Underground Thermal Energy Storage at Scale: A Review of Techniques and a Case Study for Calgary, Alberta

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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 (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 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 earth as a storage medium. UTES can also be characterized for electricity production, but this work largely explores applications in heating and cooling.

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 work focuses on a review of UTES techniques, specific applications in cold climates, and elaborates on the experimental designs of UTES in Calgary. The research team at the University of Calgary is working with major oil and gas companies, real estate developers, and other energy service companies to implement next generation geothermal energy systems. With a new storage method such as UTES, the techno-economic barrier for low-carbon district energy decreases, paving a low- and no-subsidy pathway for geothermal projects in Alberta.

1. Introduction

Energy sector decarbonization is a popular topic among policymakers. 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 & 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. 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. Cold climate regions, such as continental Canada, present design challenges for engineers more frequently trained in fossil fuel combustions systems (Kantrowitz, 2009). Perception or hearsay about the performance of geothermal and geoexchange heating and cooling systems may deter technology adopters or customers from considering subsurface energy exploitation (Maltha, 2021). Upfront expenditures for the individual geothermal and geoexchange heating and cooling operations present barriers to market entry (Hanova et al., 2007). Convincing policymakers and practitioners alike is, therefore, a paramount concern for geothermal- and geoexchange-supported decarbonization of building stock and industrial process loads.

Cold climate challenges result from a high fraction of the thermal load being apportioned to heating. On average, and dependent on load type, there is a higher fraction of heating than there is for cooling. Alberta residential structures have a disproportionately high fraction of total building energy consumption directed towards space heating and domestic hot water (DHW) preparation, for example (Figure 1). Encouraging greater adoption for geothermal and geoexchange systems may require multivalent energy applications in conjunction with thermal energy storage (TES).
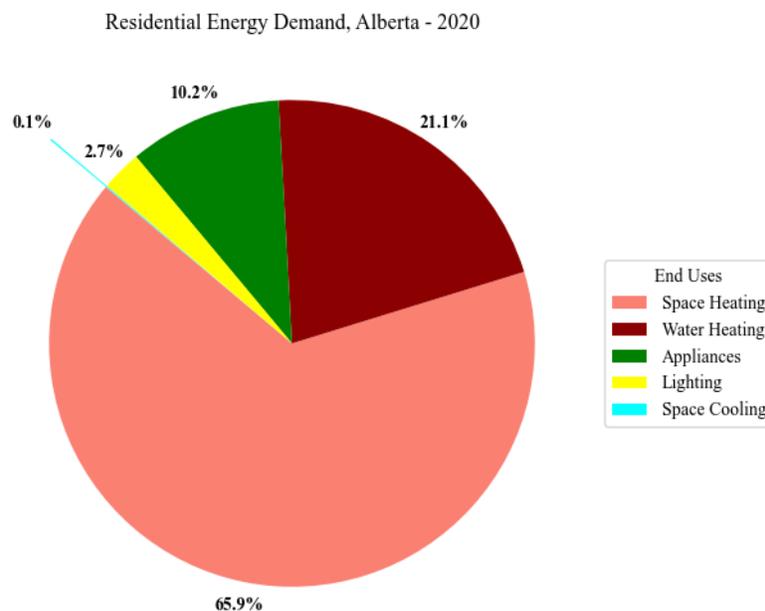

Figure 1 Alberta residential structure energy end-use allocations (adopted from: Government of Canada, 2023).

Upfront capital costs often make the adoption of sustainable energy systems, such as geothermal, a socio-economic indicator. Those that can afford to decarbonize heating and cooling processes will pay for the luxury while those that cannot are left to pay for ailing fossil fuel infrastructure. Scaling geothermal and geoexchange energy systems to a cityscape, connecting industrial processes wherever possible, is an engineering problem that can alleviate these tangible socio-economic factors (Buonocore et al., 2022). Solutions 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.

The remainder of this paper will detail common terminology, variations of UTES with their advantages and disadvantages, surface system configurations that accompany them, planning methodologies, implications, among other considerations. After establishing the concepts of UTES, a developing case study from Southern Calgary will highlight a preliminary development strategy for widescale geothermal adoption in Alberta.

1.1 Terminology

A variety of terms exist for geothermal and geoexchange systems. In most cases, except for very shallow systems of less than 15 meters depth (50'), heat flow, groundwater flow, and thermal conductivity of intersected materials are the dominant equilibrium influence on a geothermal system. Bowen (1989) notes this definition in detail and suggests the segregation between geoexchange and geothermal is not based on physical constraints. For the purposes of this paper, integrated energy systems – those which serve societal needs – are of primary interest and geothermal or geoexchange may be used interchangeably.

$/kWh – Represents the cost in dollars per kilowatt-hour and is a measure of electricity cost, both installation and operating costs are typically considered in calculation.

Aquifer Thermal Energy Storage (ATES) – An underground water source that is used as a medium of heat storage.

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 – Measures the maximum output potential of thermal energy under ideal conditions. Typically (in North America) measured in refrigerant tons for heat generation.

Cavity Thermal Energy Storage (CTES) – A system utilizing an open space underground to store heat.

Coefficient of Performance (COP) – Measures the ratio of useful heating or cooling provided to the work input required, typically electricity. This varies based on the heat pump technology, design, and operating conditions. The COP typically ranges from 3 to 5 for ground source heat pumps.

Domestic Hot Water (DHW) – Hot water that is used in the residential sector typically for showering, cleaning dishes, and other activities. Can be supplied with a water heating tank or prepared instantaneously with various energy sources.

End-user – This is the thermal demand. End-uses may include residential, commercial, industrial, or other applications with their characterization in a network as a node or agent.

Energy Savings – Compares energy savings to alternative heating and cooling systems.

Entering Water Temperature – Refers to the temperature of water entering the heat pump.

Formation Temperature – Refers to the temperature of the aquifer or the ground.

Geoexchange – A system utilizing subsurface space as a source or sink for heating and cooling.

Ground Heat Exchanger (GHX) – A system utilizing the relatively constant temperature of the ground to act as a source or sink, for heating and cooling structures.

Induced Seismicity – Seismic activity caused by human activity. In the case of geothermal systems, drilling, disruption of aquifers, and alteration of underground activities can trigger microearthquakes or other earth deformations.

