.

Keywords:

Thermal energy storage, Seasonal storage, Sensible heat storage, Tank thermal energy storage, Pit thermal energy storage, Aquifer thermal energy storage, Borehole thermal energy storage

Wordcount: 8987

Nomenclature:

ATES	Aquifer thermal energy storage	LHS	Latent heat storage
BHE	Borehole heat exchanger	MT	Mid temperature
BTES	Borehole thermal energy storage	PCM	Phase change material
CHP	Combined heat and power	PTES	Pit thermal energy storage
COP	Coefficient of performance	SHS	Sensible heat storage
DHS	District heating scheme	STES	Seasonal thermal energy storage
ERT	Electrical resistive tomography	TES	Thermal energy storage
GSHP	Ground source heat pump	THS	Thermochemical heat storage
HDPE	High-density-polyethylene	TTES	Tank thermal energy storage
HT	High temperature	UTES	Underground thermal energy storage
HTF	Heat transfer fluid		

Units:

€/kWh	Euros per kilowatt hour	m	metres
°C	Degrees Celsius	m/a	metres per annum
h	hours	mm	millimetre
J/(kg-K)	Joules per kilogram - Kelvin	MW	Megawatt
km	kilometre	m^2	metres cubed
kWh	Kilowatt hour	m^3	metres squared
kWh/t	Kilowatt hour per tonne	TWh	Terrawatt Hour
L/min	Litres per minute	W/m	Watts per metre
L/s	Litres per second	W/m-K	Watts per metre - Kelvin

1.0 Introduction

With increasing focus being placed on reducing worldwide greenhouse gas emissions, Thermal Energy Storage (TES) is being explored as a method of reducing the environmental impact of heating and cooling. Within the EU, nearly 80% of total domestic energy use is for space heating and hot water, and within industry just over 70% of energy is used for space heating and industrial processes [1]. Worldwide, heat accounts for roughly 50% of final energy consumption and 40% of CO_2 [2]. With most of the heating demand currently met through fossil fuel-based sources [3] and the demand for cooling set to increase dramatically [4], it is becoming ever more important to introduce measures of providing heating and cooling without incurring a significant increase in energy demand.

TES is a way of addressing the mismatch in supply and demand between renewable resources and energy demand. Technology such as solar collectors are only productive during the day when domestic heating demand is at its lowest, and so in the evening once demand increases the heat is no longer available. Applying TES in combination with solar collectors with a short charge and release cycle enables the use of heat generated in times of surplus to be delivered to the heating system when conventional methods of heating would otherwise be used.

Seasonal Thermal Energy Storage (STES) takes this same concept of taking heat during times of surplus and storing it until demand increases but applied over a period of months as opposed to hours. Waste or excess heat generally produced in the summer when heating demand is low can be stored for periods of up to 6 months. The stored heat can then be re-introduced to heating systems throughout the winter as demand increases, negating some of the requirement to generate new heat and so lowering total energy consumption.

Industrial excess heat is the heat exiting any industrial process at any given moment, divided into usable, internally usable, externally usable, and non-usable streams [5]. Waste heat can be recovered directly through recirculation or indirectly through heat exchangers and can be classified according to temperature as low grade (< 100 °C), medium grade (100 – 400 °C), or high grade (>400 °C) [6], with low grade the most abundant but also most difficult to recover [7]. It is estimated that the total waste heat potential in the EU is approximately 300 TWh/year, with one third of this at temperatures below 200 °C [8]. STES is capable of harnessing and storing low grade heat, with the receiving temperature range determined by storage type and redistribution target. Storing heat at higher temperatures incurs higher thermal losses, yet enables heating provision without the need for heat pumps to raise fluid temperatures further reducing energy demand.

4th generation District Heating Schemes (DHS) are heating networks that operate at lower temperatures, employing heat from locally produced renewable and secondary heat from geothermal and waste sources [9]. The introduction of 4th generation DHS represents a shift towards lower temperature distribution systems, with supply temperatures in the region of 60 °C [10]. These lower operating temperatures are more suitable for the integration of renewable energy sources, and STES [9]. Collecting, storing, and redistributing even a small portion of the available waste heat would define a reasonable contribution towards heating requirements, both in industry and domestically.

1.1 Thermal energy storage

There are three types of TES: sensible, latent, and thermochemical. Sensible Heat Storage (SHS) is considered the simplest of the three, using a material to directly store heat within the body. Latent Heat Storage (LHS) uses thermal energy to induce a phase change within a material that then releases the thermal energy upon returning to its original state [11, 12, 13]. Thermochemical Heat Storage (THS) uses reversible chemical reactions to separate chemical compounds that can be recombined to generate heat [14, 15, 16].

SHS is currently the most developed and utilised form of TES with storage materials chosen according to their heat capacity, space availability, and cost with water the most popular choice. In comparison, materials like concrete can raise their temperature to over 1200 °C, resulting in a much higher overall storage capacity. Tiskatine et al [17] present a comprehensive list of materials used for SHS and their associated material properties.

Underground Thermal Energy Storage (UTES) makes use of favourable geological conditions directly as a thermal store or as in insulator for the storage of heat. UTES can be divided in to open and closed loop systems, with Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES), and Aquifer Thermal Energy

Storage (ATES) classified as open loop systems, and Borehole Thermal Energy Storage (BTES) as closed loop. Other methods of UTES such as cavern and mine TES exist but are seldom employed commercially. UTES can be used for both space cooling and heating, with or without heat pumps, although cooling is less common in BTES, TTES, and PTES systems whereas ATES actively benefits from receiving a balanced heating and cooling load.

Seasonal SHS faces several challenges that fail to impact shorter term thermal storage. Longer storage times make it necessary to use larger storage volumes to reduce thermal losses. As a result, capital expenditure is higher, generating accurate models is more difficult, and limitations through geographical and legal requirements can be restrictive. This review will evaluate research developments within SHS, and specifically the forms of UTES mentioned above. Although the technologies are capable of storing both heat and cold it will focus on the storage of heat, and will build on the work completed in previous reviews on TES technologies such as Xu et al [18] and Sarbu and Seberchievici [19]. In doing so the study will aim to identify some of the barriers each technology faces, and review the research undertaken to overcome these barriers to facilitate wider implementation of STES within energy systems. It will identify core areas of research associated with each technology, and present common uses and storage temperatures so that future decision making may be made easier.

2.0 Aquifer thermal energy storage

An aquifer is a subsurface layer of water-bearing permeable rock that can be exploited to extract and store groundwater. While aquifers are geographically limited, they are often found underneath large population centres [20], making them useful for co-locating large storage potential with areas already likely to generate a large thermal energy demand. ATES has received renewed interest in recent years owing to its large storage capacities, low environmental impact, versatility of application, and improving economic viability [20, 21].

Two differing well designs are used to facilitate thermal storage in aquifers. Multi-well systems use one or more sets of well doublets within the aquifer to store thermal energy at spaced lateral points separating hot and cold [22]. Mono-well systems separate hot and cold storage vertically through a single well resulting in reduced drilling costs and space requirements [23], although require an aquifer with a greater thickness to effectively separate the hot and cold regions and avoid thermal interaction. *Figure 1* below indicates the difference between the two arrangements.

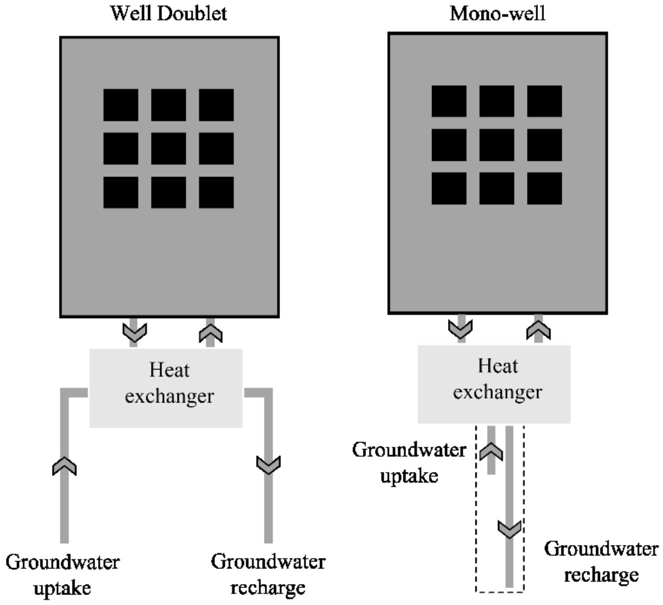

Figure 1. Well doublets (left) vs Monowell (right)

ATES passes extracted groundwater through heat exchangers, providing heating and cooling as the groundwater acts as a heat sink and heat source in the summer and winter respectively prior to being re-injected to the aquifer. Warm well injection temperatures of reviewed systems varied between 13 - 25 °C and cold injection temperatures were between 3 - 17°C [24, 25, 26]**,** with higher cooling temperatures used in hotter countries. The groundwater is re-injected with an upper limit approaching 25 °C to preserve the quality of the water within the aquifer [27]. Storage efficiencies are typically high for ATES systems, recovering between 67.5 – 87 % of stored heat and cold, with increasing storage volume serving to improve storage efficiencies [23, 28, 29]. ATES is commonly installed in universities, hospitals, large commercial buildings, and airports [26], with ventilation cooling during summer often providing the heat to be stored and subsequently used for heating throughout the winter.

Although ATES has been proven to be both energy and cost efficient the adoption rate has been slow, largely due to technical barriers such as unfamiliarity with the subsurface, presumed limited compatibility with existing energy systems, energy imbalances, and groundwater contamination, but also through legal frameworks [30, 31].

2.1 Sub-surface characterisation

Generating accurate models to predict the performance of ATES systems prior to installation is crucial to predict performance. Factors such as the composition, depth, surface area, thickness, transmissivity, and hydraulic conductivity of the aquifer must be accounted for. This must be done in conjunction with groundwater parameters such as water quality, salinity, ambient groundwater flow, groundwater quantity, and groundwater recharge. Socio-economic factors, such as local legislation, energy demand, and carbon emissions must also be considered [31].

Computational models generated from local data are used to predict ATES performance. In this way design decisions can be made that will improve the storage and extraction efficiency of thermal energy. Mapping the thermally affected zone also helps to determine the storage capacity of the aquifer. With areas of high groundwater flowrate, it is possible for the heat to move beyond the influence of the wells and therefore be lost to recovery [32]. Well spacing is also important when considering the ATES system in question as part of a network of systems operating within a given area. Wells that are close to each other can influence each other’s extraction temperatures. Interacting wells of a similar storage temperature improve system performance through positive thermal interaction reducing thermal losses throughout the aquifer, while for interacting wells of a non-similar storage temperature system performance is negatively affected [33].

Lu et al [31] performed an evaluation of global ATES potential to predict areas with a high suitability. The evaluation builds on previous work carried out such as that by Bloemendal et al [34] and Flauchaus [24], but accounts for a wider range of factors including groundwater, geo-hydrological, climatic, and socio-economic conditions, therefore improving the reliability of the results. The results are used to indicate areas predicted suitability for ATES in combination with existing urban areas, with the authors expecting findings to provide policy recommendations for governments and stimulate ATES applications. Areas with a high potential are predominantly spread throughout Europe, although coastal regions of North and South America, and Japan also present strong opportunities (*Figure 2)*. Although global analysis is useful in predicting total potential, local characterisation is also needed.

