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Geothermal Energy

REVIEW

A review of district energy technology with subsurface thermal storage integration

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Abstract

Renewable energies, such as solar and wind, traditionally suffer from temporal incongruity. Society's energy demand peaks occur at different times of day than the electricity generation potential of a photovoltaic panel or, often, a wind turbine. Heat demand, in particular, is subject to a significant mismatch between the availability of heat (in the summer) and the need for heat (in the winter). Thus, a future energy system design should incorporate underground thermal energy storage (UTES) to avoid this temporal mismatch and emphasize thermal applications. Such a basis of design would introduce new methods of energy arbitrage, encourage the adoption of geothermal systems, and decrease the carbon intensity of society. UTES techniques are becoming increasingly sophisticated. These methods of storage can range from simple seasonal storage for residential structures in a grouted borehole array (BTES), to aquifer thermal energy storage (ATES), deep reservoir storage (RTES) in basins, among others. The method that each of these techniques shares is the use of the earth as a storage medium. UTES can also be characterized for electricity production, but this work largely explores applications in heating and cooling, further limited in scope to sensible heat storage (SHS). Heating and cooling processes—residential, commercial, and industrial—make up large fractions of energy demand in North America. This is also true of other locales. With the increasing concerns of climate change, exacerbated by anthropogenic greenhouse gas emissions, developers and municipal planners are strategizing to decarbonize building heating and cooling at district scales. This review covers the integration of UTES techniques with thermal energy network (TEN) technology across large districts. Though storage has long been in use for conventional district heating networks, designs are rapidly innovating, indicating broader applications of UTES integration with a TEN is advantageous from both an efficiency and economic perspective. This rapid innovation indicates the need for the integrated review offered in this paper.

Introduction

Energy sector decarbonization is a popular topic among policymakers seeking to reduce emissions caused by human activity. Often, the most widely known opportunity for energy decarbonization is in the power sector, with a focus on eliminating emissions from power plants for electricity generation. Cityscapes and low-temperature industrial processes, however, are responsible for about 40–50% of society's emissions (Fleuchaus et al. 2018; Fox et al. 2011; Frederiksen and Werner 2013; IEA 2019). In places such as Canada, emissions from these sectors can be far greater (Government of Canada 2023).

Geothermal and geoexchange technologies can significantly reduce or eliminate emissions from building heating and cooling as well as industrial process heat (Buonocore et al. 2022; Liu et al. 2023). Policymakers and energy system design practitioners may overlook these options for a variety of reasons, such as climate zone perceptions, performance speculation, and capital cost concerns (Li et al. 2023; Maltha 2021; Robins et al. 2021). Methods to overcome the challenges should be scalable solutions to incentivize widespread adoption.

Solutions to these challenges may come in the form of thermal energy networks (TEN) and underground thermal energy storage (UTES) across large geographic areas. UTES in this paper is restricted to sensible heat storage (SHS), though others may expand the definition to include latent or thermochemical heat storage. Several researchers have studied these important technologies. However, there has yet to be a systematic and comprehensive review of these studies. The goal of this review is to provide readers insights into potential synergies between the TEN and UTES, serving as a first reference for those investigating synchronous uses of the technologies.

The remainder of this paper provides a detailed review of district energy and TEN applications, details variations of UTES with their advantages and disadvantages, discusses surface system configurations that accompany them, and discusses challenges and opportunities in regulation, policy, and subsidy, concluding with a discussion of public perception and social license.

Thermal energy network review

Introduction to thermal energy networks

District energy has undergone tremendous changes since the first commercial operations began in New York during the year 1877 with the Holly Steam Combination Company (Collins 1959). In those earliest days, steam distribution was advantageous because it did not require pumping and was later a byproduct of many communities' electric generators. The high operating temperatures and pressures, however, posed a great risk to system engineers and consumer safety (Lund et al. 2014). Therefore, a more than century long decrease in operating temperatures and pressures began (Fig. 1). Lower operating temperatures for a district energy network also make more resources applicable as a source and sink for heating or cooling (Lund et al. 2014; Zeh et al. 2021). By 2022, an interest in replacing existing gas grids with networked water systems of lower but varying temperature regimes resulted in the phrase "thermal energy networks" being codified or proposed in law across several US states (Cordes et al. 2023; Parker et al. 2022; Williams et al. 2023). This district energy evolution, taking the technology from high temperatures with fossil fuel sources to low temperatures and low emissions with multiple sources, has made the TEN a fundamental part of building stock decarbonization strategies.

Thermal energy network flexibility

Many of these new sources for a TEN are waste heat or byproducts of other processes, including other buildings, across a community (Walker et al. 2017). While one building

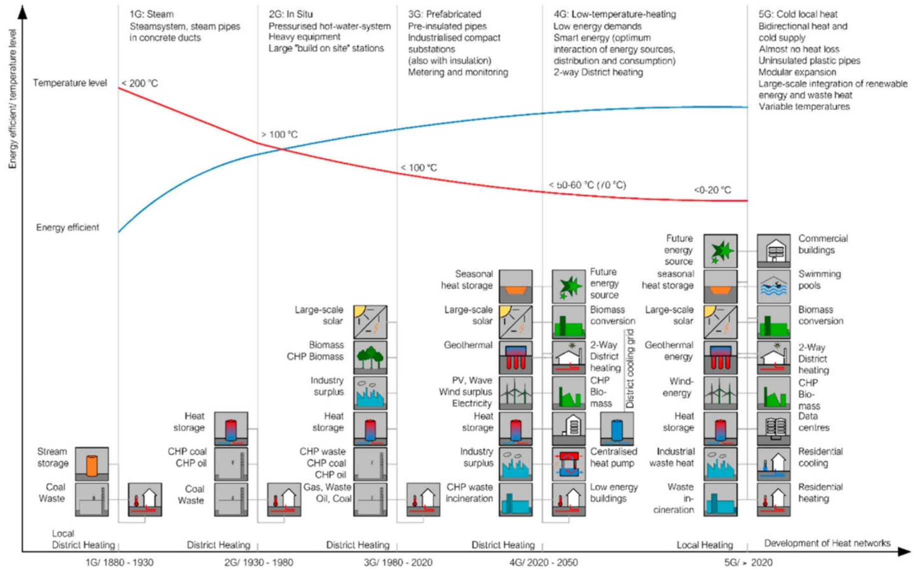

Fig. 1 Generations of district energy with progressive efficiency increase and design temperature reduction (Zeh et al. 2021)

in a community is demanding heating another may be demanding cooling, introducing the potential for load sharing. This load sharing or waste heat valorization can be a signature feature of a TEN (Lund et al. 2014; Wirtz et al. 2020). Waste heat valorization is simply the recycling of heat byproducts for a useful purpose. Load sharing allows simultaneous heating and cooling processes to exchange their heat byproduct with another across the TEN, thereby reducing primary energy consumption. Byproduct or waste heat are typically of little value to the primary generator and, therefore, may be purchased at low- or no-cost. These heat sources may decrease consumer costs on a TEN, reducing one of the financial barriers to the broader adoption of utility-style heating and cooling systems.

Since Lund et al. (2014), district heating generations have been defined by their operating temperature regimes. Some newcomers to district energy are calling fifth generation district heating and cooling (5GDHC) thermal energy networks (Home Energy Efficiency Team 2024). The TEN, however, references all generations of district energy systems—as all are a thermal network. It may be more appropriate to consider the TEN as a 'network of networks' at the city scale. The TEN may serve to connect several different topologies of district energy systems (Fig. 2), offering hydraulic separation with energy transfer stations or substations which modulate several different operating temperature regimes or 'generations' at a large scale. Examples of the TEN include projects in Leuven, Belgium (Pattijn and Baumans 2017) and Technical University of Berlin, Germany (Stanica et al. 2021). Wirtz et al. (2022) surveyed low-temperature networks across Germany and Switzerland and found seven designed to operate at substantially different temperature regimes based on the season, a feature also reflective of TEN flexibility.

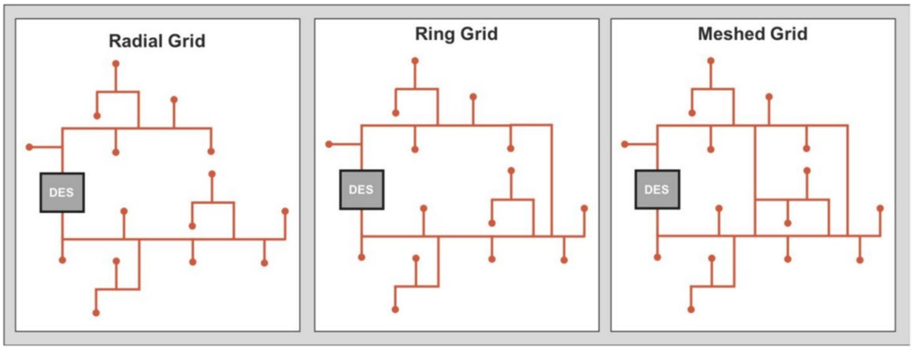

Fig. 2 District energy network topologies (von Rhein et al. 2019). Several different configurations for typical district heating and cooling networks exist with various implications for the ease of thermo-hydraulic design

Design considerations

The hydraulic design of the pipes in a TEN usually has two options: single pipe (Sommer et al. 2020), or two-pipe distribution (Boesten et al. 2019; Li and Wang 2014; von Rhein et al. 2019). Recent literature explores the advantages of disadvantages of one configuration over the other in the context of the district heating and cooling generations (Gudmundsson et al. 2022; Lund et al. 2021; Zeh et al. 2021). A main finding of this review, however, is that the inputs for a TEN are temperature agnostic, allowing good engineering practice and other socio-economic needs to dictate the thermo-hydraulic design and phasing out of other system operating conditions across communities. In-building equipment selection is also outside of the scope of this review, though countless numbers of heating, ventilation, air conditioning, and refrigeration (HVACR) technologies can reject or extract heat from a TEN.