Levelized Cost of Heat (LCOH) – Measures the cost of heat production over the lifespan of said system. Takes into account capital costs, maintenance costs, operational costs, and the expected lifespan.

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. Load profiles are useful in assessing temporal variations of electrical or heating consumption, such as diurnal or seasonal.

Payback Period – Estimates the time for the energy cost savings to offset the upfront capital costs of installation.

Permeability – Measures the ability for a material to allow fluids flowing through it. Rocks with higher permeability permit better rates of heat transfer in the context of geothermal systems.

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.

Sensible Heat Storage (SHS) – A system storing heat in a medium that does not undergo phase change.

Solar-Assisted Ground Source Heat Pumps (SAGSHPs) – A heat pump utilizing solar heat to compensate with loss of ground temperature over prolonged periods of extraction, especially in colder climates.

Solar Supply Temperature – Refers to the temperature of the heat transfer fluid from the solar collectors.

Thermal Conductivity – Measures the ability of a material to conduct heat. Rocks with higher thermal conductivity enable more efficient heat extraction in the context of geothermal systems.

Thermal Energy Networks (TEN) – A distributed district heat and cooling system for usage by multiple end points. Capable of operating across many design and drift temperatures.

Thermal Imbalance – Prolonged heat extraction or rejection can deplete thermal resources, reducing system efficiency. This is especially relevant in heating-dominated climates and can challenge the sustainability of geothermal energy.

Underground Thermal Energy Storage (UTES) – An umbrella term for all methods of subsurface energy storage.

1.2 Applications

A TEN is a piped network of working fluids, usually water, that can connect geothermal sources with geoexchange sources and sinks, or other thermal resources across a geographic area. 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 releasing the energy when the demand arises. Drawing a line from UTES to the point of energy consumption is made possible using a TEN.

As a matter of economics, this scalable 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. Once the network is in place, innovative solutions to heat recovery become possible, with the potential for ongoing network expansion (Boesten et al., 2019). Lower operating temperatures for a TEN also makes more resources applicable as a source and sink for heating or cooling.

Such a network also has the potential to decrease emissions, decrease consumer costs, and aggregate the capital costs of geothermal development to reduce financial barriers to market entry for large organizations. TEN applications mark a shift change in district energy design, making the connection of high and low temperature resources possible. They alone are not generational, as defined by Lund et al. (2014), but are a method of strategically connecting all existing district energy while offering a way to expand the systems in new ways. A typical topology for the TEN is the ringed network (Figure 2), with large transportation lines connecting hydraulically separated distribution clusters.
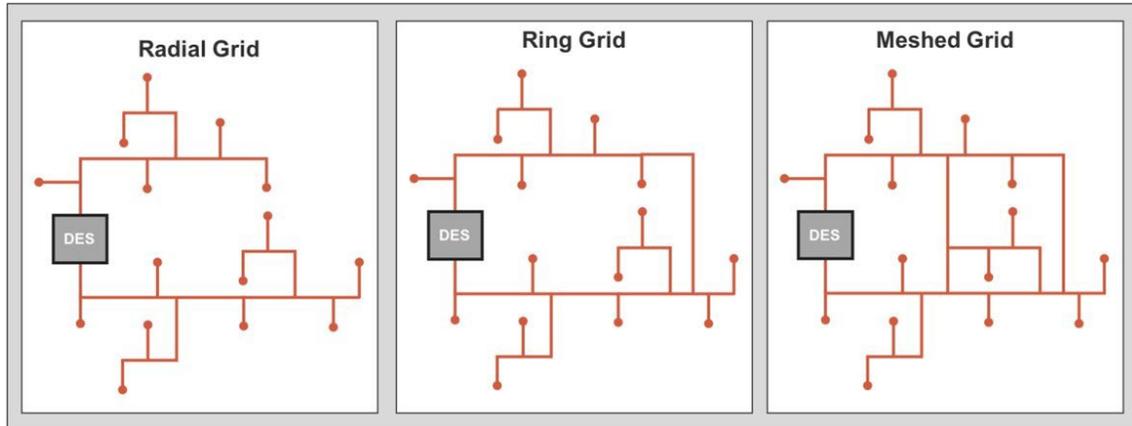
Figure 2 District energy network topologies (von Rhein et al., 2019).