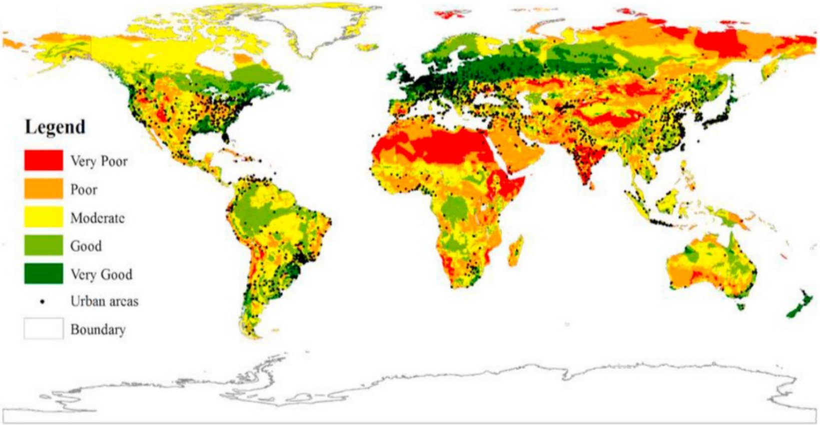

Figure 2 – Prediction of worldwide aquifer thermal storage potential with urban centres [31]

Boon et al [35] used the process set out by Kessler et al [36] and data from over 3000 historical geotechnical and geological borehole records through third parties to generate a 3D geological model. This was used to define the extent and thickness of the sand and gravel aquifer units and confining layers, however, was made easier through the extensive data already available. Using this method without historical data would require a drastic amount more work to be completed prior to the development of the underground model.

Lesparre et al [33] used electrical resistive tomography (ERT) to monitor 3D development of the thermally affected zone within an aquifer. By converting resistivity images produced through electrodes placed on the surface to temperature, an accurate picture of the extent to which heat dissipates throughout the aquifer can be developed. Visualisation of the thermally affected zone enables better placement of production and injection wells to minimise thermal interaction, but also assists in predicting the quantity of thermal energy that can be stored and subsequently recovered. SkyTEM [37] used airborne transient electromagnetics to map up to depths of 500 m, gathering data that complements the existing borehole measurements over the entirety of Denmark. Non-invasive methods are naturally preferable in terms of cost and disturbance of aquifers but require borehole measurements to validate data and ensure accuracy of results.

The effective radius of each well is dependent on the rate of groundwater flow in the area, itself a function of the porosity and density of the aquifer. Ma et al [38] recorded the impact of increasing groundwater flow rate, finding that the thermal influence radii increased from 7.4 m to 143 m with an increase of groundwater velocity from 3.15 m/a to 315 m/a. Bakr et al [39] studied 19 ATES systems installed within a 3.8 km^2 area in The Hague, The Netherlands. Both positive and negative well interference was present, with a 20% improvement in performance in the best case and 25% decrease in performance in the worst. While overall there was a net average benefit of 3.5%, the importance of proper planning when locating ATES systems is highlighted, with the location of wells with similar injection and extraction temperatures vital to avoid impeding performance. While this issue is only likely to be prevalent in more mature markets such as The Netherlands, it is an important lesson to be learned for other countries currently introducing ATES as part of its energy network. By accurately capturing the properties of the sub-surface prior to installation it will be made easier to plan a network of systems that may benefit each other.

2.2 Groundwater contamination

Aquifers are heavily relied upon for drinking water, and in many cases are subject to heavy overexploitation [40]. The re-injection of warm water can result in the precipitation of minerals and growth of micro-organisms within aquifers, negatively impacting the quality of the water [41]. These issues also negatively impact the hydraulic qualities of the aquifer, hindering the performance of the ATES system with clogging of equipment a notable issue. Clogging is primarily caused by physical, chemical, and biological mechanisms with causes including the accumulation of particle deposits, precipitation of minerals, and accumulation of micro-organisms [42].

Possemiers et al [43] reviewed the impact of ATES on groundwater quality with data taken from 69 monitoring wells between seven ATES systems in Belgium to evaluate mineral content within the water. The systems reviewed operate at small temperature differences between 6 – 16 °C with no recorded influence on the main chemical compositions within the water found, and therefore no impact on groundwater quality. Mixing of shallow with deeper groundwater during the drilling of wells was however found to have a negative impact.

Regenspurg et al [44] explored the effect of injecting hot and cold water on the chemical and microbial composition of an aquifer with a natural temperature of 17 °C. The impact of hot water injection up to a maximum temperature of 73.5 °C on chemical composition was hardly measurable, yet it was still deemed to be highly likely that carbonate precipitation would occur. Similarly, growth rates in microbial communities were small during the production and injection phases of operation. The tests were however only carried out for relatively short periods, with temperatures within the aquifer returning to normal within 13.5 days and so the effects of long-term temperature increase were unknown.

Song et al [42] performed an extensive review of recharge and clogging mechanisms within sandstone aquifers as well as the methods employed for prevention and rehabilitation. They also indicate some of the common causes and preventive measures of physical, chemical, and biological clogging, as well as rehabilitation methods used (*Table 1***)**.

Clogging Types	Causes	Rehabilitation Methods	Characteristics	Preventive Measures
Physical clogging	Suspended solids, bubbles, compaction	Backwashing, flush spray, sectional pumping or compressed air jetting, high-pressure jetting	The frequency and duration of the backwashing depends on the characteristics of the local aquifer and the recharge mode; high pressure jetting reduces air infiltration	Refine filtration process; improve well anti-corrosion technology; reduce frequent start and stop of water pump; set injection pipe lower than injection surface; high quality material riser; pressurized and dense system; ensure suspended particle concentration is less than the critical value
Chemical clogging	Chemical precipitation, electrochemical precipitation	Sodium hypochlorite, hydrochloric acid, phosphoric acid, CO2-enhanced aquifer thermal energy recovery, flocculants and disinfectants	Different acidizing and fracturing methods for thermal reservoirs and clogging, hydrochloric acid eliminates iron oxides, phosphoric acid eliminates manganese oxides;	Underground removal of iron; avoid possible oxygen infiltration; ensure the recharge water is similar to the aquifer origin water affinity; reasonable distance between wells
Biological clogging	Biochemical reaction, propagation of iron bacteria	Bioengineering, backwashing, bactericidal	Gastropod organisms can significantly reduce the biomass of benthic biofilm and open the sedimentary channel	Reduce recharge water turbidity and organic carbon content; up-flow biological anoxic filter

T*able 1 – types, causes, characteristics, and rehabilitation/preventative measures for clogging within aquifer*s [42]

The reaction of the aquifer to the injection of warm water is heavily dependent on the aquifer mineral properties and therefore aquifer qualities should be identified prior to development. This enables preventative measures to be taken, ensuring issues do not arise or impacts minimised and lowering maintenance costs. Reducing clogging also helps to prevent pressure build ups around the injection well, with increasing pressure requiring more work from the pumping system to move the groundwater.

2.3 High temperature ATES

High temperature (HT) ATES is considered as a potential development to enable the use of waste heat from a wider range of sources. While most ATES systems operate in the range of 5 – 25 °C, HT-ATES is characterised by an injection temperature of at least 50 °C, making use of heat sources such as CHP plants or incinerators [45]. The heat stored may also be used directly for heating without the need for heat pumps making it suitable for a wider range of heating applications in addition to reducing energy consumption [46]. These systems are unlikely to achieve a long-term energy balance due to the increased operating temperature, and as a result are typically located in deeper aquifers to reduce the environmental impact and likelihood of interfering with sources of drinking water [45]. To facilitate the deeper drilling depths, mono-well systems are generally used to help minimise the initial costs [47].

Although there are benefits, high storage temperatures exacerbate the issues felt in lower temperature systems such as clogging of wells due to mineral precipitation, increased mineral and CO_2 solubility, and promoting algae growth [48]. This makes extraction increasingly difficult without preventative measures, increasing the relative cost of storage, and reducing the viability of the system. In addition, losses experienced through density driven flow were found to increase non-linearly with increasing injection temperature [27], with typical recovery efficiency for low temperatures (< 30 °C) between 70 – 90% and between 40 – 70% for high temperatures (> 60 °C) [49]. Finally, to avoid rock fracturing and the loss of the entire heated water stock, injection and production rates from HT-ATES systems in low-to-medium permeability aquifers must be limited [46]. As a result, either the volume of water that can be injected and extracted is small or the loading and unloading phases must be much longer than for typical ATES systems.

Ueckert and Baumann [50] presented the results from a large-scale high-temperature heat storage test. Testing was run through a single well over five injection-production cycles with temperatures from 65 to 110 °C and a flow rate of 15 L/s. The project achieved a lower-than-expected energy recovery of 48%, with the remaining energy 'charging' the aquifer. Model results indicated that a well doublet system would only suffice for a few cycles, and so a well triplet system was suggested. In the triplet system groundwater is reinjected into an intermediary well instead of the cold well following heat extraction where it slowly flows towards the cold well, allowing it to reach equilibrium with the aquifer over time.

Feasibility studies have been carried out into the potential of HT-ATES in other areas [51]. By increasing the storage temperature the number of potential waste heat sources is also increased but also reduces storage efficiencies as more heat is lost to the surroundings. Well triplet systems could be used in future cases to recover heat that extends past the influence of the usual extraction well. Increasing the density of similar temperature injection and extraction wells will also benefit overall performance by maintaining areas of consistent temperature throughout the aquifer. By locating a number of high-temperature ATES warm wells near to one another thermal losses could be limited by reducing the thermal gradient away from the storage.

3.0 Borehole thermal energy storage

BTES uses a closed loop ground heat exchange system to store sensible thermal energy below ground in soil or rock. This is made possible by the relatively stable ground temperatures observed below the surface beyond a depth of around 10 metres [52], creating favourable conditions for the storage and subsequent extraction of heat either for direct use or through ground source heat pumps (GSHPs).

The BTES system consists of a heat source, borehole thermal storage, borehole heat exchangers (BHEs) and often a buffering tank due to the slow rate of charge and discharge [53]. The BHE is composed of a borehole, thermal grout, and u-tube arrangement encased within the grout to circulate the heat transfer fluid (HTF) along the vertical length of the borehole. Boreholes are commonly drilled to depths of between 30 - 200 m [54], however research has been conducted into boreholes of much greater depths in attempts to reduce the number of boreholes needed to generate a higher storage capacity [55]. To limit this heat loss, insulation is installed below the ground to a depth determined by the soil and insulation properties [53]. The charging temperature of the BTES is dictated by the heat source, with solar thermal collectors commonly used to provide heat at temperatures around 85 - 90 °C [56, 57]**.** Alternatively, waste heat from industrial processes and heat and power cogeneration can also be used, with low grade heat becoming more applicable with lower distribution temperatures in district heating schemes. Outlet temperatures during extraction range between approximately 25 – 45 °C [58, 59, 60] with heat pumps used to further raise the temperature of the heat transfer fluid after extraction if necessary.

The storage efficiency of the BTES system is determined by the design and arrangement of the BHEs, material properties, ground properties and operating parameters [61]. Recovery efficiencies typically start very low in the first year of operation, however by the fourth or fifth year can reach between 40 – 60 % [62, 63], with BTES commonly used to distribute heat throughout district heating schemes [57, 64, 65]. Design parameters include the length, number, and spacing of the BHEs, and must consider geological conditions such as ground thermal conductivity, and quantity and movement of groundwater. Operating parameters include inlet and outlet temperatures of the HTF, HTF velocity, and the charging/extraction operation (intermittent or continuous).