In a two-pipe distribution system (Fig. 3) a cold line and a hot line are used. When a building is rejecting heat, the fluid travels from the cold line, into the structure for heat exchange and upgrading (usually with a heat pump) if necessary, then back to the hot line. The primary advantage of this configuration is that heat sources and sinks with higher fluid temperature differentials can be separated to avoid mixing, with the potential for end-use performance improvements (Boesten et al. 2019). One of the disadvantages of the two-pipe configuration is that heat losses and gains may be incurred that degrade performance improvements (Averfalk and Werner 2020; Sulzer and Hangartner 2014).

In a single pipe portion of a TEN, one pipe distributes all the heat of fluids from the sources and sinks. The advantages include simplicity in consumer node connections, modularity, and a reduction in heat losses. Individual circulating pumps at consumer nodes reduce the primary distribution pumping requirements. Single pipe hydraulic distribution is designed for a large bandwidth of temperature drift. Temperature drift is the variation in continuous operating temperatures for the working fluid across the network. Most often the temperature range is near ambient, or near ground temperatures, not exceeding 30°C (86°F) (Lindhe et al. 2024; Sommer et al. 2020), though existing high-temperature systems can integrate, given proper controls. Lower operating temperatures make the connection of far more sources and sinks possible while reducing unwanted heat losses or gains (Sommer et al. 2020). The single pipe design is also in use for "last

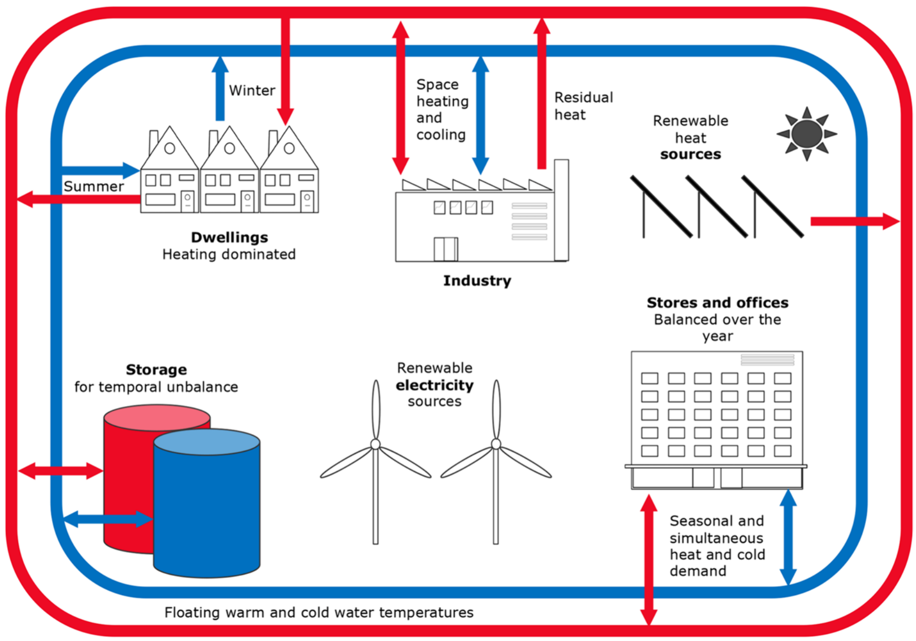

Fig. 3 Two-pipe thermal energy network (Boesten et al. 2019)

mile" heat valorization of high-temperature networks when the working fluid is changed from a water-based solution to CO_2 (Noreskar 2022). The disadvantages include higher electricity draws for pumping and larger diameter pipe requirements than previous district heating and cooling generations (Jebamalai 2023, Chapter 6; Sommer et al. 2020).

Underground thermal energy storage review

Introduction to underground thermal energy storage

Underground Thermal Energy Storage (UTES) represents an array of techniques for storing thermal energy within subsurface geological formations over a long period—usually a heating or cooling season, though it may be diurnal. Storing thermal energy in the subsurface leverages the rock medium beneath the built environment of a city or facility, providing a space-saving technique that improves the energy efficiency of heating and cooling processes. If a surface process is rejecting heat or extracting heat, it will inevitably be emitting a higher or lower temperature waste heat. Capturing that cool-th or heat-th waste heat, often available from intermittent renewable resources or other industrial processes, is possible with UTES. This section reviews a spectrum of UTES approaches, including aquifer thermal energy storage (ATES), reservoir thermal energy storage (RTES), and various engineered solutions such as borehole thermal energy storage (BTES), ground heat exchangers (GHX) and cavern thermal energy storage (CTES). Overall, UTES applications can support a TEN, mitigating society's reliance on fossil fuels and reducing greenhouse gas emissions while providing flexible and cost-effective solutions for heating, cooling, and industrial processes.

There are many different forms of UTES across literature and operating in the field. Many forms are not widely used, and others are only distinguishable from one another by construction types (Fleuchaus et al. 2018; Matos et al. 2019; Sarbu and Sebarchievici

2018). All SHS UTES capacity relies on the fundamental equation relating heat, a heat-containing medium, and heat capacity, given by Sarbu and Sebarchievici (2018):

$$Q_\mathrm{s} = \int_{T_\mathrm{i}}^{T_\mathrm{f}} m c_\mathrm{p} \mathrm{d}t \tag{1}$$

where Q_s is the quantity of heat stored in joules, m is the mass of heat storage in kg, c_p is the specific heat capacity in J/(kg*K), T_i is the initial temperature in °C, T_f is the final temperature in °C.

Underground thermal energy storage variations

Aquifer thermal energy storage

ATES first took root in Shanghai, China, during the 1960s (Gao et al. 2009). By 1975, a government-funded ATES project was underway in Mobile, Alabama, USA (Tsang 1978). Storing thermal energy from existing power plants and solar was a focus from the beginning (Rabbimov et al. 1971; Tsang 1978), where the characterized hot water temperatures were often in excess of 120 °C (248 °F). It was not widely understood, however, that temperatures below 25 °C (77 °F) would be adequate for large-scale thermal energy applications within the same aquifers.

Today ATES systems are largely in use for applications in building heating and cooling. ATES systems are popular in Europe, where high adoption rates exist in the Netherlands (Bloemendal 2018; Fleuchaus et al. 2018; Nielsen et al. 2019), often with characteristically low temperatures between about 5–20 °C (40–68 °F) (Fig. 4). This lower-temperature storage is sufficient when supplemented with a ground-source heat pump (GSHP). In those building heating and cooling applications, ATES can more appropriately be thought of as an energy efficiency measure that requires seasonal balance. Seasonal balance of the warm and cold plume is possible by combining mechanical supplements such as dry coolers and reversing valves (Bloemendal 2018; Dickinson et al. 2009).

The most common configuration for building heating and cooling is a pair of wells, each receiving warm or cool water for storage in a highly permeable formation. The depth of drilling is less important in ATES than both the water quality and the salinity (Bloemendal 2018). With a seasonal switch, the thermal plume of one well is extracted, with fluids being heat exchanged at the surface before reinjection. Where seasonal load imbalance exists, a supplemental dry cooler or other mechanical solution may be used to rebalance the thermal plumes in the subsurface. Heat recovery efficiency in heating mode may range from 50 to 80%, while cold plume recovery may approach 100% (Matos et al. 2019; Van Lopik et al. 2016). In many cases, the ambient temperatures of the aquifer may be used for passive cooling without a heat pump (Fig. 5).