The hydraulic design of the pipes in a TEN usually have two options, the single pipe, or the two-pipe distribution. In a two-pipe distribution system (Figure 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. One of the disadvantages of the two-pipe configuration is that heat losses and gains may be incurred that degrade performance improvements (Boesten et al., 2019). In a single pipe TEN, one pipe distributes all the fluid from sources and sinks. 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. Most often the temperature range is near ambient, or near ground temperatures, not exceeding 30°C (86°F). 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 mile" heat valorization when the working fluid is changed from a water-based solution to CO_2 (Noreskar, 2022).
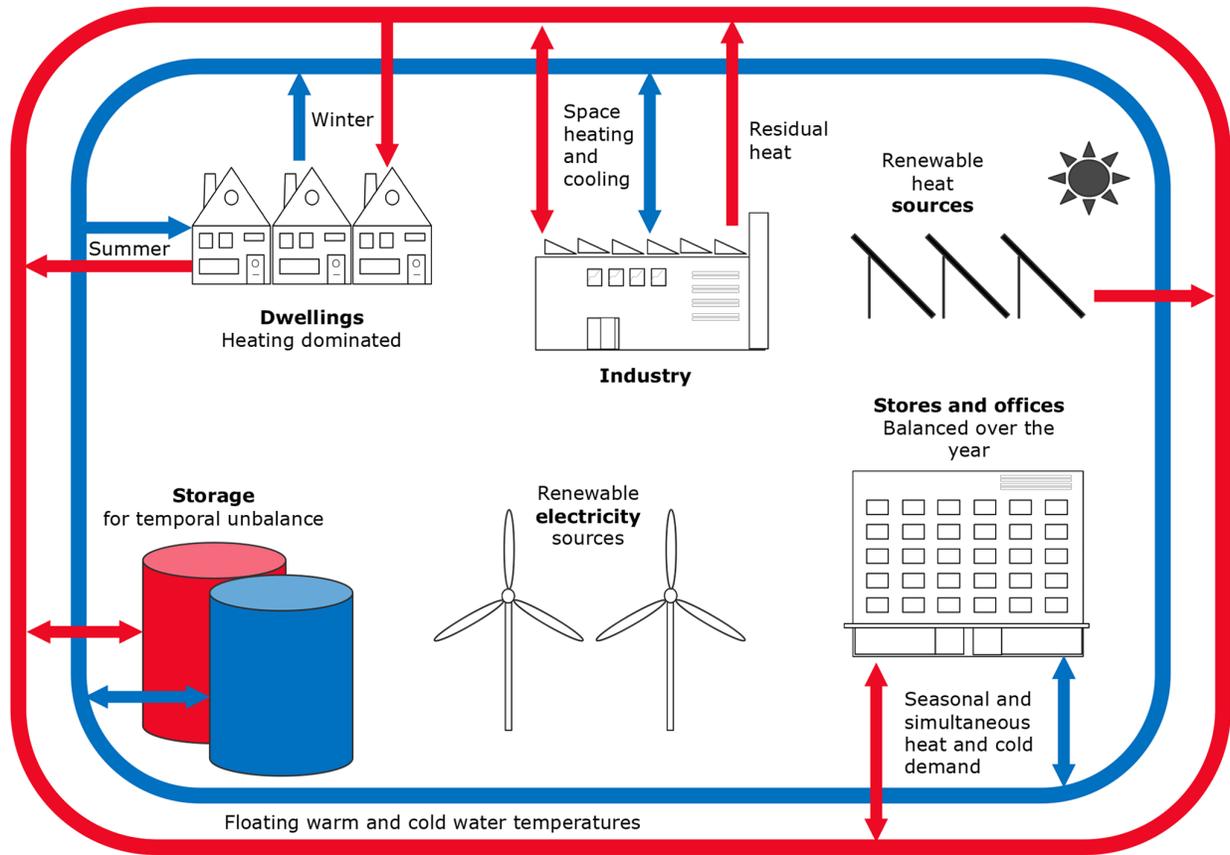
Figure 3 Two pipe thermal energy network (Boesten et al., 2019).

Heat recovery and storage is another important function of these large-scale energy networks. Subsurface thermal energy storage options began making a broader appearance in North America during the oil shocks of the 1970s (Rabbimov et al., 1971; Tsang, 1978), then known as aquifer thermal energy storage (ATES). It was not widely understood, however, that temperatures below 25°C (77°F) would be adequate for large scale thermal energy applications. While storing thermal energy from existing power plants and solar was a focus from the beginning, the characterized hot water temperatures were often in excess of 120°C (248°F).

Hot and cold storage in deeper reservoirs is increasingly distinguished in literature from ATES (Pepin et al., 2021), more widely known as reservoir thermal energy storage (RTES). Other methods of UTES in deep formations may include engineered solutions such as cavern thermal energy storage (CTES). In CTES, hard rock may be excavated, evaporites may be targeted for dissolution, or existing mine galleries may be repurposed (Matos et al., 2019). ATES systems are popular in Europe, where high adoption rates exist in the Netherlands (Bloemendal, 2018; Fleuchaus et al., 2018), often with characteristically low temperatures between about 5°C – 20°C (40°F – 68°F) (Figure 4). While ATES can be a high temperature storage medium, it can more appropriately be thought of as an energy efficiency measure that requires seasonal balance. Seasonal balance is achieved often through mechanical supplements such as dry coolers, while RTES may be more useful for waste heats and industrial process loads (Bloemendal, 2018; Matos et al., 2019; Pepin et al., 2021).
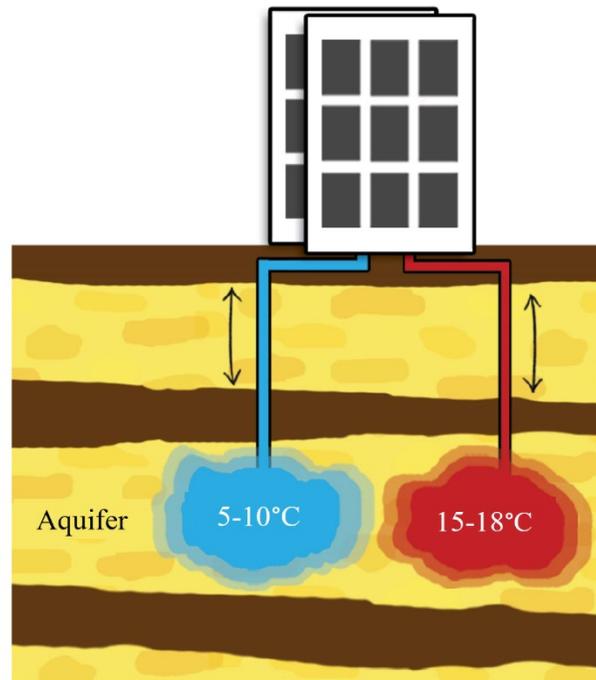
Figure 4 ATES doublet with a warm and cold well for building heating and cooling (modified from: Bloemendal, 2018).