Although established through several large and smaller scale projects [66, 67], BTES still faces several barriers to further development. These are primarily the high construction costs faced due to borehole drilling, the time taken to reach operational efficiency, and accurately predicting the interaction between numerous BHEs and the ground over several years [67]. Both design parameters (i.e. BHE depth) and operational parameters (i.e. fluid flow velocity) have been proven to have a significant impact on BHE performance [68].

3.1 Borehole arrangement

Borehole fields develop horizontal rather than vertical temperature stratification, with higher temperatures towards the centre, concentrating heat in the centre of the array. This results from heat being predominantly transferred through conduction rather than convection through the borehole arrangement [69]. The cost of drilling typically accounts for about half of the installation costs and hence depth and number of BHEs becomes a significant factor for its deployment [68]. The number of BHEs required for the system is determined according to the geological conditions and desired storage capacity.

Sensitivity analysis has shown that borehole spacing is the most effective factor in influencing storage efficiency and temperature density within the array, with an increase in spacing increasing storage efficiency but reducing temperature density [67]. Welsch et al [70] observed the impact of the length, spacing, number, and inlet temperature on the storage performance of medium-deep BHEs. Storage systems consisting of 4, 7, and 19 BHEs at spacings of 2.5, 5, and 10 m were tested. It was found that a higher number of BHEs allowed a higher initial storage efficiency, as well as achieving the largest increase in storage efficiency over the modelled period of 10 years. Increasing borehole spacing from 2.5 to 5 m served to improve storage efficiency and increase specific heat extraction rates, whilst further expanding to 10 m decreased these values.

Gultekin et al [71] investigated the impact of borehole spacing on small borehole fields of 2, 3, 5, and 9 boreholes with spacings of 1 to 10 m (*Figure 3*). Performance was evaluated by comparing the heat transfer rate of the critical borehole as an individual and then as part of an expanding array, with the singular borehole achieving a heat transfer rate of 42.7 W/m and 41 W/m for 1800 and 2400 hours of continuous operation, respectively. Performance loss decreases with increasing borehole spacing, with a spacing of 6 m enough to keep the performance loss of the critical borehole below 10%, and a spacing of 4.5 m keeping total borehole field performance loss below 10%.

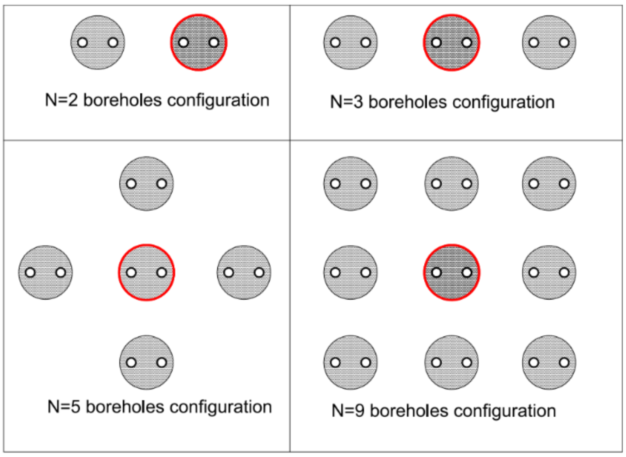

Figure 3 – Borehole arrangement and critical borehole evaluated in each array marked in red [71]

Accurate computational models can reduce costs by avoiding poor design. Zhang et al [72] present a comprehensive summary of the current methods of computational analysis for BHE ground thermal response and thermal interaction of multiple BHEs. A process for determining the optimal borehole arrangement and subsequent equations is presented in [71]. The empiric formula is based upon the impacts of the aspect ratio between arrangement geometry and number of boreholes and is intended to optimise the design process.

3.2 Borehole charging

Borehole fields can take up to 5 years to reach their maximum operating efficiency, with much of the injected heat lost throughout the charging season prior to reaching a steady state of operation (*Figure 4*) [73]. With each year of operation, lateral heat transfer away from the borehole field to the ground reduces as the thermal gradient between borehole temperature and ground temperature decreases [74]. The low thermal efficiency encountered in the initial years of operation encourage improvements to charging methods to help the BTES system reach operating efficiency in a shorter timeframe.

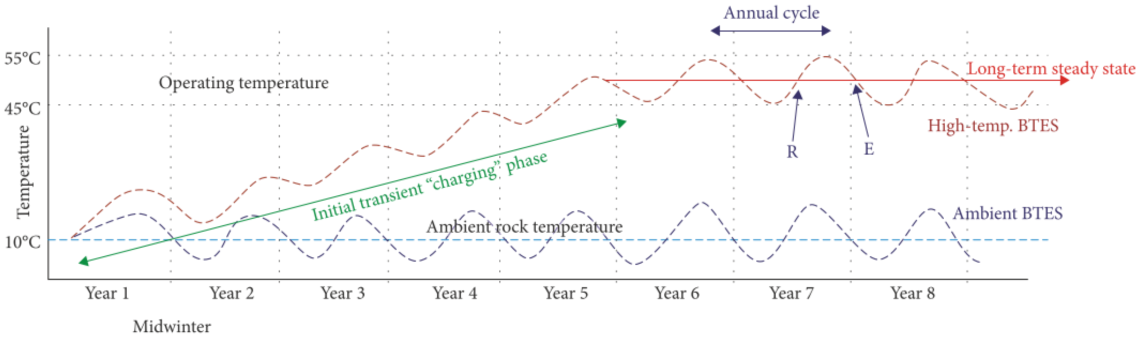

Figure 4 – Example BTES system operating temperature over time [73]

Boreholes are connected in series, parallel, or mixed arrangements (*Figure 5*) [75]. Traditionally, charging occurs by circulating water through boreholes at the centre of the array as a priority and radiates outwards throughout the boreholes to concentrate most of the heat in the centre of the array.

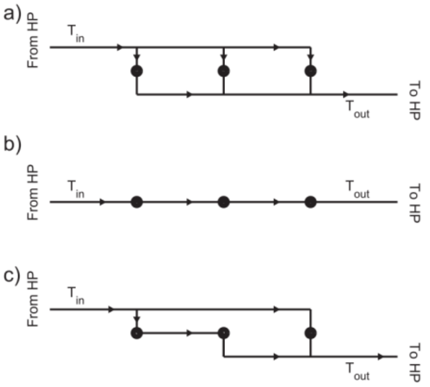

Figure 5 - Different possible BHE arrangements; a) parallel; b) series; c) mixed [75]

Lim et al [76] proposed an alternative method through which the fluid inlet position is moved between boreholes closer or further from the centre throughout charging. Inlet position is determined by the inlet fluid temperature to maintain the radial temperature gradient within the borehole array. By applying the inlet positioning method, the thermal storage efficiency was increased by 7.7%, 18.4%, and 24.4% at the end of the first, second, and third years of operation respectively. The energy sharing ratio was increased by 69.4%, enough to create an increase in the energy storage per unit volume, resulting in a reduction in the size of the BTES.

Altering the fluid inlet temperature during charging and discharging, fluid velocity, and the mode of operation can improve the rate of heat transfer between the HTF and the ground. Heat injection rate increases almost linearly with an increase in temperature difference between the inlet temperature and the average temperature of the BTES [77]. Amongst operating parameters, Woloszyn [61] found it necessary to achieve the highest possible inlet temperature during charging and lowest possible inlet temperature during discharging to obtain high efficiency values.

Zhu et al [78] explored the charging and stopping time frames used for an intermittent charging operation. Following the results, they suggested an operation with intervals of 5 – 11.5 h or more than 17.5 h for charging, and a stopping duration of between 11.5 – 24 h in between. Conversely, Wei et al [79] reported that a concentrated charging strategy led to a more efficient system performance when compared with intermittent charging. Under intermittent charging it was found that heat losses were higher over the whole charging season as the heat did not have time to accumulate, whereas with a concentrated approach heat loss only occurred as charging began which was comparatively later in the season. Han and Yu [68] showed that for a particular BHE, intermittent extraction was preferable to continuous. Continuous extraction can remove greater quantities of heat from the ground but at the cost of lower extraction efficiency, where extraction efficiency is defined as the extracted energy divided by the operational period. In contrast, intermittent mode allows the ground temperature to recover between periods of extraction, improving efficiency and increasing the COP of the heat pump.

3.3 Material improvement / borehole resistance

The performance of a BHE is dependent upon the thermal resistance of the borehole as well as the thermal properties of the ground. Total borehole resistance was defined by Beier and Ewbank [80] as the resistance between the circulating fluid in the BHE and the undisturbed ground temperature. Zero borehole resistance infers instantaneous heat transfer from the HTF to the ground and vice versa [81]. With increasing thermal conductivity of the soil, thermal resistance decreases, resulting in an overall decrease of the borehole resistance. It is desirable to reduce the thermal resistance of the borehole as this helps to reduce the number and/or depth of BHEs required.

Initially, plain sand or cement grouts were used to backfill boreholes but more recently grout is usually made of bentonite, quartz with sand, or water. Bentonite has a typical thermal conductivity of 0.8 – 1.0 W/m-K, thermally enhanced grout with quartz 1.0 – 1.5 W/m-K, water saturated quartz sand 1.5 – 2.0 W/m-K and stagnate water 0.6 W/m-K [82]. High-density-polyethylene (HDPE) is the pipe material of choice due to its low cost, corrosion resistance, and easy handling [83]. Badenes et al [83] demonstrated that the optimal pipe and grouting combination is not always the combination with the highest thermal conductivity, but that materials should be determined in accordance with local ground conditions. Through this method a 22% reduction in the required length of the BHE could be achieved in the modelled conditions. Kurevija et al [84] compared savings in electricity with investment cost, also concluding that there is no real benefit from implementing enhanced grouts in ground with low to average thermal conductivity. In addition to material changes, methods such as introducing internal fins within the u-tube have been explored to encourage turbulent mixing [85]. Zhang et al [86] achieved a 15.63% saving on initial investment by considering the positioning of the u-tube within the borehole as next to the wall rather than centred as is more likely to be seen in real systems, with the savings achieved by reducing the required length of the BHE.

3.4 Medium-deep boreholes

In further efforts to reduce costs the use of increasingly deeper boreholes is being explored. Deeper boreholes have less impact on shallow aquifers, require fewer boreholes, and are predicted to achieve efficiencies of up to 83% through early studies [56]. At greater depths ground permeability tends to decrease, limiting the transfer of heat away from the storage volume by groundwater flow. The thermal gradient between the storage area and surrounding rock is also reduced, enabling higher extraction temperatures as stored heat does not dissipate away from the BHE [87]. Co-axial borehole arrangements are used for deep borehole systems (*Figure 6*) to reduce pressure losses for the circulating fluid whilst allowing for larger mass flow rates and improved thermal extraction. The inner piper is also insulated to prevent thermal interaction between the down and up flow [88].