Where free (passive) cooling can be introduced to the mechanical system, significant improvements in the coefficient of performance (COP) are possible. The COP is the ratio of useful heating or cooling provided to the work input required, typically electricity. When COP improves, the imported electricity for the vapor compression cycle of a heat pump is reduced or eliminated, and the heating and cooling system becomes far more sustainable. An example of COP comparisons from Sweden for ATES variants appears in Table 1. Here it becomes apparent that free cooling and heating applications have the highest COP values, since the only electrical input for the system is from circulation or

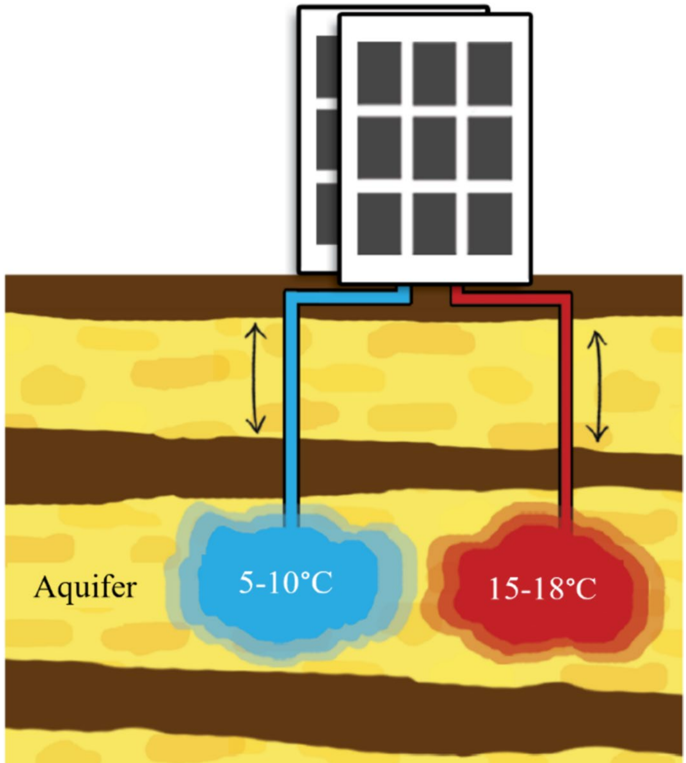

Fig. 4 ATES doublet with a warm and cold well for building heating and cooling (modified from: Bloemendal 2018)

production pumping. This can be contrasted with a typical GHX-connected GSHP COP of 3–6 or commercial air-source heat pumps (ASHP) COP of 1.5–1.8 in cold weather operation (Buonocore et al. 2022; Kitz 2021).

Reservoir thermal energy storage

Hot and cold storage in deeper reservoirs is increasingly distinguished in literature from ATES (Pepin et al. 2021), more widely referred to as RTES. Although RTES and ATES both use subsurface pore space for fluid storage, Pepin et al. (2021) delineates RTES by describing the reservoirs as those containing slower-moving fluids with mature geochemical characteristics. More simply, less saline fluids—those often used for drinking water—are found in the same formations useful for ATES, whereas RTES fluids are brackish and are not useful for drinking water without additional treatment. The regulatory burden for drinking water uses other than consumption is high, perhaps making RTES more useful for the large-scale collection of waste heat and industrial process loads (Matos et al. 2019; Pepin et al. 2021; Zhang et al. 2023).

Heat recovery efficiencies in these systems are thought to improve over time, much like ATES, as the reservoir equilibrates to the hot or cold plume. Van Lopik et al. (2016), referring to deep, high-temperature (HT), brackish reservoir thermal storage as HT-ATES, found recovery efficiencies approach 70% while accounting for fluid density differences, increasing up to 78% without free convection. Each instance was run over 4 cycles for 80°C injection temperatures. Pepin et al. (2021) found that cooling recovery

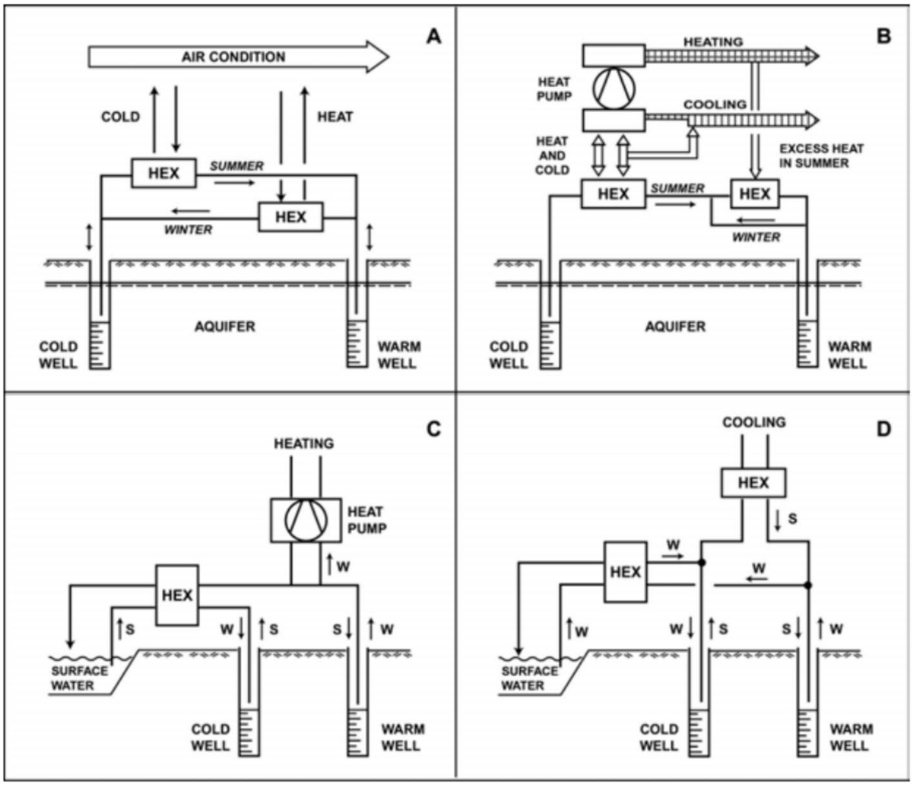

Fig. 5 Various schematic representations of ATES applications, including passive heating and cooling (**A**), heating and cooling with a heat pump (**B**), heating only (**C**), and multivalent passive cooling (**D**) (Andersson et al. 2003)

Table 1 Examples of ATES performance from Sweden, considering baseline fossil costs (Andersson et al. 2003)

Application	Performance factor	Energy savings (%)	Payback (years)
1. Passive heating and cooling	20–40	90–95	0–2
2. Heating and cooling with a heat pump	5–7	80–87	1–3
3. Heating only with a heat pump	3–4	60–75	4–8
4. Multivalent passive cooling	20–60	90–97	0–2

efficiency was the most effective means of thermal recovery in RTES, with values ranging from 96.3 to 99.3% over a 5-year cycling period. To achieve such efficiencies, Pepin et al. (2021) recommend priming the reservoir with cool-th or heating plumes prior to peak operational performance cycles. The initial reservoir temperature is generally expected to have negligible effects on the long-term performance of RTES, with more influential factors including advective flow, convection, temperature-induced fluid buoyancy, and vertical permeability (Matos et al. 2019; Pepin et al. 2021; Van Lopik et al. 2016).

Variations on reservoir thermal energy storage Physical differences in RTES can be divided into two primary categories—porous media and cavity storage (Matos et al. 2019). CTES or cavity storage systems (Fig. 6) are either found naturally in the subsurface or they may be engineered, as is the case in the dissolution of salt caverns. Porous

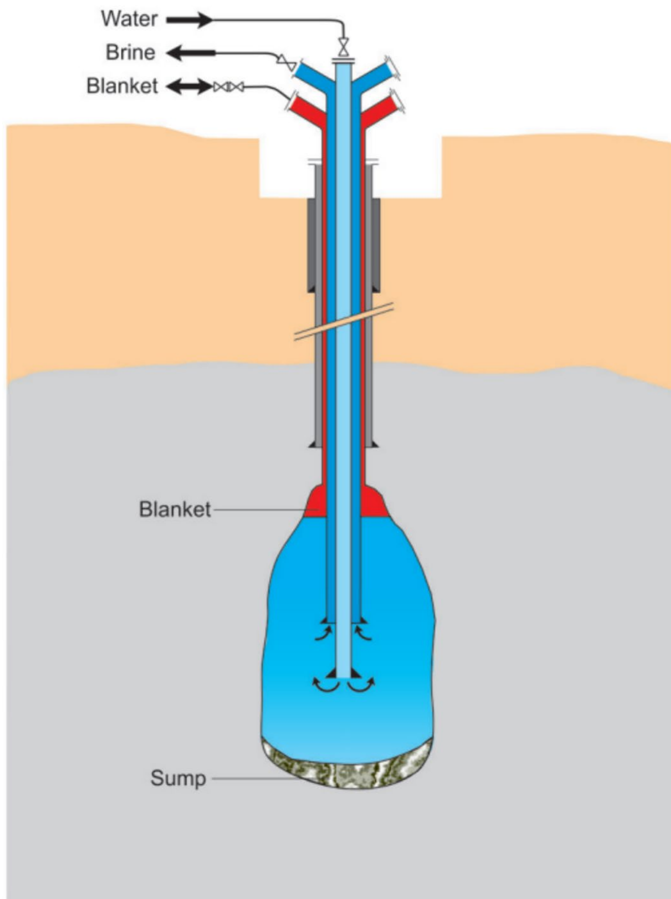

Fig. 6 Salt cavern dissolution, useful for CTES (DEEP.KBB GmbH, n.d. 2023). Fluids can be injected into the center of the salt domes, dissolving salt, which can then be extracted from an outer brine annulus. A surrounding pressure blanket of fluids controls further vertical dissolution

media RTES is most frequently discussed in sedimentary aquifers or depleted oil and gas reservoirs. Reservoir stimulation, such as hydraulic stimulation, may be in use for either variant of RTES. These two categories are further defined by the capacity of storage they can handle. Porous media can have far greater capacity than CTES, though the quantity of sites available for this method is limited by geologic conditions. In CTES, hard rock may be excavated, evaporites may be targeted for dissolution, or existing mine galleries may be repurposed (Hahn et al. 2023; Matos et al. 2019).