A more prevalent form of UTES is borehole thermal energy storage (BTES). Some literature segregates borehole arrays or geoexchange from BTES. In this sense an individual vertical borehole reaching 150' – 650' (45 m – 200 m) may provide a medium with which to store heat seasonally. In borehole arrays it is most common to use reverse return field gathering systems in buried plastic pipes, 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 flow in series, typically cylindrical (Figure 5). The difference is largely an engineering preference with performance and more sector coupling potential for the reversible BTES (Kitz, 2021). The serially connected cylindrical BTES installation is not a central topic of discussion in this paper. Some refer to the borehole arrays as geothermal heat exchangers (GHX), rather than BTES. Fundamentally the same process is taking place in the subsurface at different scales with a different magnitude of influence on the surrounding soil or rock material.
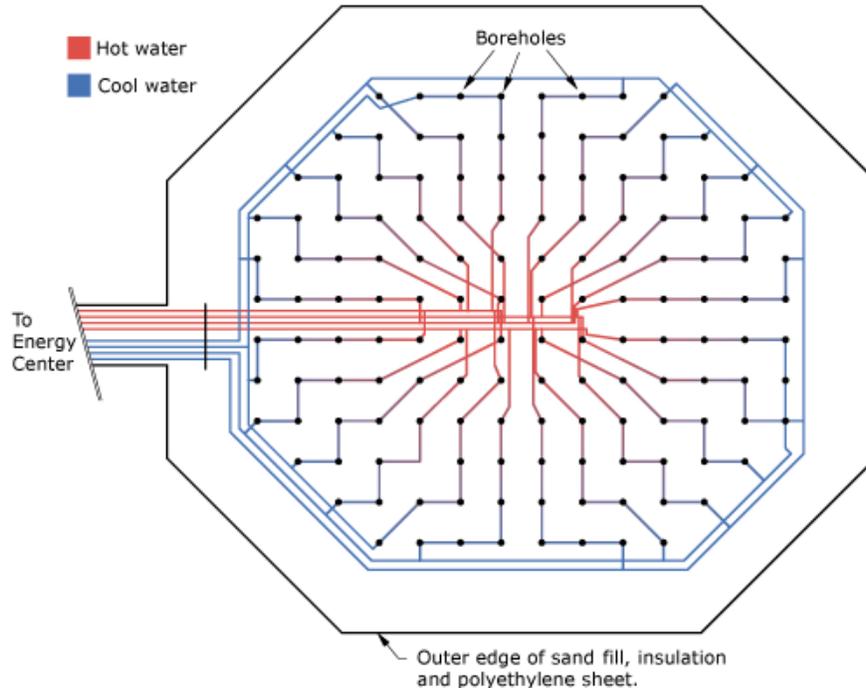
Figure 5 Drake's Landing Solar Community (DLSC) BTES schematic top view of the high temperature heating system ("Borehole Thermal Energy Storage: DLSC," n.d.).

Major advantages for the BTES or GHX variations are 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 installer 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 500' (150 m) does not often require special mineral or oil and gas permitting. Drinking water aquifers are isolated from the borehole through grouting (Kavanaugh & Rafferty, 2014). In some cases, in competent rocks like granites, the medium that joins plastic u-tubes with the formation can be a water fill (Spitler et al., 2016).

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 (Figure 6). Furthermore, existing district energy systems (~100°C – 25°C, or 212°F – 77°F) – 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 rings operating at divergent temperatures.
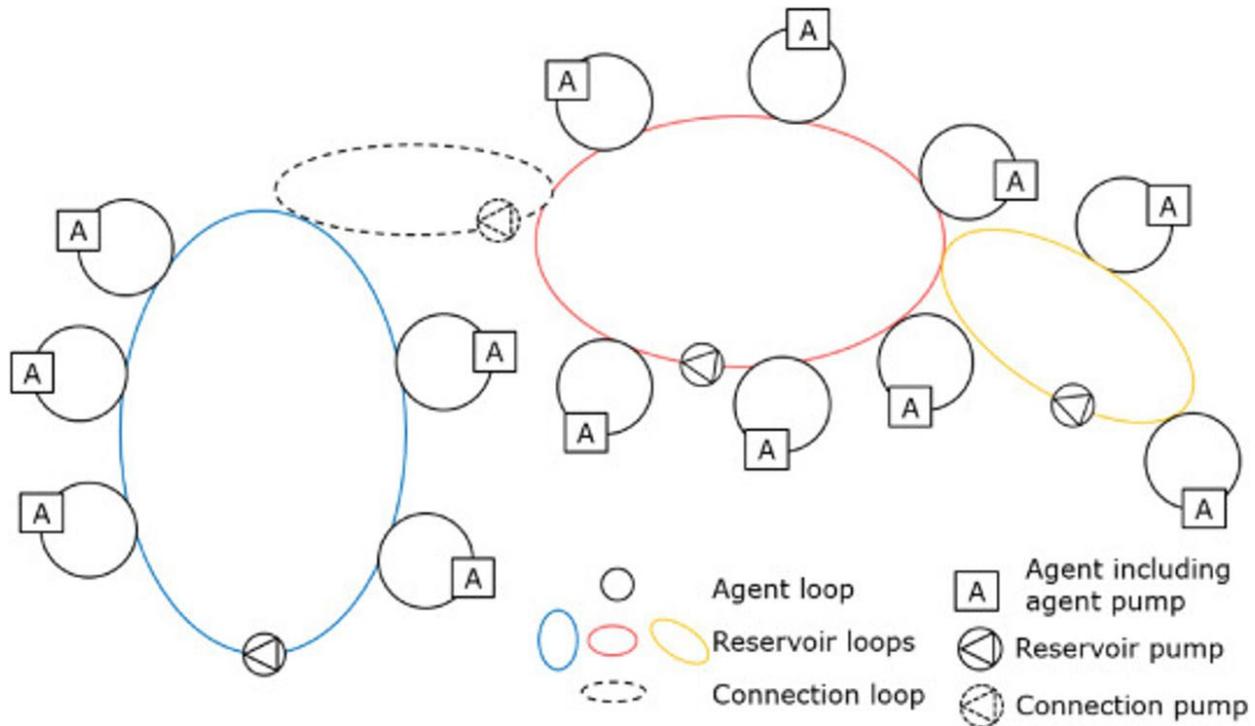
Figure 6 The reservoir network, a type of TEN, acting as a storage medium itself while connecting other sources and sinks (Sommer et al., 2020).

1.3 Challenges

There are numerous challenges with the adoption, construction, and implementation of subsurface supported heating and cooling systems. These include adopter education, first costs, regulatory structures, engineering design, site selection, among others (Fleuchaus et al., 2018; Maltha, 2021; Matos et al., 2019; Sommer et al., 2020). Potential adopters of UTES technologies are often unaware or opposed to their implementation because of misperception, misguidance, or misplaced subsidy. In terms of first costs, the cost associated with drilling is significantly higher than conventional combustion-driven equipment and solutions. Regulatory structures often impair the development of UTES through groundwater law, mineral and petroleum law, or public service monopolization (Matos et al., 2019). Engineers, geoscientists, and support staff must be aware of the need for collaboration throughout stakeholder engagement and design phases, from pre-feasibility through commissioning.