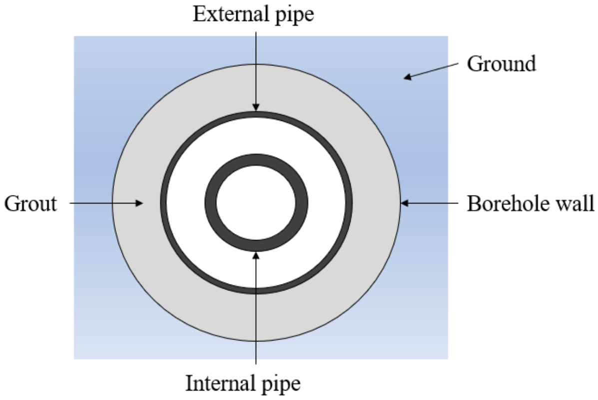

Figure 6 – co-axial borehole arrangement

Medium-deep boreholes exist up to depths of 2 - 3 km, allowing for much fewer boreholes to provide the same storage capacity, enable much higher storage temperatures without impacting shallow aquifers, and benefit increasingly from geothermal heat [59]. The boreholes in question delivered a heat transfer rate of 61 – 144 W/m, a large increase when compared with the 40 W/m generally achieved through standard depth boreholes. Consequently, the heat extraction through one deep BHE can be equivalent to between 30 – 70 standard depth BHEs, with the average outlet temperature over 5 test sites reaching 33 °C.

Wang et al [60] carried out a field test and numerical investigation on the optimal design of a deep BHE. Increasing the outer diameter of the pipe increases the initial cost but increases outlet temperature and heat extraction. By increasing the outer diameter from 168.3 mm to 244.5 mm, the outlet temperature increased by 11.6% and the heat extraction by 32.3%. This can be attributed to a larger heat exchange surface area created by the wider diameter.

4.0 Pit/tank thermal energy storage

Although often employed as buffer storage, TTES is also used seasonally. The storage tank is made of reinforced concrete, steel, or fiber-reinforced plastics [20], using water as a storage material with internal liners to create a watertight layer. As the tank is purpose-built the storage can be located anywhere, independent of the local geological conditions that dictate the suitability of borehole and aquifer systems. The tank is either fully or partially buried in the ground to insulate against the ambient temperature, reducing the level of thermal insulation required [89].

PTES uses excavated ground to create a sunken storage area. The excavated soil can be used to raise the banks at the sides of storage, increasing the overall volume of the storage. The lid is either supported by the sidewalls of the pit or floats on the surface and is often the most expensive part of the PTES construction [90]. PTES generally uses water as a storage material, but also sometimes employ a mixture of water and gravel. Due to the water-gravel mix having a lower thermal capacity than the just water case, the volume of the basin needs to be approximately 50% higher in this case [91] but is often applied to avoid the costs of disposing of the excavated ground material. The cost of building PTES is around a quarter of that to build TTES [92]. Insulation is commonly used along the top and sides of the storage, with the thickness determined by the storage temperate and local ambient and geological conditions.

Despite use differing geometries TTES and PTES operate under the same principles. Heat is charged and discharged into and out of the water within the container either by directly pumping water into the store, or through a heat exchanger with another thermal system. Hot and cold regions naturally develop within the storage due to the differences in density between the hot and cold water. This enables hot water to be extracted from the top of the tank and cold water to then be re-injected to the storage at the bottom of the tank without overly disturbing either region. It is desirable to maintain these thermal regions with as little mixing as possible to prevent heat losses throughout the storage.

Tanks and pits are designed to store water up to temperatures of around 90 – 95 °C [57]. Inlet temperatures are dependent on the heat sources used in conjunction with the thermal storage as well as the use or non-use of heat pumps. Solar collectors, bio-mass boilers, and industrial waste heat are often employed as heat sources, generating charging temperatures between 70 - 95 °C [64, 93, 94, 95]. As a result of the high storage temperatures, the stored heat is commonly utilised through district heating schemes [57, 64, 94]. Storage efficiencies between approximately 45 – 65% are common [93, 96, 97, 98], with instances of up to 90% achieved [64].

4.1 Thermal stratification

Stratification occurs as water is separated into regions of consistent temperature due to the density variations caused by temperature differences. Thermal stratification is enhanced by increasing temperature difference between the top and bottom of the tank, lower inlet velocities and higher aspect ratios [99]. Weather conditions, inlet and outlet flow arrangements, geometry parameters, and levels of thermal insulation all impact the thermal stratification of the storage [97]. A thermocline region is formed between the hot water at the top of the tank and the cold water at the bottom. This thermocline region acts as a buffer between the hot and cold regions, preventing mixing (*Figure 7*). In general, the thermocline layer should be as thin as possible as this allows for a greater volume of hot water within the storage tank indicating reduced mixing [100].

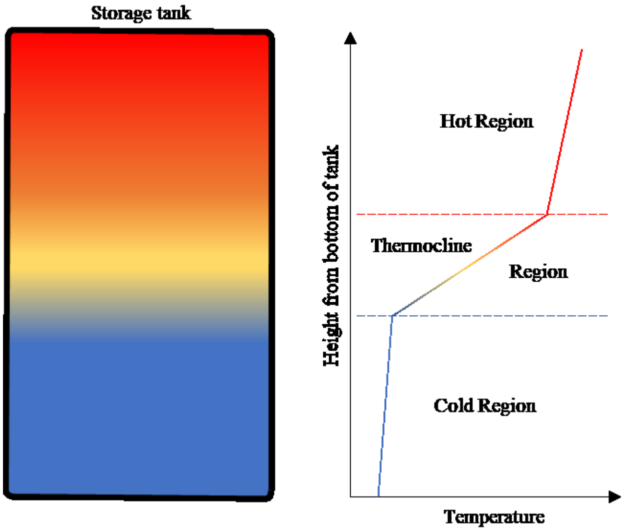

Figure 7 – Thermocline region separating hot and cold sections (Adapted from [100]).

Heat losses enhance convective mixing within the tank by creating interacting regions with different temperatures, ultimately reducing the efficiency of the storage [101]. Therefore, preserving stratification using insulation as well as tank and inlet device design has been a key area of research in advancing the thermal efficiency of tanks and pits.

4.2 Inlet device

The quality of the thermal stratification is largely determined by the inlet device and the flow properties that are derived from it. Poor inlet design induces mixing within the storage negatively impacting the stratification.

Moncho-Esteve et al [102] simulated several elbow geometries and a diffuser as the inlet (*Figure 8*), supplementing earlier experimental work [103]. They concluded that the degree of stratification was predominantly determined by inlet direction and inlet velocity profile, both products of the inlet design. When evaluating the preservation of stratification and the thermocline region, results showed that the conical diffuser performed better with a flow rate of 16 L/min when compared with the designed elbows at a flow rate of 6 L/min. The best thermal efficiency during charging was achieved by using the upwards facing elbow (Figure 8, d) or diffuser design (Figure 8, b), with minimal difference measured between them.

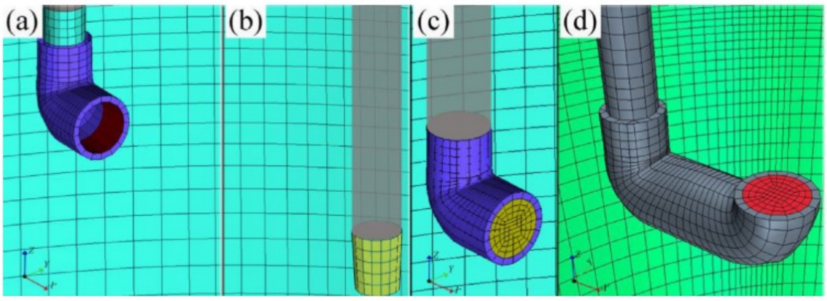

Figure 8 – Elbow and diffuser designs used during simulation where a, c, and d are elbow designs and b is a diffuser [102]

Wilk et al [104] used thermal coils within the tank to introduce and extract heat from the water. A hot water coil at the top, cold water coil at the bottom, and an extra coil utilizing waste heat from a refrigeration cycle within a stratification device to reduce mixing were monitored. The individual operation of the upper coil served to develop stratification but also increased the thickness of thermocline with time. This resulted in excessive buoyancy and convective mixing, effectively destroying the stratification.

Al-Habaibeh [105, 106] propose a novel ‘water snake’ to maintain stratification within the storage. The water snake moves vertically within the storage according to the buoyancy of the water being injected, ensuring that the water entering is within a layer of water with the same density. Although initial testing of the water snake proved that it was an effective method of reducing mixing, all the testing times are over short periods with further testing needed to indicate performance over longer periods with a wider range of tank and inlet temperatures.

As it stands, diffusers offer high inlet rates with low levels of mixing within the water storage. By reducing inlet flow rates, stratification can be better preserved however to do so may require the use of an intermediary storage vessel that would incur losses of its own. Immersion coils are beneficial in that they do not directly deposit water into the storage and so there is no overt disturbance of the thermocline but are restricted to heat transfer by conduction through the walls of the coil.

4.3 Tank design

Water tanks and pits are expensive to construct, consequently making it important to first accurately model and predict the performance of the storage geometry. When designing the storage, parameters such as ambient conditions, soil properties, tank geometry, and material choices are all considered [92].

As man-made freestanding structures, cylindrical tanks are generally used, partially or fully buried to reduce thermal losses whilst also being a more efficient use of space [107]. In a study investigating the impact of geometrical parameters on storage efficiency and stratification [108], it was found beneficial to increase the height-to-diameter ratio of the storage. A height to diameter ratio of 2 results in a smaller contact surface between the hot and cold-water limiting mixing and reduced the thickness of the thermocline from 40% to 16% of the total tank height.

Pits are dug with the angle between the side wall and the horizontal limited to between 30 – 40 degrees to avoid the collapse of the sidewall's inwards [109]. Heat loss through the walls creates a downward flow of cooler water towards the base of the pit. Hotter water at the center of the tank rises, creating the stratification. Chang et al [110] investigated the impact of pit wall angle and depth on thermal performance. They found that reduced pit depth results in reduced thermal efficiency, with deeper pits achieving clearer thermal stratification. Steep slope angles of the sidewalls were found to lead to more significant temperature stratification.

To create a watertight storage, polymer or metal liners are installed. Polymers such as Polypropylene and polyethylene are popular due to their low cost and ease of use, however sometimes face issues with temperature resistance [111]. The permeability of polymer liners is heavily temperature dependent [112], and if moisture does occur within the insulation layer it can lead to long term degradation [113]. Double liners can be used to ensure the water tightness of the storage, given that the internal layer in contact with the water may be subject to degradation through heating over time.

In comparison metal liners are more expensive but offer improved heat resistance. Ochs et al [113] compared capital costs of stainless steel and polymer liners for tanks and shallow pits alongside trafficable and non-trafficable covers. For large storage volumes of 2,000,000 m^3, the difference in cost between the two was relatively low, whereas for small volumes of 100,000 m^3 the difference is much more significant. The cover of the shallow pit is a major contributor to the overall cost; however, the significance decreases with increasing storage volume. When only considering the liner, polymers are more economically feasible than steel, even if required to be replaced over the respectively shorter lifetime.

As the structure is the most expensive part of the storage, choosing the correct materials drastically impacts the overall cost and longevity of the system. Although tanks are the most expensive form of seasonal thermal storage [114], their cost is countered by the fact that they are independent of local conditions and therefore can be installed anywhere.

4.4 Insulation

Tanks and pits have large contact areas between the ground or air and the walls of the storage and therefore can incur large thermal losses in these regions. Thermal insulation is often one of the most expensive investments in tank and pit thermal storage and so using it efficiently helps to reduce overall costs.

Bai et al [96] developed a simplified model of an underground water pit buried 1 m underground featuring 0.3 m thick concrete walls and a 0.2 m thick polystyrene layer on top of the lid. This model was then used to evaluate heat loss coefficients along the top, sides, and bottom of the storage. For a maximum temperature difference between the top and bottom of the pit of 31.3 °C the average heat loss coefficients were found to be 0.172 W/m^2, 0.702 W/m^2, and 0.366 W/m^2 along the top, side wall, and bottom respectively. The low heat loss coefficient along the top was attributed to the use of the polystyrene layer. The higher temperatures measured closer to the top of the pit as well as the thermal stratification contribute to a higher heat loss coefficient along the sides than the bottom.