Relationship between ATES and RTES

ATES and RTES each have similar physical relationships for thermal storage volume and thermal plume sizes.

Thermal storage capacity can further be described as the energy flux per square meter of reservoir (Burns et al. 2020), by the formula:

$$E'_{\mathrm{th}} = bn\rho_{\mathrm{w}}c_{\mathrm{w}}\Delta T \tag{2}$$

where E'_{th} is the thermal storage capacity per unit area in Joules per m^2. b is the reservoir thickness in meters. n is the porosity. ρ_w is the density of water in kilogram per m^3. c_w is the specific heat of water in Joules per kilogram °C. ΔT is the temperature differential from production to injection.

The radius of a thermal plume for either ATES or RTES is dependent on the fluid and rock properties (Bloemendal 2018), describe by this formula:

$$R_{th} = \sqrt{\frac{c_w V_{in}}{c_{aq} \pi L}} \tag{3}$$

where R_{th} is the radius of the thermal plume in meters. c_w is the volumetric heat capacity of the reservoir fluid in MJ per m^3 Kelvin. c_{aq} is the volumetric heat capacity of the aquifer in MJ per m^3 Kelvin. V_{in} is the volume of fluid injected into the well in cubic meters. L is the well screen length in meters.

In certain jurisdictions, such as the Netherlands this thermal radius is the basis of regulated well separation factors. Bloemendal et al. (2014) suggests that these regulated factors—often some multiple of the thermal radius—are over dimensioned to the point that they may inhibit sustainable heating and cooling adoption through the permitting of under- or unused subsurface volumes. Therefore, careful use of these physical relationships between ATES and RTES is necessary for both engineering and policy.

Other engineered UTES

Other methods of engineered UTES include BTES and the GHX. These are the most prevalent forms of UTES across the world, making up 72% of worldwide geothermal (ground source) heating and cooling applications (Lund and Toth 2021). Some literature segregates borehole arrays or geoexchange from BTES (Liu et al. 2021). In this sense, an individual vertical borehole, typically reaching 100’–850’ (30 m–260 m), may provide a medium with which to store heat seasonally (Kavanaugh and Rafferty 2014; Nordell 1993; Zymnis and Whittle 2021). In borehole arrays, it is most common to use reverse return field gathering systems in buried plastic pipes (Kavanaugh and Rafferty 2014), while a pure BTES system would have a seasonally reversible flow to leverage a lateral stratification of high and low temperatures across a dense array with hydraulic connection in series, typically cylindrical (Fig. 7). Liu et al. (2021) describes many of the developing differences between BTES and GHX, including emerging modeling, control, and installation techniques. The difference is largely an engineering preference with performance and more sector coupling potential for the reversible BTES (Kitz 2021; Reuss 2015).

Some refer to the borehole arrays as GHX rather than BTES. The GHX arrays rely on adequate separation distances between the boreholes to prevent thermal interference from the distributed heat transfer processes. The composition of these arrays may consist of closed loop u-tubes inserted into a grouted borehole, or open-hole coaxial completions with annular flow to a production liner in competent bedrock, though other minor variants exist. The convective heat transfer is a minor part of the closed loop u-tube, otherwise dominated by the conductive heat transfer through the grout and rock or soil, while the coaxial borehole may have annular flow—the

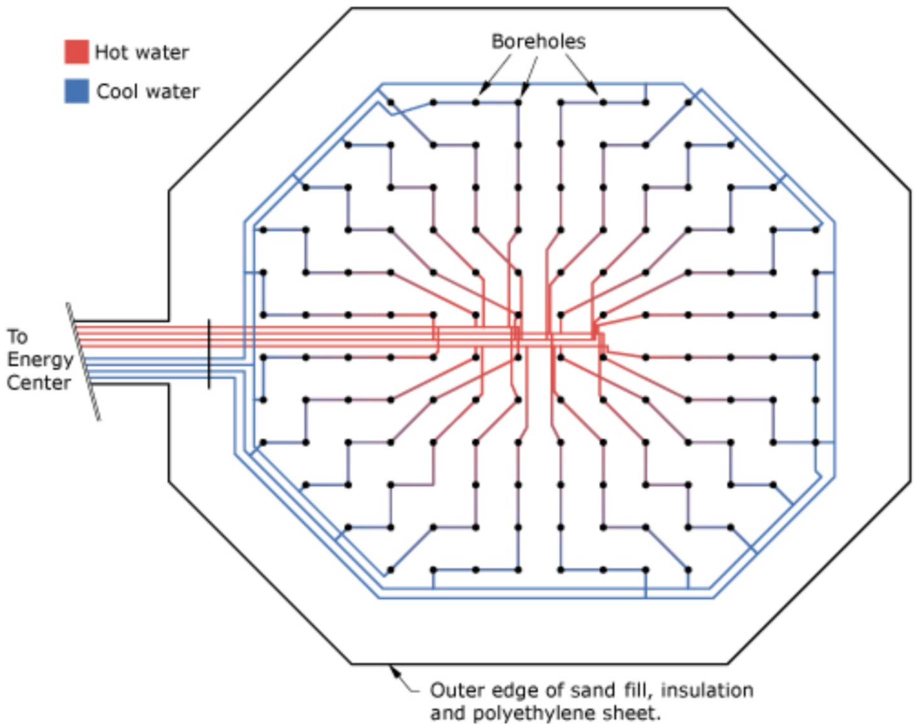

Fig. 7 Drake's Landing Solar Community (DLSC) BTES schematic top view of the high-temperature heating system ("Borehole Thermal Energy Storage: DLSC," n.d. 2023) During operations, hot water is injected into the center of the system with connections of pipes in series. Heat transfer to the surrounding ground results in cooler fluids being produced from the outer portion of the BTES

convective heat transfer—exposed directly to the borehole wall. Another minor fraction of the heat transfer in an ungrouted coaxial completion may be from fractured flow arising from the borehole wall, also known as advection. Fundamentally, the same mechanisms of heat transfer are taking place in the subsurface for both BTES and GHX, albeit at different scales and with a different magnitude of influence on the surrounding soil or rock material.

BTES is conceptualized in a slightly different manner than GHX. In BTES, no balance may be required on the load side to achieve the unambiguous goal of supplying thermal energy at times of demand that vary from different times of thermal energy production (Reuss 2015). Furthermore, BTES is appropriate for high-temperature thermal storage, as is the case in Drake's Landing, Alberta, Canada (Sibbitt et al. 2012). The materials selection may change from plastic pipes to metal. Rather than operating with one direction of flow, a seasonal switch—or reversing valve—can change the direction of fluid flow to leverage the lateral temperature differences from the inside of the cylinder to the outside. Some have suggested a functional application for BTES is coupling with a thermal power generation cycle (Falta et al. 2023; McDaniel & Kosanovic 2016), though the energy efficiency of thermal energy valorization for high grade production presents techno-economic challenges. Characterization of the BTES annual heat extraction efficiency (E) is dependent on the following formulas (Catolico et al. 2016):

$$E = \frac{J_{\text{out}}}{J_{\text{in}}} \tag{4}$$

$$J_{\text{out}} = \sum_{j=1}^{n} \left(\text{T}c_j - \text{T}o_j\right) Q_j \Delta t_j c \rho B \tag{5}$$

$$J_{\text{in}} = \sum_{j=1}^{m} \left(\text{Tc}_j - \text{To}_j\right) Q_j \Delta t_j c \rho B \tag{6}$$

where J_{out} is energy extracted during discharging periods. J_{in} is the energy injected during charging periods. m is the total charging periods for the year. n is the total discharging periods for the year. Tc_j is the temperature in the center of the BTES in °C. To_j is the temperature at the outside of the BTES in °C. Q_j is the volumetric flow rate in m^3 per second. Δt_j is the jth time interval in seconds. c is the heat capacity of water in Joules per kilogram °C. ρ is the density of water in kilograms per m^3. B is the number of borehole series in the cylinder.

Variations on GHX

The remainder of the discussion on GHX systems will focus on the closed-loop borehole array variations, as they are most relevant to UTES. For a discussion of other GHX variants the reader is encouraged to reference Kavanaugh and Rafferty (2014) or Minea (2022).