2. Design Methodology Review

2.1 Storage Configurations

There are many different forms of UTES across literature and operating in the field. Many are not widely used, and others are only distinguishable from one another by construction types (Fleuchaus et al., 2018; Matos et al., 2019; Sarbu & Sebarchievici, 2018). This design review will focus on GHX, BTES, ATES, and RTES with an overview of the mechanical systems connecting the subsurface and surface energy applications. All STS UTES capacity relies on the fundamental

equation relating heat, a heat containing medium, and heat capacity, given by (Sarbu & Sebarchievici, 2018):

$$Q_s = \int_{T_i}^{T_f} mc_p \mathrm{d}t \qquad (1)$$

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 in J/(kg*K)
T_i is the initial temperature in °C
T_f is the final temperature in °C

2.1.1 Monovalent Ground Heat Exchangers

Geoexchange or borehole thermal storage systems connected to a heat pump, have been used since 1946 (Kemler, 1947). A single u-tube made of plastic pipe, typically 1" to 1.25" (25 – 32 mm) diameter, is inserted into a borehole of 200 – 650' (60 – 200 m) depth to extract and reject heat from a connected load. A load is the heating and cooling demand of something, most often a building for commercial or residential use. The u-tube is frequently backfilled with thermally enhanced low-permeability grout to protect drinking water from contamination (Figure 7). Seasonal balance of the heating and cooling load is essential for reliable operation of a monovalent GHX. The reverse return borehole field are in sections of 8-16 boreholes connected in series to headers at the plant room (Figure 8). The connected loads must be carefully considered before designing the borehole field to prevent thermal saturation. Thermal imbalance, if not properly addressed in design, is costly to the operator and bad for the industry. Simulations should be undertaken over the long term to understand system behavior. 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 (Cullin et al., 2015; Wei Victor, 2019). Heat recovery efficiency for GHX and BTES is similar, often approaching 40% (Matos et al., 2019).
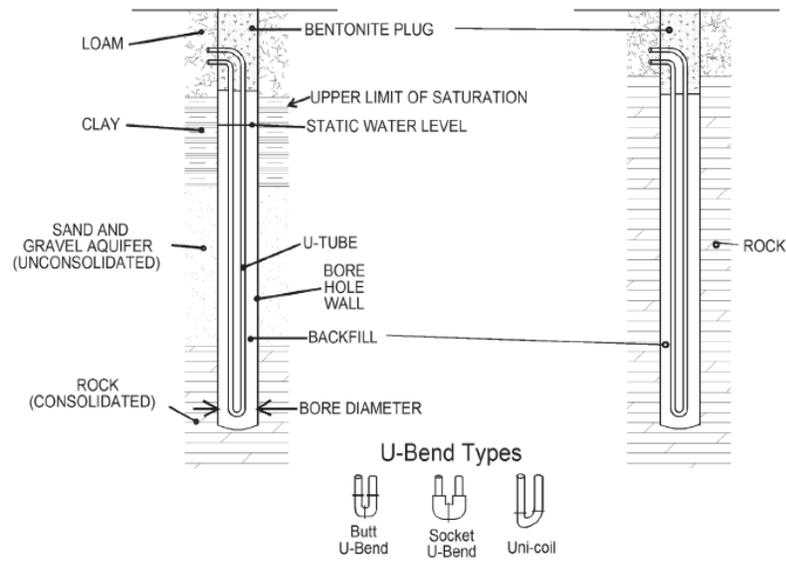
Figure 7 Conventional borehole heat exchangers (Kavanaugh & Rafferty, 2014).

Figure 8 Borehole array header in the plant room at the Calgary International Airport, May 2023.

2.1.2 Multivalent Ground Heat Exchangers

Similar to the monovalent system configuration, the energy system connected to multiple heat sources meets the heating and cooling needs of connected loads. The difference, often, is an efficiency gain. In practice, early multi-valent geoexchange systems had boiler backup. 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 boiler). This is attributable to the lack of understanding on the part of the operator, the design engineer, or both (Kavanaugh & Rafferty, 2014).

One possible way to compensate for load profiles with a significant seasonal imbalance 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. Multiple low-temperature sources can be connected to the same borehole with double u-tubes (Figure 10). A solar-supported ground-source heat pump borehole energy storage configuration (Figure 11) can improve overall efficiency for heating dominant loads while increasing the life of the borehole array (Lazzarin, 2020). 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 & Yavuzturk (2003) estimated the total length of the borehole field could be reduced by 14.4 – 25.3' (4.5 – 7.7 m) for every additional 10.8 ft^2 (1 m^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):

$$H = \frac{E - \frac{E}{SPF}}{t q_{tb}}$$ (2)

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 6
t is the operating time of the system in hours
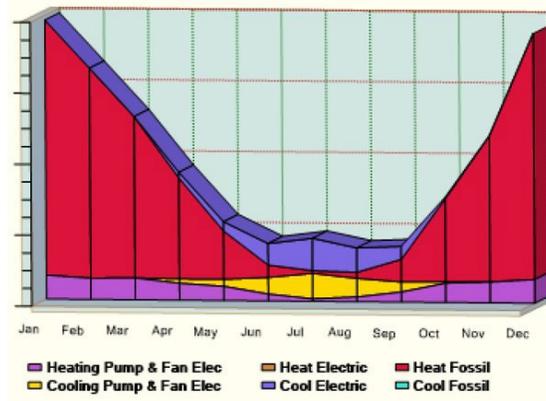q_{tb} is the specific heat extraction in W per meter of borehole length

Figure 9 Dimensionless load profile of typical residential heating and cooling demand in Calgary, Alberta structure (IAPMO, 2022).
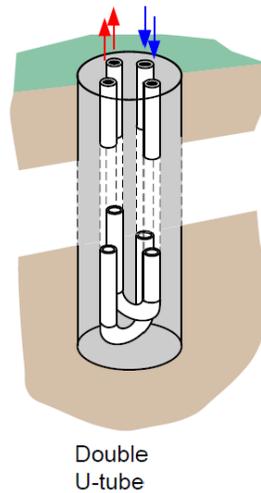