While heat transfer from the tank to the soil is intentionally suppressed for small storage tanks this can lead to the tank reaching capacity prematurely, resulting in the discarding of waste heat that could otherwise be stored. Huang et al [115] proposed reducing the level of insulation around the tank to allow heat to be transferred to the ground. Five levels of insulation were proposed as shown in *Figure 9*. They argue that by reducing the level of insulation the capacity of the storage is effectively increased by using the surrounding soil as further thermal storage. Heat lost through the tank walls but within a range of 3 – 4 m of the wall was recoverable once the temperature of the tank fell below the temperature of the ground. As a result, for a temperature difference of 80 °C within the tank the cross-seasonal heat storage capacity was increased by 9.85% when reducing the insulation from full to partly covered. This only remains beneficial for tanks with small storage volumes that are likely to reach max storage capacity prior to the end of the charging season. The use of insulation must be taken from an engineering as well as economical point of view, as in some cases it may be beneficial to allow marginally higher thermal losses to save on the initial investment.

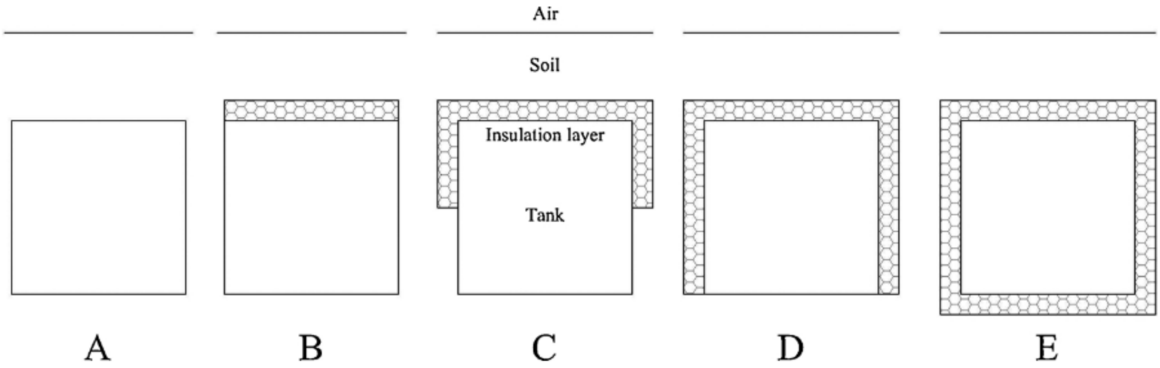

Figure 9 – levels of insulation evaluated to determine heat transfer away from the storage [115]

5.0 Waste heat for STES

The recovery of waste heat is an important development to improve the efficiency of energy systems whilst reducing environmental impact. Industrial waste heat is the energy lost in industrial processes to the environment [116], with heat classified into low, medium, and high temperature grades. Waste heat accounts for around 70% of the energy input in industrial processes [117], with the waste heat potential of the EU estimated to be between 300 – 350 TWh per year [118, 119]. Waste heat is often produced in large quantities, consistently and predictably over long periods of time making it particularly suited to STES.

Reviews of potential waste heat sources within the UK and EU identified several potential industrial processes for heat recovery such as aluminium, food and drink, cement, iron and steel, pulp and paper, ceramics, chemicals, and glass [118, 120]. These waste heat sources were categorised according to the heat recovery potential and the temperature of the available waste heat, with most of the recoverable heat falling between 100 – 200 °C [120]. Other potential forms of waste heat include CHP [121, 122], and data centres [123]. The heat source temperature determines the value of the waste heat, with higher temperature sources allowing more scope for matching with potential heat sinks [124].

As available waste heat is classified according to its temperature range, heat recovery methods are similarly grouped. Jouhara et al [116] and Stevenson and Hyde [125] reviewed waste heat recovery technologies, identifying plate heat exchangers, heat pumps, heat pipes, regenerators, economisers, and hot water storage as some of the suitable methods for low to medium temperature waste heat. Woolley et al [126] then present a four-stage approach to selecting the most appropriate solution for heat recovery in an industrial scenario. Methods of heat recovery suitable for liquid to liquid or gas to liquid heat transfer are required to facilitate the use of STES as HTFs are used to charge the thermal storage. By altering the heat transfer surface area and mass flow rate of the heat exchanger the temperature of the HTF to any STES can be controlled.

Following the identification of a waste heat recovery method, priorities for its use can be established according to the following hierarchy based upon capital costs [120, 124]:

1. Direct use of heat (requiring only piping/ducting, usually within same process)
2. Onsite heat transfer using heat exchanger
3. Provide chilling using absorption chiller for use on site
4. Upgrade heat for use on-site using heat pump
5. Generating electricity
6. Export heat for use off site

Using waste heat directly is a priority as this incurs the smallest losses. Storage through STES is between 2 and 4, with excess waste heat stored using heat exchangers with the option to use heat pumps to increase the delivery temperature following extraction. The maximum delivery temperature of high temperature heat pumps is 150 °C, suitable for some processes in the food, paper, chemicals, and tobacco industries [127].

Stevenson and Hyde [125] defined several end processes, heat sinks, and their temperature levels. Processes are separated into drying, space heating, high and low temperature, with the lowest target temperatures at 90 °C for water pre-heating in hot water boilers and space heating, and 100 °C for water pre-heating for steam boilers. This shows that although industry produces significant quantities of waste heat, when STES is concerned there may be limited uses for it within industrial processes. This is because the storage and delivery temperatures from any STES system would be below much of the useful temperature range, even with the use of heat pumps, and therefore additional demands such as district heating schemes or ventilation heating must be considered. It can be more difficult to match supply with demand in these cases due to industry often being separated from communities, with the transportation of heat incurring significant losses.

Miro et al [128] reviewed a number existing industrial waste heat sources with thermal energy storage. Of the cases evaluated only a few used water as a storage material due to the high exhaust temperatures of the industrial processes. These examples were found in the chemical, pulp and paper, and food and beverages industries, with storage temperatures between 25 – 60 °C. Short-term TTES is used in each case, however indicates that each process would also be suitable for STES either through TTES or another means providing that the supply and demand was sufficiently large.

Guo and Yang [129] simulated a large scale BTES system using waste heat from a copper plant, supplemented by solar collectors. Waste heat from the copper plant was generated and stored at 70 °C, with outlet temperatures during extraction at 40 °C. They predicted a storage efficiency of 83.1%, with the extracted heat supplying a district heating scheme.

A HT-BTES at Emmaboda, Sweden [130], stores waste heat from a foundry in an array of 140, 150 m deep boreholes. Heat is stored at between 40 – 45 °C, with the highest efficiency achieved to date at 19% in its sixth year of operation. Below expected levels of extraction is owed to lower than anticipated quantity and quality of excess heat, hindering the storage from reaching the required temperatures for extraction. Despite this, the amount of bought district heating was reduced by approximately 4 GWH/year. This experience highlights the importance of proper quantification of waste heat and subsequent system design. By using heat pumps heat can be extracted at lower temperatures with minimal energy demand therefore making the stored heat more viable.

When considering the use of STES in conjunction with industrial waste heat the following must first be considered: supply rate, quantity, and temperature of the waste heat, location of supply and demand relative to one another, heat recovery technology, the mass flow rate of both the supply and the sink, and any geographical limitations that may prevent the installation of any STES technology. As storage temperatures for BTES are typically between 40 – 90 °C, and 70 – 95 °C for tank/pit TES they are more suited to receiving higher temperate waste heat from industry. Tank and pit TES are beneficial in that they can be installed anywhere, however the size of the tank can be a limiting factor. In contrast, storage temperatures for ATES are between 13 – 25 °C, more suitable for processes such as air-cooled data centres that produce waste heat between 25 – 35 °C [123]. The advent of mid-deep BTES will also improve the ability of the STES to meet the demands of high temperature processes.

6.0 Discussion

Derived from the technology properties in the above sections, *Table 2* summarises common heat sources, storage temperatures, storage efficiencies, and uses for the stored heat as found within literature.

Type of TES	Heat source	Storage temperature	Storage efficiency	Common applications
Aquifer	Heat recovery within ventilation, geothermal wells	13 - 25 °C in low temperature storage [24, 25, 26, 30] > 50 °C in high temperature [45, 50, 51]	67.5 - 90% [23, 39, 49, 28, 29]	Universities, hospitals, large commercial buildings, and airports for both heating and cooling [26, 131] District heating and cooling [20, 132]
Borehole	Solar collectors, industrial waste heat, heat and power co-generation	40 - 90 °C [56, 57,130]	40 - 60% once at operational efficiency [62, 63, 65, 76]	District heating schemes [57, 64, 65] Internal heating system [130]
Tank / Pit	Solar collectors, bio-mass boilers, industrial waste heat	70 - 95 °C [64, 93, 94, 95]	45 - 90% [64, 93, 96, 97, 98]	District heating schemes [57, 64, 94, 133] Cooling [20]

Table 2 – Typical heat sources, storage temperatures, efficiencies, and applications of STES technologies

Whilst considering the intended heat source, storage temperature, and targeted destination for any stored heat, the relative benefits and drawbacks of each technology must also be accounted for when determining which type of STES to include (*Table 3).*

TTES and PTES are more independent of the local geological and hydrogeological conditions whereas ATES and BTES suitability is heavily dependent on local conditions, therefore making accurate characterisation of sub-surface highly important. Increasing storage temperatures in high-temperature ATES and mid-deep boreholes would create more opportunities for easier to recover waste heat, however, is inhibited by limitations on storage temperatures within aquifers and expensive drilling costs with increasing depths. Further research on the impact of injecting high temperature water on the composition of aquifers would be beneficial towards the development and use of high-temperature ATES systems. Issues with maintaining water quality can be limited by closely monitoring injection temperatures in lower temperature systems, as well as requiring heating and cooling loads to be approximately balanced over the course of the year. Thermal losses throughout the aquifer can be improved by better mapping of hydrogeological conditions to improve the placement of extraction wells relative to injection wells. Although deeper drilling depths are costly, the increased rate of heat transfer along the length of the borehole can reduce the number of boreholes required to store and recover the same quantity of thermal energy. Issues with long times to reach operational efficiency and low storage efficiencies are being addressed through material improvements, charging operations, and borehole spacing to create a more stable temperature distribution throughout the borehole field.

The geometry of tanks and pits has been shown to affect the thermal performance of the storage. By considering the angle of the walls and the height to diameter ratio, losses through the side walls can be reduced. Tanks are limited in the size to which they can be built, and therefore the storage size although large is restricted. In comparison pits can be dug to almost any size, with the lid the only limiting factor. Further improvements to inlet and extraction devices to maintain stratification would help improve storage efficiencies and in turn help to lower costs by reducing material demands.

Although solar thermal collectors are widely used to provide heat for STES they are not as effective in many climates, and therefore waste heat is often used as an alternate or supplementary source. Bio-mass boilers and CHP units are also employed, with STES enabling the operation of electricity production independently of heating demand for CHP.

The development of CFD and other methods of computational modelling has made predicting system performance somewhat easier and is helping to envisage systems in a variety of scenarios. There are still however physical engineering issues within each storage type that when addressed result in improved storage efficiencies, higher outlet temperatures, and lower costs.