Monovalent ground heat exchangers Geoexchange or closed-loop borehole thermal storage systems connected to a heat pump, have been used since 1946 (Kemler 1947). Often, a single u-tube made of plastic pipe, typically 25–32 mm (1″–2″) in diameter, is inserted into a borehole of about 60–260 m (200–850’) depth to extract and reject heat from a connected load. The pipe and fluid properties are selected to optimize heat transfer to cost ratios, minimize friction losses, accommodate tremie lines for grouting, and prevent pipe bursting, among other reasons (Gagné-Boisvert and Bernier 2017; McCartney et al. 2017; Proffer 2022). The u-tube is frequently backfilled with thermally enhanced low-permeability grout to protect drinking water from contamination (Fig. 8).

A load is the heating and cooling demand of the end use, most often a building for commercial or residential use. The seasonal balance of the heating and cooling load is essential for the reliable operation of a monovalent GHX. Monovalent simply means that there is one source or sink for heat in the heat exchanger. The reverse return borehole fields are in sections of 8–16 boreholes connected in series to headers, which run to manifolds at the plant room (Fig. 9). The connected loads must be carefully considered before designing the borehole field to prevent thermal saturation. Thermal saturation is often the result of load imbalance between heating and cooling hours over the course of a year. Simulations should be undertaken over the long term to understand system behavior (Kavanaugh and Rafferty 2014). The most frequently used simulation techniques are based on line source methods because they are inexpensive, easy to understand for production-level engineers, and highly accurate for decadal scale planning

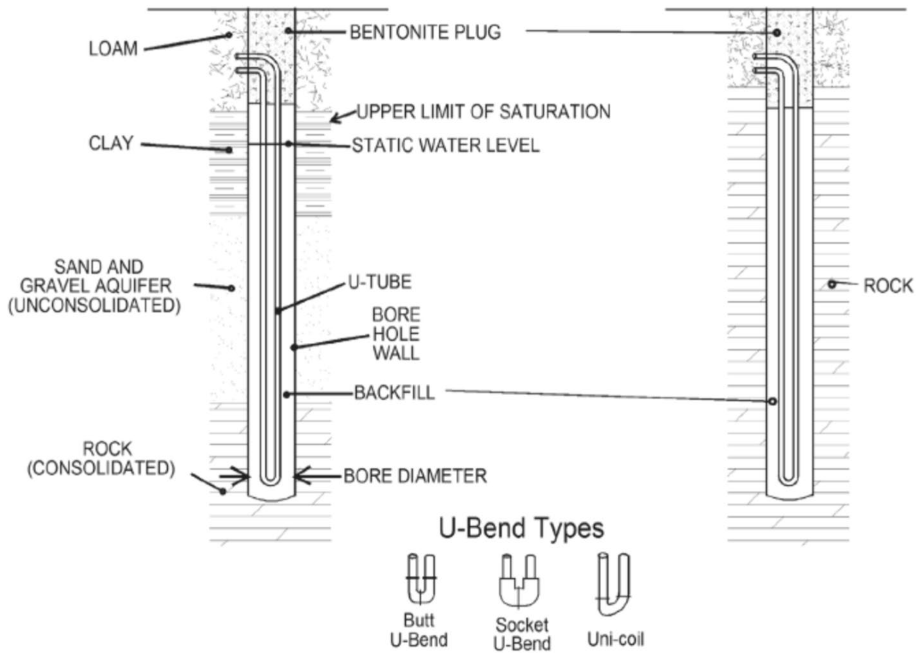

Fig. 8 Conventional borehole heat exchangers (Kavanaugh and Rafferty 2014)

Fig. 9 Borehole array manifold in the plant room at the Calgary International Airport, May 2023. The manifold connects pipes to the borehole field for GHX arrays

(Cullin et al. 2015; Wei Victor 2019). Without thoughtful load balancing on the borehole arrays, the heat recovery efficiency may be unacceptably low (Schincariol and Raymond 2023).

Heat recovery efficiency for GHX and BTES is similar, often approaching 40% (Matos et al. 2019). Wang et al. (2021), while referring to GHX as BTES, set up a sandbox experiment of short-term (4 h) TES capacity using a plate heat exchanger passthrough in combination with vertical, closed loop boreholes, finding a decreasing heat recovery and increasing heat loss to surrounding soils with increasing injection temperatures. Therefore, a narrower temperature bandwidth, the differential between injection temperatures and extraction temperature requirements, is preferable to increase heat recovery efficiency. Wang et al. (2021) note the decrease of heat recovery efficiency, even at lower injection temperatures—those closer to the initial formation temperature—after many cycles of heat rejection and abstraction.

Multivalent ground heat exchangers Similar to the monovalent system configuration, the energy system connected to multiple heat sources (multivalency) meets the heating and cooling needs of connected loads. The difference, often, is an efficiency gain. Where the preferable narrow temperature bandwidth cannot be achieved, as described by Wang et al. (2021), because the heating and cooling demands are imbalanced, the GHX is supplemented by additional sources or sinks. In practice, many early multi-valent geoexchange systems had boiler backup, reportedly to decrease the necessary drilling for a GHX (Jensen 2015; Rafferty 1996; Staffell et al. 2012; Wagers and Wagers 1985). Problems in material durability or thermal saturation often arise when the design attempts to connect a low-temperature system (e.g. borehole heat exchange) with a high-temperature system (e.g. gas or electric boiler). This is attributable to the lack of understanding on the part of the operator, the design engineer, or both (Kavanaugh and Rafferty 2014).

One possible way to compensate for load profiles with a significant seasonal imbalance (Fig. 10) is multivalency using only low-temperature resources (those below ~ 35 °C, or 95°F) on the ground loop. This prevents pipe damage, avoids tripping ground-source heat pumps at high temperatures, and provides an opportunity for the designer to increase the seasonal performance factor for the system. Tripping in this context refers to a state where the electrical demand exceeds the available service, resulting in a breaker trip and equipment shut down. Multiple low-temperature sources can be connected to the same borehole with double u-tubes (Fig. 11). A solar-assisted ground-source heat pump (SAGSHP) borehole energy storage configuration (Fig. 12) can improve overall efficiency for heating dominant loads while increasing the life of the borehole array (Lazzarin 2020). Such multivalent systems were first suggested as a serious capital cost limiting factor during a 1982 conference on the subject (Aranovitch et al. 1984; De Hoe et al. 1982). These systems work in warm and cool climates and can be coupled with any UTES technology. A solar thermal plate collector contributing as little as 10% of the total heat extraction for the system can significantly improve the long-term performance of the borehole field (Busato et al. 2013). Another important benefit of multivalency is the reduction in capital costs associated with drilling. Chiasson and Yavuzturk (2003) estimated that the total length of the borehole field could be reduced by 4.5–7.7 m (14.4’–25.3’) for every additional 1 m^2 (10.8 ft^2) of solar thermal collector connected to the heating and cooling system. Borehole length is generally dependent on the following formula (Stauffer et al. 2014):

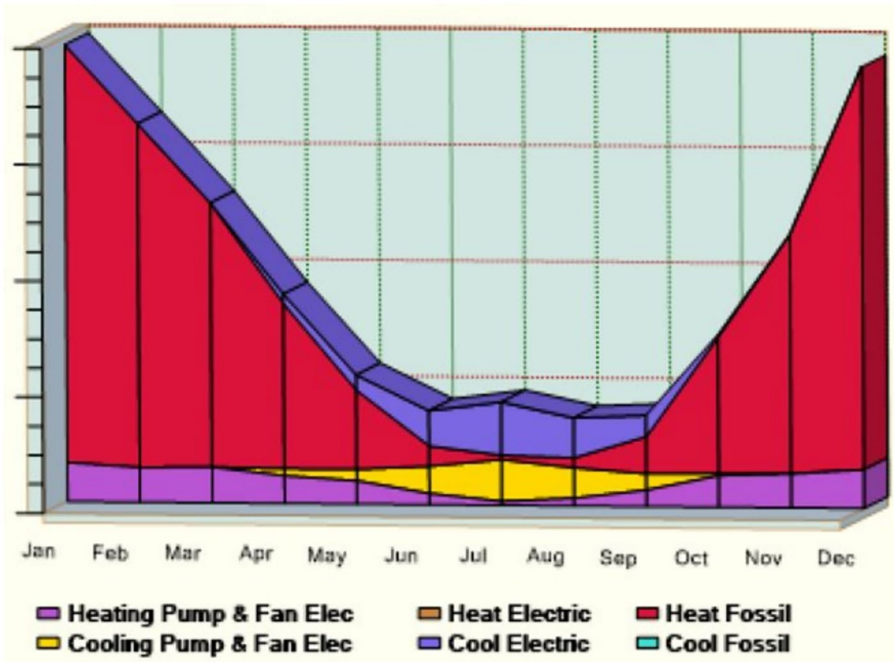

Fig. 10 Dimensionless load profile of typical residential heating and cooling demand in Calgary, Alberta structure (IAPMO 2022)