Double
U-tube

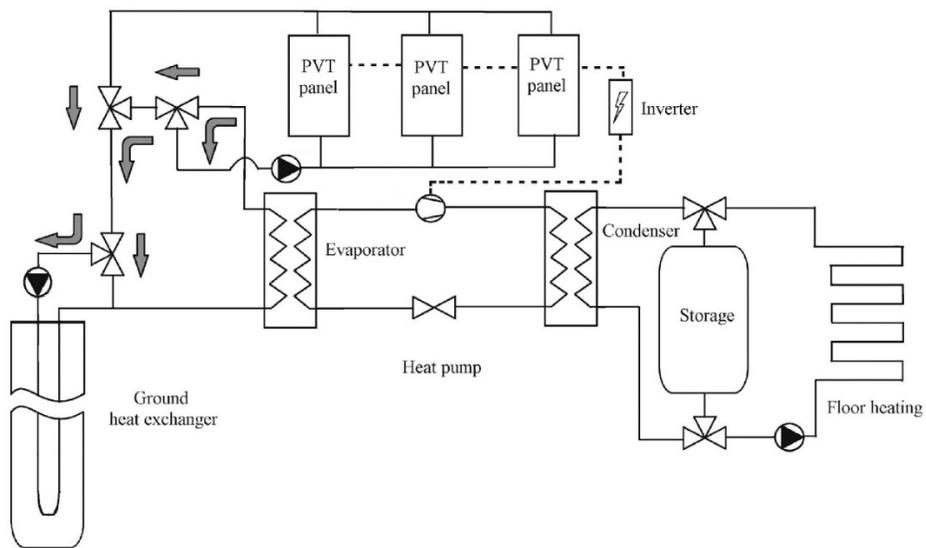**Figure 10 Double u-tube borehole design can be coupled with multiple heat sources (Rees, 2016).**

Figure 11 Solar-assisted borehole thermal energy storage heating system (Lazzarin, 2020).

2.1.3 Borehole Thermal Energy Storage

BTES is conceptualized in a slightly different manner than GHX. In BTES, no balance may be required on the load side to achieve the goal of supplying thermal energy at varying times of demand. Furthermore, BTES is appropriate for high-temperature thermal storage, as is the case in Drake's Landing, Alberta, Canada. 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 (Figure 12). Some have suggested a functional application for BTES is coupling with an organic Rankine cycle (ORC) (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):

$$E = \frac{J_{out}}{J_{in}} \tag{3}$$

$$J_{out} = \sum_{j=1}^{n}(Tc_j - To_j)Q_j\Delta t_j c\rho B \tag{4}$$

$$J_{in} = \sum_{j=1}^{m}(Tc_j - To_j)Q_j\Delta t_j c\rho B \tag{5}$$

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 m³ 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 m³
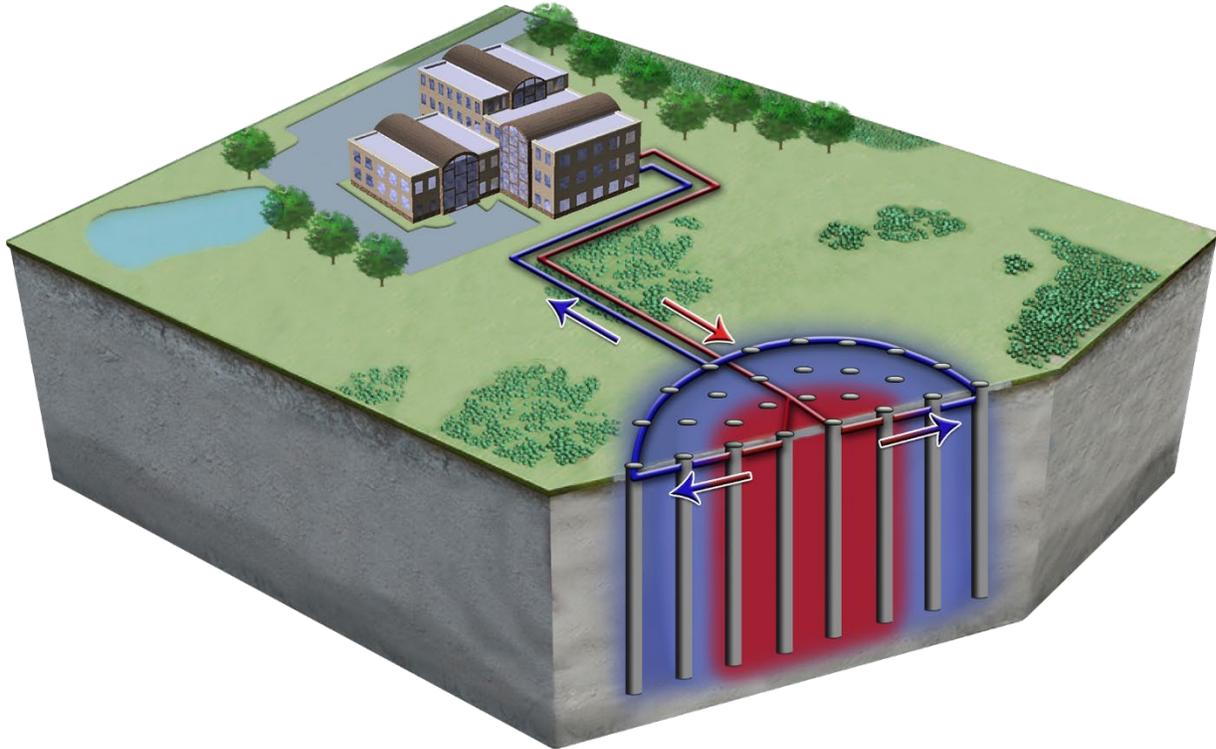B is the number of borehole series in the cylinder

Figure 12 BTES in summer operation mode, with cooling demand from the connected load (Underground Energy, 2023).