Type of TES	Advantages	Disadvantages	Factors influencing performance
Aquifer	Large storage volumes	Only applicable where aquifers are present	Groundwater flow rate
	Benefits from balanced heating and cooling load	Potential negative impact to drinking water	Groundwater quantity
	Low cost	Storage temperatures limited by law	Groundwater recharge
	Aquifers often located under large population centres	Requires accurate subsurface characterisation	Heating and cooling demand
	Nearby doublets of similar temperature can improve performance	Nearby doublets of similar temperature can decrease performance	Local legislation
		Prone to clogging	
Borehole	Storage efficiency increases with increasing storage volume	Takes approx. 5 years to reach operating conditions	Design and arrangement of borehole heat exchanger
	Relatively low cost	Drilling costs	Ground and construction material thermal properties
	Modular storage approach that can be expanded	Thermal losses to surroundings when surface area to volume ratio is high	Groundwater flow
	Benefits from stable temperatures below surface		Charging and discharging operation
	Deep boreholes (> 1km) will significantly improve performance		
Tank / Pit	Independent of hydrogeological conditions	Expensive	Atmospheric conditions
	Partially/fully burying below ground reduces space and insulation requirements	Tank size restricted with construction limits Losses within the storage if stratification isn’t preserved	Application of insulation Tank geometry
	Storage volume made to suit demand		Material choices
	High storage efficiencies		Preservation of stratification
	High storage temperatures		

Table 3 – Advantages, disadvantages, and factors influencing performance of different types of seasonal thermal energy storage

6.0 Conclusion

This paper discusses four STES technologies, including operating parameters, barriers to development, and research areas devoted to improving them. By evaluating current uses and performances of existing STES systems decision making in future systems can be improved. For uses of STES, district heating schemes as well as large scale heating and cooling loads have been most studied although as the technologies improve so will their suitability for use within a wider range of systems.

With the advent of 4th and 5th generation district heat schemes, STES is becoming more relevant as an effective means of meeting thermal energy demand. Borehole, tank, and pit TES are all used throughout the current generation of district heating schemes, with ATES more commonly used to meet heating and cooling loads in large public and commercial spaces. As systems move to 5th generation district heating and distribution temperatures are reduced the number of viable sources of waste heat for direct distribution will increase. Whether the technologies are adopted will come down to cost, and so reaching a point where it is cheaper to store and re-deliver waste heat rather than creating new heat is a long-term goal. The introduction of latent and thermochemical heat storage will inevitably change the landscape of STES, but for now it remains clear that the methods of storage evaluated here represent the best possible opportunities for using and storing large quantities of waste heat over several months to provide a better outlook for current energy systems.

Acknowledgements

This work is funded by the Scottish Research Partnership in Engineering (SRPe-IDP/012) and Free Running Buildings.

References

[1] Energy DFOR. EUROPEAN COMMISSION DIRECTORATE-GENERAL FOR ENERGY Directorate C. 2 – New energy technologies, innovation and clean coal 2020.

[2] IEA. Renewables 2019 – Analysis - IEA. Int Energy Agency 2019.

[3] Abergel T. IEA (2020), *Heating*, IEA, Paris https://www.iea.org/reports/heating

[4] IEA. The Future of Cooling: Opportunities for energy-efficient air conditioning. Future Cooling Opportunities Energy-Efficient Air Conditioning 2018:92.

[5] Anastasovski A, Rasković P, Guzović Z. A review of heat integration approaches for organic rankine cycle with waste heat in production processes. Energy Convers Manag 2020;221. https://doi.org/10.1016/j.enconman.2020.113175.

[6] Woolnough D. (2011, February 11). Waste heat recovery. Retrieved from http://thermopedia.com/content/1250/

[7] Xu ZY, Wang RZ, Yang C. Perspectives for low-temperature waste heat recovery. Energy 2019;176:1037–43. https://doi.org/10.1016/j.energy.2019.04.001.

[8] Papapetrou M, Kosmadakis G, Cipollina A, La Commare U, Micale G. Industrial waste heat: Estimation of the technically available resource in the EU per industrial sector, temperature level and country. Appl Therm Eng 2018;138:207–16. https://doi.org/10.1016/j.applthermaleng.2018.04.043.

[9] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.

[10] Zühlsdorf B, Christiansen AR, Holm FM, Funder-Kristensen T, Elmegaard B. Analysis of possibilities to utilize excess heat of supermarkets as heat source for district heating. Energy Procedia 2018;149:276–85. https://doi.org/10.1016/j.egypro.2018.08.192.

[11] Cabeza LF, Martorell I, Miró L, Fernández AI, Barreneche C. Introduction to thermal energy storage (TES) systems. Woodhead Publishing Limited; 2015. https://doi.org/10.1533/9781782420965.1.

[12] Umair MM, Zhang Y, Iqbal K, Zhang S, Tang B. Novel strategies and supporting materials applied to shape-stabilize organic phase change materials for thermal energy storage–A review. Appl Energy 2019;235:846–73. https://doi.org/10.1016/j.apenergy.2018.11.017.

[13] Nithyanandam K, Stekli J, Pitchumani R. High-temperature latent heat storage for concentrating solar thermal (CST) systems. Elsevier Ltd; 2017. https://doi.org/10.1016/B978-0-08-100516-3.00010-1.

[14] Hauer, A. Storage Technology Issues and Opportunities, International Low-Carbon Energy Technology Platform. In Proceedings of the Strategic and Cross-Cutting Workshop "Energy Storage—Issues and

[15] Pardo P, Deydier A, Anxionnaz-Minvielle Z, Rougé S, Cabassud M, Cognet P. A review on high temperature thermochemical heat energy storage. Renew Sustain Energy Rev 2014;32:591–610. https://doi.org/10.1016/j.rser.2013.12.014.

[16] Carrillo AJ, González-Aguilar J, Romero M, Coronado JM. Solar Energy on Demand: A Review on High Temperature Thermochemical Heat Storage Systems and Materials. Chem Rev 2019;119:4777–816. https://doi.org/10.1021/acs.chemrev.8b00315.

[17] Tiskatine R, Oaddi R, Ait El Cadi R, Bazgaou A, Bouirden L, Aharoune A, et al. Suitability and characteristics of rocks for sensible heat storage in CSP plants. Sol Energy Mater Sol Cells 2017;169:245–57. https://doi.org/10.1016/j.solmat.2017.05.033.

[18] Xu J, Wang RZ, Li Y. A review of available technologies for seasonal thermal energy storage. Sol Energy 2014. https://doi.org/10.1016/j.solener.2013.06.006.

[19] Sarbu I, Sebarchievici C. A comprehensive review of thermal energy storage. Sustain 2018;10. https://doi.org/10.3390/su10010191.

[20] Schmidt T, Pauschinger T, Sørensen PA, Snijders A, Djebbar R, Boulter R, et al. [21. Energy Procedia 2018;149:585–94. https://doi.org/10.1016/j.egypro.2018.08.223.

[21] Matos CR, Carneiro JF, Silva PP. Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. J Energy Storage 2019. https://doi.org/10.1016/j.est.2018.11.023.

[22] Babaei M, Nick HM. Performance of low-enthalpy geothermal systems: Interplay of spatially correlated heterogeneity and well-doublet spacings. Appl Energy 2019;253:113569. https://doi.org/10.1016/j.apenergy.2019.113569.

[23] Zeghici RM, Oude Essink GHP, Hartog N, Sommer W. Integrated assessment of variable density-viscosity groundwater flow for a high temperature mono-well aquifer thermal energy storage (HT-ATES) system in a geothermal reservoir. Geothermics 2015;55:58–68. https://doi.org/10.1016/j.geothermics.2014.12.006.

[24] Fleuchaus P, Godschalk B, Stober I, Blum P. Worldwide application of aquifer thermal energy storage – A review. Renew Sustain Energy Rev 2018. https://doi.org/10.1016/j.rser.2018.06.057.

[25] Gao L, Zhao J, An Q, Wang J, Liu X. A review on system performance studies of aquifer thermal energy storage. Energy Procedia 2017;142:3537–45. https://doi.org/10.1016/j.egypro.2017.12.242.

[26] Bozkaya B, Zeiler W. The effectiveness of night ventilation for the thermal balance of an aquifer thermal energy storage. Appl Therm Eng 2019;146:190–202. https://doi.org/10.1016/j.applthermaleng.2018.09.106.

[27] Bonte M. Impacts Of Shallow Geothermal Energy On Groundwater Quality. London: IWA Publishing 2015.

[28] Bloemendal M, Hartog N. Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. Geothermics 2018;71:306–19. https://doi.org/10.1016/j.geothermics.2017.10.009.

[29] Schout G, Drijver B, Schotting R. The influence of the injection temperature on the recovery efficiency of high temperature aquifer thermal energy storage: Comment on Jeon et al., 2015. Energy 2016;103:107–9. https://doi.org/10.1016/j.energy.2016.02.122.

[30] Pellegrini M, Bianchini A, Guzzini A, Saccani C. Classification through analytic hierarchy process of the barriers in the revamping of traditional district heating networks into low temperature district heating: An Italian case study. Int J Sustain Energy Plan Manag 2019;20:51–66. https://doi.org/10.5278/ijsepm.2019.20.5.

[31] Lu H, Tian P, He L. Evaluating the global potential of aquifer thermal energy storage and determining the potential worldwide hotspots driven by socio-economic, geo-hydrologic and climatic conditions. Renew Sustain Energy Rev 2019. https://doi.org/10.1016/j.rser.2019.06.013.

[32] Bozkaya B, Li R, Labeodan T, Kramer R, Zeiler W. Development and evaluation of a building integrated aquifer thermal storage model. Appl Therm Eng 2017;126:620–9. https://doi.org/10.1016/j.applthermaleng.2017.07.195.

[33] Lesparre N, Robert T, Nguyen F, Boyle A, Hermans T. 4D electrical resistivity tomography (ERT) for aquifer thermal energy storage monitoring. Geothermics 2019;77:368–82. https://doi.org/10.1016/j.geothermics.2018.10.011.

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

[35] Boon DP, Farr GJ, Abesser C, Patton AM, James DR, Schofield DI, et al. Groundwater heat pump feasibility in shallow urban aquifers: Experience from Cardiff, UK. Sci Total Environ 2019. https://doi.org/10.1016/j.scitotenv.2019.133847.

[36] Kessler H, Mathers S, Sobisch HG. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. Comput Geosci 2009;35:1311–21. https://doi.org/10.1016/j.cageo.2008.04.005.

[37] Effersø F, Brown B. Mapping Groundwater with SkyTEM. White Pap 2018:1–14. https://doi.org/10.1192/bjp.177.2.123.

[38] Ma ZD, Jia GS, Cui X, Xia ZH, Zhang YP, Jin LW. Analysis on variations of ground temperature field and thermal radius caused by ground heat exchanger crossing an aquifer layer. Appl Energy 2020;276. https://doi.org/10.1016/j.apenergy.2020.115453.

[39] Bakr M, van Oostrom N, Sommer W. Efficiency of and interference among multiple Aquifer Thermal Energy Storage systems; A Dutch case study. Renew Energy 2013;60:53–62. https://doi.org/10.1016/j.renene.2013.04.004.

[40] Herbert C, Döll P. Global Assessment of Current and Future Groundwater Stress With a Focus on Transboundary Aquifers. Water Resour Res 2019;55:4760–84. https://doi.org/10.1029/2018WR023321.