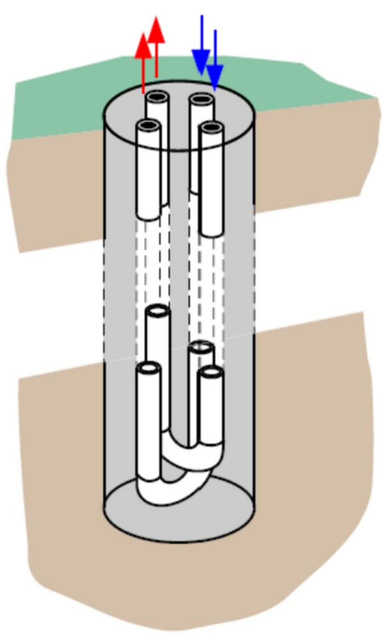

Fig. 11 Double u-tube borehole design can be coupled with multiple heat sources (Rees 2016)

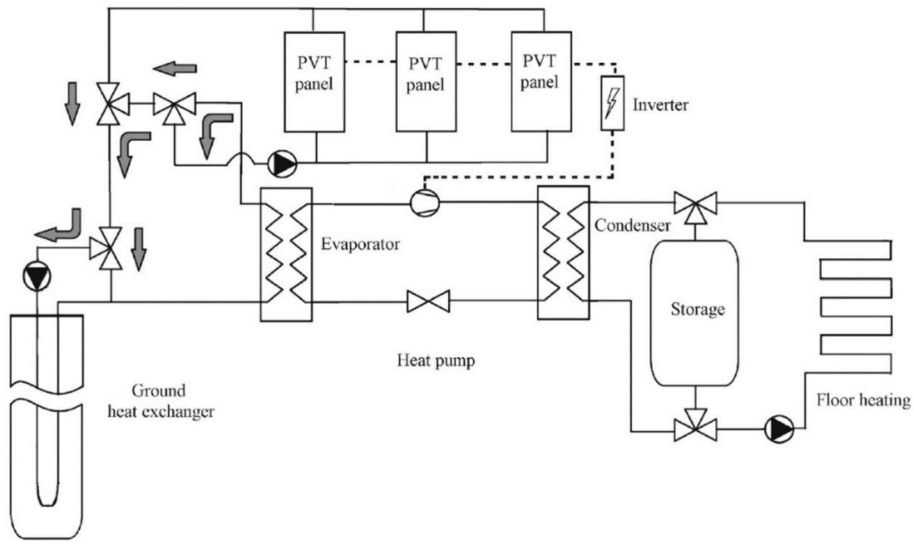

Fig. 12 Solar-assisted borehole thermal energy storage heating system (Lazzarin 2020). Photovoltaic thermal panels support ground-source heat pumps to produce hot fluids for domestic hot water and space conditioning

$$H = \frac{E - \frac{E}{\mathrm{SPF}}}{tq_{tb}} \quad (7)$$

where H is the borehole length in meters. E is the annual energy demand in Wh. SPF is the seasonal performance factor, usually between 3 and 5. t is the operating time of the system in hours. q_{tb} is the specific heat extraction in W per meter of borehole length.

A major advantage for the BTES or GHX variations is the closed loop interaction with lithologies in a given locale. This reduces the regulatory barriers when compared to groundwater exploitation methods and does not limit the engineer or designer to a specific geologic setting (Matos et al. 2019). No fluids are produced from formation during operation, and the owner is therefore not responsible for proving non-consumptive use to authorities having jurisdiction (AHJ). Standard permitting for installations reaching a depth of less than 150 m (500') does not often require special mineral or oil and gas permitting, a regulatory barrier in many locations across North America. Even the allowable drilling depth in the legacy oil and gas regulatory regime is changing, with a recent example of New York State allowing drilling depths to exceed the arbitrary 150 m (500') (NY Governor's Press Office 2023).

Subsurface considerations

The UTES designer faces numerous subsurface considerations. These may include designing the coupled surface and subsurface system for efficient operation over decadal scales (Pepin et al. 2021; Schincariol and Raymond 2023), reducing capital costs to support UTES implementations, overcoming the challenge of competing groundwater and pore space uses (Matos et al. 2019), other constraints imposed by the formation fluid—such as near borehole damage caused by temperature-induced solids precipitation (Hahn et al. 2023; Kumar et al. 2021) or thermal plume migration from buoyancy changes (Van Lopik et al. 2016)—and geologic settings—such as faults, other structural features (Matos et al. 2019), or the geomechanical limits of pressure-induced stress from production and injection cycles (Zhang et al. 2023), among others.

In GHX and BTES, shallow lithology plays a key role in heat extraction efficiency (Fig. 13). Placement of a GHX in primarily unconsolidated till versus high thermal conductivity granites will have a direct impact on capital costs, vis-à-vis drilling lengths (Chiasson and Yavuzturk 2003; Cullin et al. 2015; Grobe et al. 2009). Dehkordi and Schincariol (2014) and Schincariol and Raymond (2023) each make arguments that unregulated borehole heat exchanger completions should be subject to greater scrutiny from AHJs as most designs fail to capture any understanding of groundwater interaction with the systems, often resulting in premature failures or exorbitant capital costs from drilling. Dehkordi and Schincariol (2014) and Schincariol and Raymond (2023) suggest that numerical modeling methods provide a solution to incumbent analytical techniques. No arguments, however, could be found in literature that address the inherent cost increases associated with the additional rigor of numerical modeling in BTES or GHX design.

In ATES, it is preferable to find high permeability, low salinity aquifers, with relatively low regional flow rates (Bloemendal 2018; Fleuchaus et al. 2018). Having a thermal plume which drifts away from the recoverable zone surrounding a well incurs thermal losses which may not be economically or physically possible to extract from the system. Furthermore, thermal pollution of the same aquifer can decrease to overall performance between neighboring ATES systems, particularly where adoption rates are high (Bloemendal et al. 2014).

In RTES, it is preferable to exploit higher salinity formations from a regulatory standpoint (Bloemendal et al. 2014; Matos et al. 2019). Where there is less competition for pore space, particularly that used for drinking water, there may be more opportunity for RTES. Furthermore, RTES requires consideration of many of the more complicated

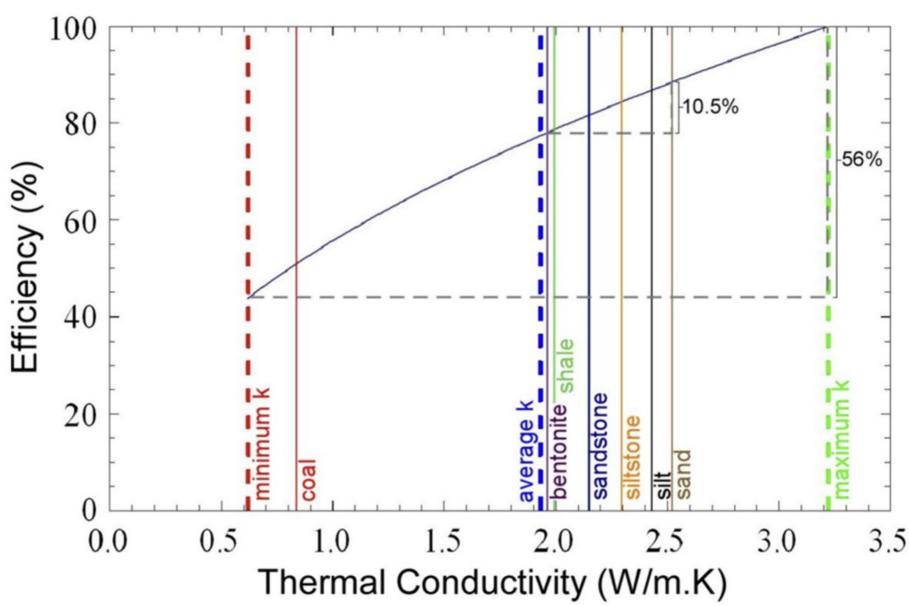

Fig. 13 Thermal conductivity of the shallow lithology has a direct impact on heat extraction efficiency for the ground source heat pump supported GHX (Grobe et al. 2009)

geologic criteria related to conventional geothermal systems, including specific consideration of structures like traps, pressure at depth, or even induced seismicity (Burns et al. 2020; Matos et al. 2019).

Matos et al. (2019) suggest that seismic monitoring for UTES systems is necessary in the pre- and post-development phases. Induced seismicity, for example, might be an affordable risk when operators are producing a transportable commodity from the subsurface at greater distances from population centers, such as oil and gas (Ivanova 2023). This, however, is not the case for most urban or suburban utilities with a relatively low revenue margin—often with rates controlled by public service commissions (Ross 2022). The tolerance for failure is much less for sustainable heating and cooling. Formation deformation or subsidence are other related risks which span across technology sets from GHX to RTES. Fleuchaus and Blum (2017) investigated an event in Germany where GHX drillers failed to control fluid leakage into a bisected anhydrite formation, causing significant ground swelling, resulting in more than €500,000 of damage to historic buildings. Returning to points made by Schincariol and Raymond (2023), no UTES or TEN project is strictly a mechanical engineering problem or strictly a hydrogeological problem. Interdisciplinary teaming is necessary for safety and design performance.