2.1.4 Aquifer Thermal Energy Storage

Aquifer thermal energy storage 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). 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 50-80% while cold plume recovery may approach 100% (Matos et al., 2019). In many cases, the ambient temperatures of the aquifer may be used for passive cooling without a heat pump (Figure 13). The radius of a thermal plume is dependent on the fluid and rock properties, describe by this formula (Bloemendal, 2018):

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

(6)

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 m³ Kelvin
c_{aq} is the volumetric heat capacity of the aquifer in MJ per m³ Kelvin
V_{in} is the volume of fluid injected into the well in cubic meters
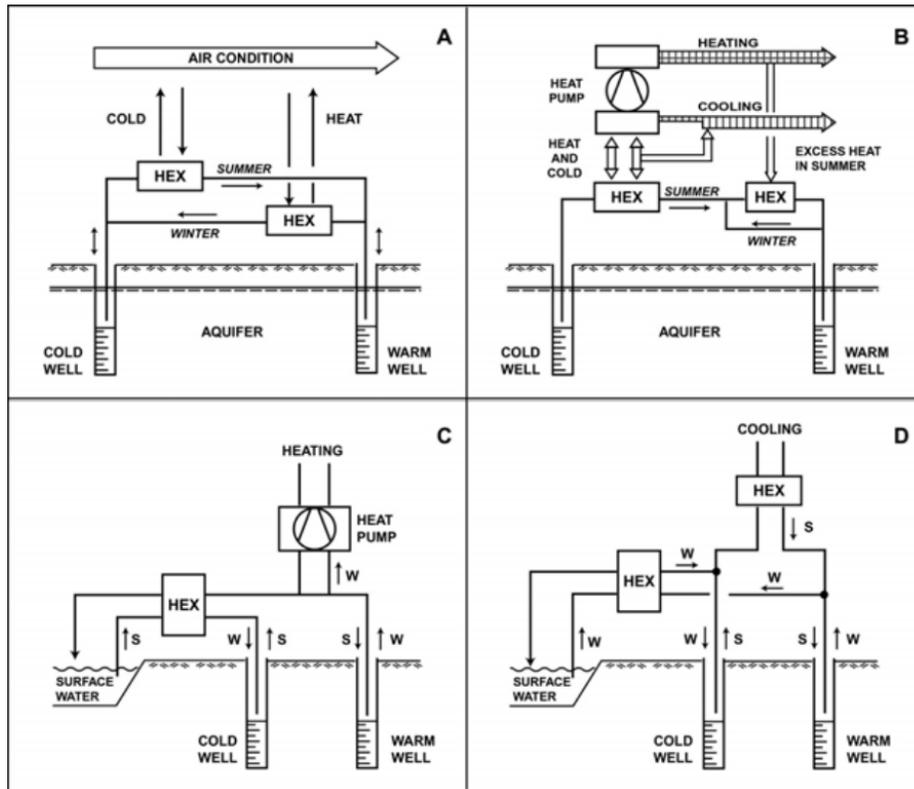
L is the well screen length in meters

Figure 13 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).

Where free cooling can be introduced to the mechanical system, significant improvements in the COP are possible. 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. This can be contrasted with a typical GHX 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).

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

2.1.5 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 (Figure 14) are either found naturally in the subsurface or they may be engineered, as is the case in dissolution of salt caverns. Porous media RTES is most frequently discussed in sedimentary aquifers or depleted oil and gas reservoirs. 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. RTES capacity can further be described as the energy flux per square meter of reservoir (Burns et al., 2020), by the equation:

$$E'_{th} = bn\rho_w c_w \Delta T \tag{7}$$

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
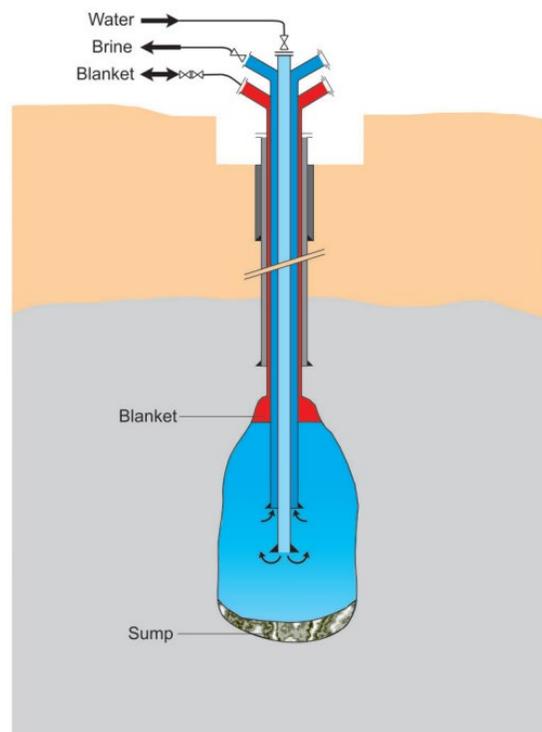ΔT is the temperature differential from production to injection

Figure 14 Salt cavern dissolution, useful for CTES (DEEP.KBB GmbH, n.d.).