[41] Bonte M, Stuyfzand PJ, Van Den Berg GA, Hijnen WAM. Effects of aquifer thermal energy storage on groundwater quality and the consequences for drinking water production: A case study from the Netherlands. Water Sci Technol 2011;63:1922–31. https://doi.org/10.2166/wst.2011.189.

[42] Song W, Liu X, Zheng T, Yang J. A review of recharge and clogging in sandstone aquifer. Geothermics 2020;87:101857. https://doi.org/10.1016/j.geothermics.2020.101857.

[43] Possemiers M, Huysmans M, Batelaan O. Influence of Aquifer Thermal Energy Storage on groundwater quality: A review illustrated by seven case studies from Belgium. J Hydrol Reg Stud 2014;2:20–34. https://doi.org/10.1016/j.ejrh.2014.08.001.

[44] Regenspurg S, Alawi M, Norden B, Vieth-Hillebrand A, Blöcher G, Kranz S, et al. Effect of cold and hot water injection on the chemical and microbial composition of an aquifer and implication for its use as an aquifer thermal energy storage. Geothermics 2020. https://doi.org/10.1016/j.geothermics.2019.101747.

[45] Wesselink M, Liu W, Koornneef J, van den Broek M. Conceptual market potential framework of high temperature aquifer thermal energy storage - A case study in the Netherlands. Energy 2018. https://doi.org/10.1016/j.energy.2018.01.072.

[46] Collignon M, Klemetsdal ØS, Møyner O, Alcanié M, Rinaldi AP, Nilsen H, et al. Evaluating thermal losses and storage capacity in high-temperature aquifer thermal energy storage (HT-ATES) systems with well operating limits: insights from a study-case in the Greater Geneva Basin, Switzerland. Geothermics 2020;85:101773. https://doi.org/10.1016/j.geothermics.2019.101773.

[47] Zeghici RM, Oude Essink GHP, Hartog N, Sommer W. Integrated assessment of variable density-viscosity groundwater flow for a high temperature mono-well aquifer thermal energy storage (HT-ATES) system in a geothermal reservoir. Geothermics 2015;55:58–68. https://doi.org/10.1016/j.geothermics.2014.12.006.

[48] Hähnlein S, Bayer P, Ferguson G, Blum P. Sustainability and policy for the thermal use of shallow geothermal energy. Energy Policy 2013;59:914–25. https://doi.org/10.1016/j.enpol.2013.04.040.

[49] Drijver B, Aarssen M Van, Zwart B De. High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable. Innostock 2012 - 12th Int Conf Energy Storage 2012;1:1–10.

[50] Ueckert M, Baumann T. Hydrochemical aspects of high-temperature aquifer storage in carbonaceous aquifers: evaluation of a field study. Geotherm Energy 2019;7. https://doi.org/10.1186/s40517-019-0120-0.

[51] Pasquinelli L, Felder M, Gulbrandsen ML, Hansen TM, Jeon J-S, Molenaar N, et al. The feasibility of high-temperature aquifer thermal energy storage in Denmark: the Gassum Formation in the Stenlille structure. Bull Geol Soc Denmark 2020;68:133–54. https://doi.org/10.37570/bgsd-2020-68-06.

[52] Cheruy F, Dufresne JL, Aït Mesbah S, Grandpeix JY, Wang F. Role of Soil Thermal Inertia in Surface Temperature and Soil Moisture-Temperature Feedback. J Adv Model Earth Syst 2017;9:2906–19. https://doi.org/10.1002/2017MS001036.

[53] Lim HS, Ok JS, Park JS, Lee SJ, Karng SW, Kang YT. Efficiency improvement of energy storage and release by the inlet position control for seasonal thermal energy storage. Int J Heat Mass Transf 2020;151. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119435.

[54] Ann Cruickshank C, Baldwin C. Sensible Thermal Energy Storage: Diurnal and Seasonal. Elsevier Inc.; 2016. https://doi.org/10.1016/B978-0-12-803440-8.00015-4.

[55] Morchio S, Fossa M. On the ground thermal conductivity estimation with coaxial borehole heat exchangers according to different undisturbed ground temperature profiles. Appl Therm Eng 2020;173:115198. https://doi.org/10.1016/j.applthermaleng.2020.115198.

[56] Sarkar J, Bhattacharyya S. Characteristics of medium deep borehole thermal energy storage. Arch Thermodyn 2012;33:23–40. https://doi.org/10.1002/er.

[57] Pavlov GK, Olesen BW. Seasonal ground solar thermal energy storage - Review of systems and applications. 30th ISES Bienn Sol World Congr 2011, SWC 2011 2011;6:4864–74. https://doi.org/10.18086/swc.2011.29.24.

[58] Li C, Mao J, Zhang H, Li Y, Xing Z, Zhu G. Effects of load optimization and geometric arrangement on the thermal performance of borehole heat exchanger fields. Sustain Cities Soc 2017;35:25–35. https://doi.org/10.1016/j.scs.2017.07.018.

[59] Deng J, Wei Q, Liang M, He S, Zhang H. Field test on energy performance of medium-depth geothermal heat pump systems (MD-GHPs). Energy Build 2019;184:289–99. https://doi.org/10.1016/j.enbuild.2018.12.006.

[60] Wang Z, Wang F, Liu J, Ma Z, Han E, Song M. Field test and numerical investigation on the heat transfer characteristics and optimal design of the heat exchangers of a deep borehole ground source heat pump system. Energy Convers Manag 2017;153:603–15. https://doi.org/10.1016/j.enconman.2017.10.038.

[61] Wołoszyn J. Global sensitivity analysis of borehole thermal energy storage efficiency for seventeen material, design and operating parameters. Renew Energy 2020;157:545–59. https://doi.org/10.1016/j.renene.2020.05.047.

[62] Reuss M. The use of borehole thermal energy storage (BTES) systems. vol. i. Woodhead Publishing Limited; 2015. https://doi.org/10.1533/9781782420965.1.117.

[63] Renaldi R, Friedrich D. Techno-economic analysis of a solar district heating system with seasonal thermal storage in the UK. Appl Energy 2019;236:388–400. https://doi.org/10.1016/j.apenergy.2018.11.030.

[64] Schmidt T. Monitoring results from large-scale solar thermal plants with long term storage in Marstal, Brædstrup and Dronninglund, Denmark. 4th Int Sol Dist Heat Conf 2016.

[65] Wong B, Mesquita L. Drake landing solar community: Financial summary and lessons learned. Proc ISES Sol World Congr 2019 IEA SHC Int Conf Sol Heat Cool Build Ind 2019 2020:482–93. https://doi.org/10.18086/swc.2019.11.03.

[66] Mesquita L, McClenahan D, Thornton J, Carriere J, Wong B. Drake Landing solar community: 10 years of operation. ISES Sol World Congr 2017 - IEA SHC Int Conf Sol Heat Cool Build Ind 2017, Proc 2017:333–44. https://doi.org/10.18086/swc.2017.06.09.

[67] Zhu L, Chen S. Sensitivity analysis on borehole thermal energy storage under intermittent operation mode. Energy Procedia 2019;158:4655–63. https://doi.org/10.1016/j.egypro.2019.01.740.

[68] Han C, Yu X. Sensitivity analysis of a vertical geothermal heat pump system. Appl Energy 2016;170:148–60. https://doi.org/10.1016/j.apenergy.2016.02.085.

[69] Schmidt T, Miedaner O. Solar district heating guidelines, Fact sheet 7.2. Food Eng Ser 2005:93–123. https://doi.org/10.1007/0-387-27613-0_4.

[70] Welsch B, Rühaak W, Schulte DO, Bär K, Homuth S, Sass I. A Comparative Study of Medium Deep Borehole Thermal Energy Storage Systems Using Numerical Modelling. Proc World Geotherm Congr 2015 2015:1–6.

[71] Gultekin A, Aydin M, Sisman A. Thermal performance analysis of multiple borehole heat exchangers. Energy Convers Manag 2016;122:544–51. https://doi.org/10.1016/j.enconman.2016.05.086.

[72] Zhang C, Wang Y, Liu Y, Kong X, Wang Q. Computational methods for ground thermal response of multiple borehole heat exchangers: A review. Renew Energy 2018;127:461–73. https://doi.org/10.1016/j.renene.2018.04.083.

[73] Skarphagen H, Banks D, Frengstad BS, Gether H. Design Considerations for Borehole Thermal Energy Storage (BTES): A Review with Emphasis on Convective Heat Transfer. Geofluids 2019;2019. https://doi.org/10.1155/2019/4961781.

[74] Başer T, McCartney JS. Transient evaluation of a soil-borehole thermal energy storage system. Renew Energy 2020;147:2582–98. https://doi.org/10.1016/j.renene.2018.11.012.

[75] Marcotte D, Pasquier P. Unit-response function for ground heat exchanger with parallel, series or mixed borehole arrangement. Renew Energy 2014;68:14–24. https://doi.org/10.1016/j.renene.2014.01.023.

[76] Lim HS, Ok JS, Park JS, Lee SJ, Karng SW, Kang YT. Efficiency improvement of energy storage and release by the inlet position control for seasonal thermal energy storage. Int J Heat Mass Transf 2020;151. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119435.

[77] Guo F, Zhu X, Zhang J, Yang X. Large-scale living laboratory of seasonal borehole thermal energy storage system for urban district heating. Appl Energy 2020. https://doi.org/10.1016/j.apenergy.2020.114763.

[78] Zhu L, Chen S, Yang Y, Tian W, Sun Y, Lyu M. Global sensitivity analysis on borehole thermal energy storage performances under intermittent operation mode in the first charging phase. Renew Energy 2019;143:183–98. https://doi.org/10.1016/j.renene.2019.05.010.

[79] Wei W, Gu C, Huo D, Le Blond S, Yan X. Optimal Borehole Energy Storage Charging Strategy in a Low Carbon Space Heat System. IEEE Access 2018;6:76176–86. https://doi.org/10.1109/ACCESS.2018.2883798.

[80] Beier RA, Ewbank GN. In-Situ Test Thermal Response Tests Interpretations OG&E Ground Source Heat Exchange Study 2012.

[81] Sanner B. Ground Source Heat Pumps – history , development , current status , and future prospects. 12th IEA Heat Pump Conf 2017 2017:1–14.

[82] Rad FM, Fung AS. Solar community heating and cooling system with borehole thermal energy storage - Review of systems. Renew Sustain Energy Rev 2016;60:1550–61. https://doi.org/10.1016/j.rser.2016.03.025.

[83] Badenes B, Sanner B, Mateo Pla MÁ, Cuevas JM, Bartoli F, Ciardelli F, et al. Development of advanced materials guided by numerical simulations to improve performance and cost-efficiency of borehole heat exchangers (BHEs). Energy 2020;201. https://doi.org/10.1016/j.energy.2020.117628.

[84] Kurevija T, Macenić M, Borović S. Impact of grout thermal conductivity on the long-term efficiency of the ground-source heat pump system. Sustain Cities Soc 2017;31:1–11. https://doi.org/10.1016/j.scs.2017.02.009.

[85] Languri EM, Cunningham G. Thermal Energy Storage Systems. Lect Notes Energy 2019;70:169–76. https://doi.org/10.1007/978-3-030-05636-0_9.

[86] Zhang L, Luo X, Huang G, Zhang Q. Comparative analysis of U-pipe location on the sizing of borehole heat exchangers. Appl Therm Eng 2019;150:666–73. https://doi.org/10.1016/j.applthermaleng.2019.01.017.