Combining underground thermal energy storage and thermal energy network applications

Coupled system outlook

A TEN is a piped network of working fluids, usually water, which can connect geothermal sources with geoexchange sources and sinks, or other thermal resources (solar thermal, heat rejection from cooling operations, electric-to-thermal conversions, or many others) across a geographic area. Demands for both heating and cooling across the TEN will have a diurnal variation and seasonal variation which provides the opportunity to implement different scales of UTES. Storing large amounts of hot or cold fluids in UTES allows the energy system to produce from subsurface resources at a more convenient time, charge the storage, and release the energy when the demand arises. This increased capability over conventional district heating and cooling is often referred to as demand-side management (DSM) (Nielsen et al. 2019). The benefits of combining conventional district heating and surface thermal storage is widely known (Bertelsen and Petersen 2017; Jebamalai et al. 2020; Lake et al. 2017). Therefore, drawing a line from UTES to the point of energy consumption is made possible using a TEN. Optimization potential increases for a variety of metrics in a TEN when coupled with UTES (Buonocore et al. 2022; Lake et al. 2017; Oh and Beckers 2023).

As a matter of economics, this scalable DSM solution may also alleviate the capital-intensive nature of individual geothermal and geoexchange systems. Communities, including commercial and residential, or industrial process heat users, may benefit from higher heating and cooling efficiencies with the savings of a utility-scale product (Oh and Beckers 2023). Li et al. (2023) found that, although a district heating and cooling network costs about twice as much in upfront capital costs as an electrification using ASHP, a network connected to a load balanced BTES shows a levelized cost of heating and cooling 2/3 that of ASHP. Notably, the expected life of equipment for ASHP is 20 years, while the balanced BTES subsurface material is expected to operate for a minimum of 50 years. Furthermore, once the network is in place, innovative solutions to heat recovery become possible, with the potential for ongoing network expansion (Boesten et al. 2019; Sommer et al. 2020).

Regardless of the chosen subsurface storage configuration, a TEN may support the connection of multiple sources and sinks, thereby providing a transportation method for thermal energy with a variety of end-use applications. A real estate developer, policymaker, electric utility company, or other stakeholder may become the beneficiary of high-performance thermal energy exchange across vast geographic areas while mitigating problematic heat losses common in older generations of district energy systems (Sommer et al. 2020). A TEN is also modular, making system expansion more feasible from the outset and increasing the value proposition of geothermal and geoexchange systems. Furthermore, existing district energy systems (typically operating at ~ 25–100 °C, or 77–212°F)—are often coined as first, second, third, fourth, or fifth-generation district heating and cooling systems (Buffa et al. 2019; Frederiksen & Werner 2013; Lund et al. 2014, 2018)—may become one small part of a larger TEN with outlying networks operating at divergent temperatures (Fig. 14).

A recent investigation of five campus-style ambient temperature loops, a variant of the TEN operating with seasonal drift temperatures using closed-loop borehole arrays,

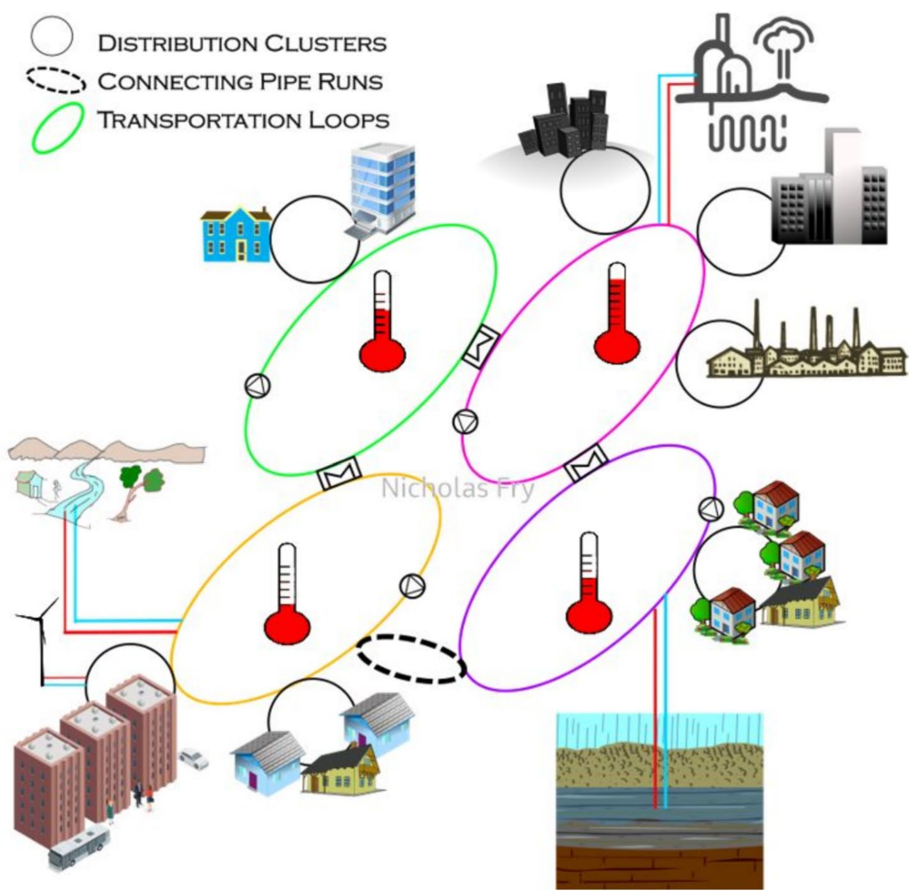

Fig. 14 Thermal energy network as the all-encompassing term for district energy at every temperature regime, connecting cityscapes. Multiple sources and sinks, including UTES, can support the TEN

shows average COPs of 3.1–13.7 with no significant difference in cost or performance found between centralized energy plants or distributed heat pump systems (Oh and Beckers 2023). This finding opens the possibility of integrating many different sources and sinks without the need to marry all future TENs to a specific topology or temperature regime. In this sense, greenfield development is relatively easy since the only concerns are reducing the overall temperature regime and eliminating combustion processes onsite.

Literature that attempts to capture the regional techno-economic benefits of combining UTES & TEN applications does not yet exist. Liu et al. (2023) studied no deployment and mass deployment impacts for individual GSHP systems, finding several scenarios with avoided costs of transmission and distribution infrastructure construction approaching or exceeding $1 trillion in the US market alone. Keeping that metric in mind, where the typical individual GSHP COP ranges from 3 to 6, and the typical TEN COP ranges from 6 to 14 (Oh and Beckers 2023)—with potentials for COP values in excess of 20 (Andersson et al. 2003), it is apparent that the combination of UTES & TEN technologies warrants significant attention from policymakers, researchers, and design engineers alike.

Regulatory, subsidy, and social license outlook

Market potential for the adoption, construction, and implementation of subsurface supported TENs is a function of regulations' ability to overcome entrenched industry practices, the regional ability to address parity in subsidy, and developers' willingness to seek societal trust. These include adopter education, first costs (capital), regulatory structures, engineering design and site selection (see Sect. "Underground thermal energy storage review"), among others (Fleuchaus et al. 2018; Li et al. 2023; Maltha 2021; Matos et al. 2019; Sommer et al. 2020). Potential adopters of UTES technologies, or UTES adjacent technologies—such as heat pumps or chillers, are often unaware or opposed to their implementation because of misperception, misguidance, or misplaced subsidy (Barich et al. 2022; Karytsas and Theodoropoulou 2014; Spampatti et al. 2022; Strauss 2022). Understanding the influence of initial investment costs on sustainable energy system adoption is an important starting point.

In terms of first costs, the expenses associated with drilling are significantly higher than conventional combustion-driven equipment and solutions (Hanova et al. 2007; Li et al. 2023; Robins et al. 2021). In a US context, Strauss (2022) describes a long history of undulating subsidies for geothermal heating and cooling applications that stifle advanced manufacturing development and adoption. Furthermore, fewer than ¼ states provide owner–operator credits for realized avoided energy costs from geothermal system installations. Buonocore et al. (2022) found that a drastic shift towards seasonal thermal energy storage and the deployment of ground-source heating and cooling systems is necessary to avoid the implementation of inappropriate electrification strategies—such as the use of ASHP—across significant portions of the US. In addition to financial challenges, the regulatory environment plays a crucial role in shaping the feasibility and development of UTES systems.

Regulatory structures often impair the development of UTES through groundwater law, mineral and petroleum law, or public service monopolization (Matos et al. 2019;

NY Governor's Press Office 2023; Strauss 2022). Prior to 2023, New York—like many other locations throughout the US—had regulations in place which made deep commercial structure heating and cooling retrofits using UTES more onerous by requiring geothermal drilling below a certain depth to draw the same permits as oil and gas field developers. Another example is from the State of Minnesota, where law prohibits Health Commissioners from issuing more than 10 permits per year for groundwater-producing systems with a maximum yield between 20 and 50 gallons per minute (Jennifer 2022). Despite lacking any basis in hydrogeological performance norms, this law still exists as a response to an unfortunate history of shallow geothermal systems with poor design practices, leading to a drawdown of drinking water aquifers and various permutations of ATES and geoexchange prohibitions from 1989 through today (Lundy et al. 2022, sec. 6.1.4; Minnesota Department of Natural Resources 2015). Some portions of this statute are under review, which may improve the potential for large-scale UTES systems adoption in Minnesota (Office of the Revisor of Statutes 2024). As regulatory conditions shape the legal landscape of UTES, public perception provides reciprocating influences on market potential that developers should consider.