[87] Schulte DO, Rühaak W, Oladyshkin S, Welsch B, Sass I. Optimization of Medium-Deep Borehole Thermal Energy Storage Systems. Energy Technol 2016;4:104–13. https://doi.org/10.1002/ente.201500254.

[88] Beier RA. Thermal response tests on deep borehole heat exchangers with geothermal gradient. Appl Therm Eng 2020;178:115447. https://doi.org/10.1016/j.applthermaleng.2020.115 447.

[89] Languri EM, Cunningham G. Thermal Energy Storage Systems. Lect Notes Energy 2019;70:169–76. https://doi.org/10.1007/978-3-030-05636-0_9.

[90] Kallesøe AJ, Vangkilde-Pedersen T. HEATSTORE. Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. 2019.

[91] Novo A V., Bayon JR, Castro-Fresno D, Rodriguez-Hernandez J. Review of seasonal heat storage in large basins: Water tanks and gravel-water pits. Appl Energy 2010. https://doi.org/10.1016/j.apenergy.2009.06.033.

[92] Kubiński K, Szabłowski Ł. Dynamic model of solar heating plant with seasonal thermal energy storage. Renew Energy 2020;145:2025–33. https://doi.org/10.1016/j.renene.2019.07.120.

[93] Summary technical description of the SUNSTORE 4 plant in Marstal System history of Marstal The beginning 2013:1–7.

[94] Hakkarainen E, Hannula I, Vakkilainen E. Bioenergy RES hybrids − assessment of status in Finland, Austria, Germany, and Denmark. Biofuels, Bioprod Biorefining 2019;13:1402–16. https://doi.org/10.1002/bbb.2019.

[95] Ahrens MU, Foslie SS, Moen OM, Bantle M, Eikevik TM. Integrated high temperature heat pumps and thermal storage tanks for combined heating and cooling in the industry. Appl Therm Eng 2021;189:116731. https://doi.org/10.1016/j.applthermaleng.2021.116731.

[96] Bai Y, Wang Z, Fan J, Yang M, Li X, Chen L, et al. Numerical and experimental study of an underground water pit for seasonal heat storage. Renew Energy 2020. https://doi.org/10.1016/j.renene.2019.12.080.

[97] Chang C, Wu Z, Navarro H, Li C, Leng G, Li X, et al. Comparative study of the transient natural convection in an underground water pit thermal storage. Appl Energy 2017;208:1162–73. https://doi.org/10.1016/j.apenergy.2017.09.036.

[98] Meister C, Beausoleil-Morrison I. Experimental and modelled performance of a building-scale solar thermal system with seasonal storage water tank. Sol Energy 2021;222:145–59. https://doi.org/10.1016/j.solener.2021.05.025.

[99] Karim A, Burnett A, Fawzia S. Investigation of stratified thermal storage tank performance for heating and cooling applications. Energies 2018;11. https://doi.org/10.3390/en11051049.

[100] Li G. Sensible heat thermal storage energy and exergy performance evaluations. Renew Sustain Energy Rev 2016;53:897–923. https://doi.org/10.1016/j.rser.2015.09.006.

[101] Villasmil W, Fischer LJ, Worlitschek J. A review and evaluation of thermal insulation materials and methods for thermal energy storage systems. Renew Sustain Energy Rev 2019;103:71–84. https://doi.org/10.1016/j.rser.2018.12.040.

[102] Moncho-Esteve IJ, Gasque M, González-Altozano P, Palau-Salvador G. Simple inlet devices and their influence on thermal stratification in a hot water storage tank. Energy Build 2017. https://doi.org/10.1016/j.enbuild.2017.06.012.

[103] García-Marí E, Gasque M, Gutiérrez-Colomer RP, Ibáñez F, González-Altozano P. A new inlet device that enhances thermal stratification during charging in a hot water storage tank. Appl Therm Eng 2013;61:663–9. https://doi.org/10.1016/j.applthermaleng.2013.08.023.

[104] Wilk J, Bałon P, Smusz R, Rejman E, Świątoniowski A, Kiełbasa B, et al. Thermal stratification in the storage tank. Procedia Manuf 2020;47:998–1003. https://doi.org/10.1016/j.promfg.2020.04.306.

[105] Al-Habaibeh A, Shakmak B, Fanshawe S. Assessment of a novel technology for a stratified hot water energy storage – The water snake. Appl Energy 2018;222:189–98. https://doi.org/10.1016/j.apenergy.2018.04.014.

[106] Al-Habaibeh A, Shakmak B, Fanshawe S. The development of an experimental test rig to evaluate the performance of a new technology for stratified hot water storage-The Water Snake. Energy Procedia 2017;142:3644–53. https://doi.org/10.1016/j.egypro.2017.12.257.

[107] Ucar A, Inalli M. Thermal and economic comparisons of solar heating systems with seasonal storage used in building heating. Renew Energy 2008;33:2532–9. https://doi.org/10.1016/j.renene.2008.02.019.

[108] Kocijel L, Mrzljak V, Glažar V. Numerical analysis of geometrical and process parameters influence on temperature stratification in a large volumetric heat storage tank. Energy 2020;194. https://doi.org/10.1016/j.energy.2019.116878.

[109] Chang C, Leng G, Li C, Nie B, She X, Peng X, et al. Investigation on transient cooling process in a water heat storage tank with inclined sidewalls. Energy Procedia 2017;142:142–7. https://doi.org/10.1016/j.egypro.2017.12.023.

[110] Chang C, Nie B, Leng G, Li C, She X, Peng X, et al. Influences of the key characteristic parameters on the thermal performance of a water pit seasonal thermal storage. Energy Procedia 2017;142:495–500. https://doi.org/10.1016/j.egypro.2017.12.077.

[111] Grabmann M, Wallner G, Grabmayer K, Buchberger W, Nitsche D. Effect of thickness and temperature on the global aging behavior of polypropylene random copolymers for seasonal thermal energy storages. Sol Energy 2018;172:152–7. https://doi.org/10.1016/j.solener.2018.05.080.

[112] Schmidt T, Pauschinger T, Sørensen PA, Snijders A, Djebbar R, Boulter R, et al. Design Aspects for Large-scale Pit and Aquifer Thermal Energy Storage for District Heating and Cooling. Energy Procedia 2018;149:585–94. https://doi.org/10.1016/j.egypro.2018.08.223.

[113] Ochs F, Dahash A, Tosatto A, Bianchi Janetti M. Techno-economic planning and construction of cost-effective large-scale hot water thermal energy storage for Renewable District heating systems. Renew Energy 2019. https://doi.org/10.1016/j.renene.2019.11.017.

[114] Shah SK, Aye L, Rismanchi B. Seasonal thermal energy storage system for cold climate zones: A review of recent developments. Renew Sustain Energy Rev 2018;97:38–49. https://doi.org/10.1016/j.rser.2018.08.025.

[115] Huang H, Xiao Y, Lin J, Zhou T, Liu Y, Zhao Q. Thermal characteristics of a seasonal solar assisted heat pump heating system with an underground tank. Sustain Cities Soc 2020;53:101910. https://doi.org/10.1016/j.scs.2019.101910.

[116] Jouhara H, Khordehgah N, Almahmoud S, Delpech B, Chauhan A, Tassou SA. Waste heat recovery technologies and applications. Therm Sci Eng Prog 2018;6:268–89. https://doi.org/10.1016/j.tsep.2018.04.017.

[117] Kermani M, Wallerand AS, Kantor ID, Maréchal F. Generic superstructure synthesis of organic Rankine cycles for waste heat recovery in industrial processes. Appl Energy 2018;212:1203–25. https://doi.org/10.1016/j.apenergy.2017.12.094.

[118] Agathokleous R, Bianchi G, Panayiotou G, Arestia L, Argyrou MC, Georgiou GS, et al. Waste heat recovery in the EU industry and proposed new technologies. Energy Procedia 2019;161:489–96. https://doi.org/10.1016/j.egypro.2019.02.064.

[119] Papapetrou M, Kosmadakis G, Cipollina A, La Commare U, Micale G. Industrial waste heat: Estimation of the technically available resource in the EU per industrial sector, temperature level and country. Appl Therm Eng 2018;138:207–16. https://doi.org/10.1016/j.applthermaleng.2018.04.043.

[120] Norman JB. Industrial Energy Use and Improvement Potential 2013.

[121] Zhang Y, Xiong N, Ge Z, Zhang Y, Hao J, Yang Z. A novel cascade heating system for waste heat recovery in the combined heat and power plant integrating with the steam jet pump. Appl Energy 2020;278:115690. https://doi.org/10.1016/j.apenergy.2020.115690.

[122] Musharavati F, Khanmohammadi S, Pakseresht A, Khanmohammadi S. Waste heat recovery in an intercooled gas turbine system: Exergo-economic analysis, triple objective optimization, and optimum state selection. J Clean Prod 2021;279:123428. https://doi.org/10.1016/j.jclepro.2020.123428.

[123] Wahlroos M, Pärssinen M, Manner J, Syri S. Utilizing data center waste heat in district heating – Impacts on energy efficiency and prospects for low-temperature district heating networks. Energy 2017;140:1228–38. https://doi.org/10.1016/j.energy.2017.08.078.

[124] Law R, Harvey A, Reay D. Opportunities for low-grade heat recovery in the UK food processing industry. Appl Therm Eng 2013;53:188–96. https://doi.org/10.1016/j.applthermaleng.2012.03.024.

[125] Energy E, ECOFYS, College I, Stevenson P, Hyde R. The potential for recovering and using surplus heat from industry Final Report for DECC Element Energy Ecofys 2014:1–47.

[126] Woolley E, Luo Y, Simeone A. Industrial waste heat recovery: A systematic approach. Sustain Energy Technol Assessments 2018;29:50–9. https://doi.org/10.1016/j.seta.2018.07.001.

[127] Frate GF, Ferrari L, Desideri U. Analysis of suitability ranges of high temperature heat pump working fluids. Appl Therm Eng 2019;150:628–40. https://doi.org/10.1016/j.applthermaleng.2019.01.034.

[128] Miró L, Gasia J, Cabeza LF. Thermal energy storage (TES) for industrial waste heat (IWH) recovery: A review. Appl Energy 2016;179:284–301. https://doi.org/10.1016/j.apenergy.2016.06.147.

[129] Guo F, Yang X. Long-term performance simulation and sensitivity analysis of a large-scale seasonal borehole thermal energy storage system for industrial waste heat and solar energy. Energy Build 2021;236:110768. https://doi.org/10.1016/j.enbuild.2021.110768.

[130] Nordell B, Andersson O, Rydell L, Liuzzo-scorpo A. Long-term Performance of the HT-BTES in Emmaboda, Sweden n.d.

[131] Abuasbeh M, Acuña J, Lazzarotto A, Palm B. Long term performance monitoring and KPIs' evaluation of Aquifer Thermal Energy Storage system in Esker formation: Case study in Stockholm. Geothermics 2021;96. https://doi.org/10.1016/j.geothermics.2021.102166.

[132] J. Remmelts S. Tensen CIF. Seasonal thermal energy storage for large scale district heating. 13th IEA Heat Pump Conf 2020 2020.

[133] Bauer D, Marx R, Nußbicker-Lux J, Ochs F, Heidemann W, Müller-Steinhagen H. German central solar heating plants with seasonal heat storage. Sol Energy 2010;84:612–23. https://doi.org/10.1016/j.solener.2009.05.013.