Public perception of UTES—much like geothermal—reflects education level, socioeconomic status, scientific awareness, social and political trust, and outreach (Barich et al. 2022; Karytsas and Theodoropoulou 2014). Karytsas and Theodoropoulou (2014) performed a survey in Greece on GSHP system knowledge, finding that about 75% of respondents considered themselves well-versed in environmental issues, and only 40% of respondents were aware of geothermal heating and cooling applications for their own residence. Studying ATES in New York State, Maltha (2021) found preexisting negative biases on the part of engineers and public stakeholders were the result of hearsay about the performance of other geothermal and geoexchange heating and cooling systems. Both Kantrowitz (2009) and Maltha (2021) cite a history of incompetent design and drilling practices, mainly in the 1980s and 1990s, which contributed to UTES's bad reputation in Sweden, the US, and Canada. Barich et al. (2022) explored geothermal systems implementation in the context of a social license to operate (SLO)—an unwritten agreement of implied consent, falling outside the bounds of the regulatory structure, from stakeholders to industry or businesses that wish to deploy geothermal technologies. Elements of the geothermal SLO can become positive or negative, evoking risk to development and operations. These elements for high-enthalpy through low-enthalpy systems include the perception of mutual benefit, environmental factors such as groundwater contamination risks, noise pollution, and trust. Barich et al. (2022) went on to describe several case studies with TEN implementation—such as the case of Tres Cantos, Madrid—where retaining expert consultants (a proponent) to educate and defend end-user interests established significant SLO, while more complex construction projects—such as the geothermal district heating system in Szeged—may raise many anxieties with stakeholders having a preexisting distrust of regional political conditions. Building on the weight of SLO is the accompanying messaging on UTES and TEN development, which has outsized impacts on public acceptance of the now niche technologies.

It is also important to frame messaging for combinations of UTES and TEN projects. Knowing the audience is important when applying transparency to stakeholder engagement. Spampatti et al. (2022) tested explanations of negative and positive risks in a survey of stakeholders across Western Switzerland. They found that messages such as "…There is still a need for further geological data to improve the geothermal cost performance. The availability of local geothermal reserves are also poorly understood" resulted in a strong downward effect on the acceptance of shallow geothermal system development, where the opposite was true of more favorable statements (less significant increase in acceptance with shorter term impact on perception), such as "For decades, geothermal heating has provided safe, reliable, environmentally benign heating used in a sustainable manner with mature technologies to provide direct heating services." Engineers, geoscientists, and support staff must, therefore, be aware of the need for coherent messaging throughout stakeholder engagement and design phases, from pre-feasibility through commissioning.

Conclusion

There is a temporal and geographic mismatch between the production of many waste heat resources and the heating or cooling demand of buildings. To address the temporal mismatch UTES can capture these streams of waste heat. To overcome the geographic challenge of matching the supply of waste heat to the heating and cooling demands of buildings or industrial processes, a TEN is an appropriate application.

This review examines different implementation techniques of UTES that may integrate with TEN technologies to decarbonize building stock heating and cooling. While it is evident that the GHX remains the predominant application of UTES due to regulatory simplicity and the closed-loop interaction with geology, the future may shift towards porous media storage. This shift may result from advantages that include larger storage capacities and lower costs per unit of energy storage. Such technological shifts are crucial for the mass adoption of effective decarbonization strategies, leveraging both direct use and heat pump-supported applications.

Despite the many advantages that UTES may offer for sustainable city-scale heating and cooling, implementation barriers remain, including public awareness, inconsistencies in subsidy, and complex regulatory frameworks that only sometimes comport with good engineering or hydrogeological practices. Integration of UTES with the TEN may help overcome some of these barriers by sharing the mutual benefits of higher efficiencies and reliability across utility and end-user stakeholder groups.

Sustainable heating and cooling are now a regulatory requirement set forth by the authorities in many jurisdictions. This review reaffirms that widescale geothermal and UTES integration will be a key to meeting those requirements sustainably. This review also reveals a critical lack of integrated UTES–TEN research and implementation. Moving forward, it is imperative that researchers, policymakers, engineers, geoscientists, and other stakeholder groups collaborate to address challenges for these sustainable energy systems. Such collaboration may revolutionize building system efficiencies, paving the way for carbon–neutral thermal utilities.

Appendix A: Terminology dictionary

$/kWh—Cost in dollars per kilowatt-hour, encompassing installation and operating costs.

Aquifer thermal energy storage (ATES)—Using subsurface water-bearing zones for heat storage and reclamation.

Borehole thermal energy storage (BTES)—A system utilizing the working fluid within boreholes for storing heat within adjacent materials, usually with grouted borehole arrays.

Capacity—Maximum thermal energy output potential, often measured in refrigerant tons.

Cavity thermal energy storage (CTES)—Using underground open spaces for heat storage.

Coefficient of performance (COP)—Ratio of useful heating/cooling to work input, typically electricity.

Demand side management (DSM)—Strategies to manage and reduce energy consumption for efficiency.

Diurnal variation—Fluctuations in energy demand or temperatures over a day.

Domestic hot water (DHW)—Hot water used for various purposes in the residential and commercial sector, including cooking, cleaning, and other activities.

End-user—The recipient of thermal energy in various applications.

Energy flux—Rate of energy transfer per unit area in thermal storage systems.

Energy savings—Comparison of energy use to alternative heating/cooling systems.

Entering water temperature—Temperature of water entering a heat pump or chiller appliance.

Formation temperature—Temperature of the aquifer or ground in geothermal systems.

Geoexchange—Using subsurface space, fluids, or materials for heating and cooling heat exchange.

Ground heat exchanger (GHX)—A subsurface heat exchanger that utilizes the relatively constant temperature of the ground as a source or sink for heating and cooling structures.

Ground source heat pump (GSHP)—Heat pump using ground source systems for temperature modulation.

Grouted borehole arrays—Clustered drilled boreholes for thermal energy transfer.

Heat pump—Device transferring heat energy from a source to a heat sink by way of the vapor compression cycle.

Thermo-hydraulic design—Design of piping systems in TENs for efficient fluid transport and heat transfer.

Induced seismicity—Earth movements caused by human activities, often associated with fluid injection.

Injection and extraction wells—Wells used for injecting/extracting fluids in ATES and RTES systems.

Levelized cost of heat (LCOH)—Total cost of heat production over a system's lifespan.

Load balancing—Even distribution of thermal demand (heating and cooling) prevent thermal saturation in subsurface heat storage systems.

Load profile—The energy consumption of a building over the course of a period. A sizable proportion is typically composed of space heating and cooling, which can vary seasonally.

Payback period—Time taken for energy savings to offset initial installation costs.

Permeability—A measure of the ability of materials to allow fluid flow.

Reservoir thermal energy storage (RTES)—A system utilizing a body of water in a permeable or open subsurface zone as a medium of heat storage.

Recovery factor—Recovery factor, sometimes called the heat recovery factor, is a the ratio of heat recovered to that heat which is injected to a UTES system.

Seasonal balance—Maintaining equilibrium in thermal injection and extraction over seasons in UTES.

Seasonal performance factor (SPF)—This metric is similar to the coefficient of performance (COP), but it typically applies over a longer period, such as a season or a year. While the COP measures performance at a specific moment, the SPF provides a broader view by considering performance over an extended period. These terms are often used interchangeably in literature.

Sensible heat storage (SHS)—Heat storage in a medium without phase change.

Solar-assisted ground source heat pumps (SAGSHP)—Heat pumps using solar heat to aid ground temperature maintenance.

Thermal conductivity—Material's ability to conduct heat.

Thermal drift—Variation in continuous operating temperatures of working fluid in a TEN.

Thermal energy networks (TEN)—Catch all phrase for multiple generations of district heating and cooling. Capable of operating as modular, nested networks.

Thermal imbalance—Difference in heating and cooling load in a system over a time frame.

Thermal saturation—Reduced capacity for heat transfer in a geothermal system due to unbalanced thermal loading resulting in severe, long-term temperature offset from initial conditions and design expectations.

Underground thermal energy storage (UTES)—Broad term for subsurface thermal energy storage methods.

Waste heat valorization—Recycling of waste heat for practical use in heating and cooling applications.

Well separation factor—Regulated distance between thermal wells to prevent system interference, sometimes on the basis of radial thermal plume calculations.

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NF contributed to the conceptualization, investigation, and writing, including the original draft preparation. PA contributed to the investigation and writing, including reviews. RT contributed to the gathering of resources, including the writing of the original glossary. RS provided supervision, project administration, and writing, including reviewing and editing. AM provided supervision and writing, including reviewing and editing.

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Competing interests
The authors declare that they have no competing interests.

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