2.2 Subsurface Considerations

The UTES designer faces numerous subsurface considerations. In GHX and BTES, the shallow lithology plays a key role on heat extraction efficiency (Figure 15). 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 & Yavuzturk, 2003; Cullin et al., 2015; Grobe et al., 2009). 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. In RTES it is preferable to exploit higher salinity formations from a regulatory standpoint. Where there is less competition for pore space, particularly that used for drinking water, there may be more opportunity for RTES. Further, RTES requires many of the more complicated geologic criteria as conventional geothermal systems, including specific consideration of structures like traps, pressure at depth, or even induced seismicity (Matos et al., 2019).
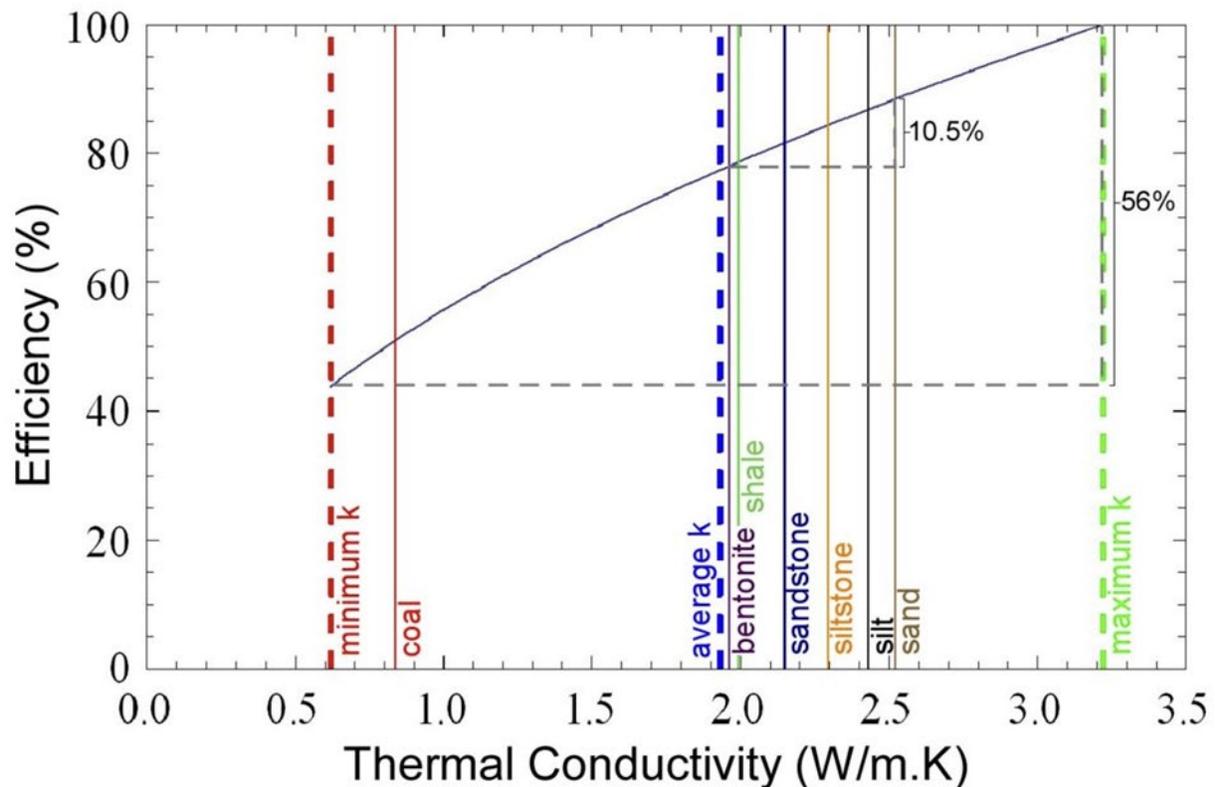

Figure 15 Thermal conductivity of the shallow lithology has a direct impact on heat extraction efficiency for the ground source heat pump supported GHX (Grobe et al., 2009).

2.3 Multivalency

The future of energy requires an integrated approach. This is no different for sustainable subsurface supported heating and cooling systems like UTES or the TEN that connects them. Integrated geothermal heating and cooling systems, much like geothermal electricity generating systems, still use the consistent supply of heat in the subsurface as a baseload while supplementing that heat with another resource. A baseload meets the majority of demand throughout the year while some alternative resources meet the remainder of demand (Figure 16). Once such alternative resource to supply the remainder of demand is solar thermal. 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). Under that assumption the research team at the University of Calgary is experimenting with these multivalent systems at several property development sites.
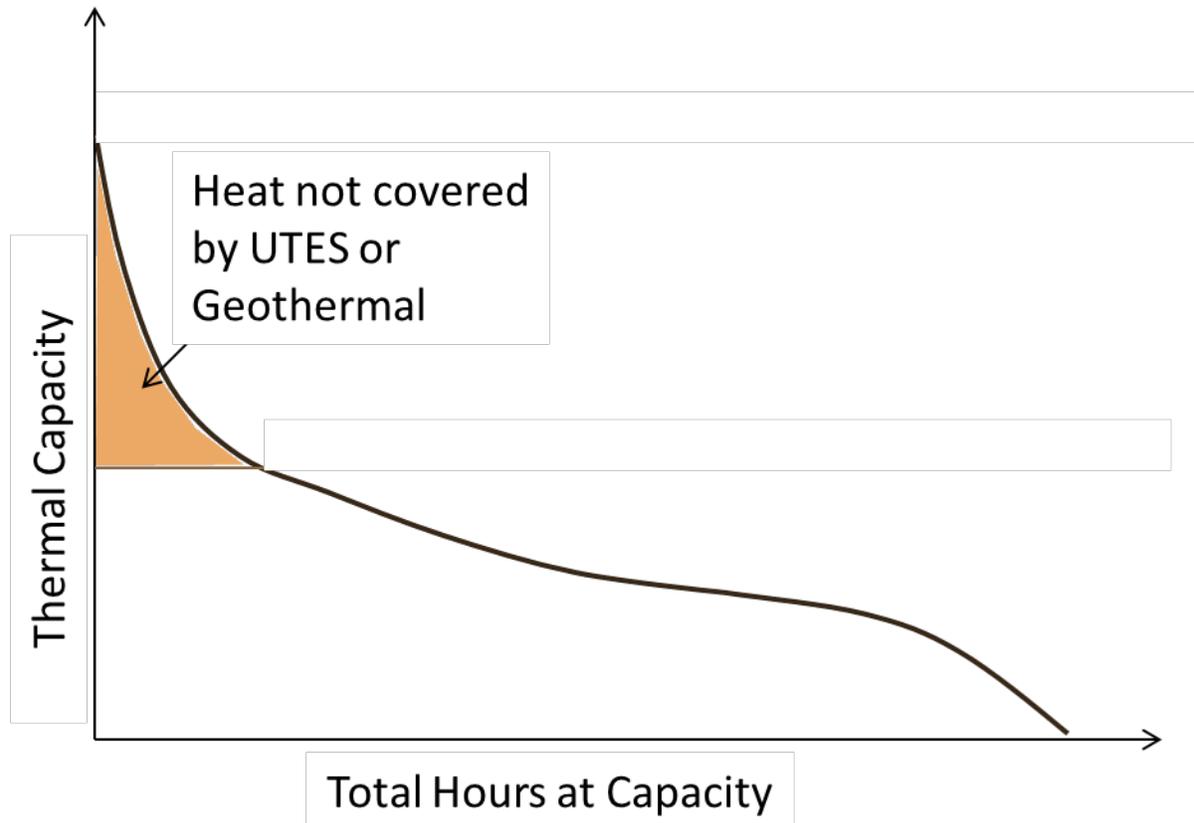

Figure 16 Multivalent load duration curve.

2.4 Risks

Mitigating risks associated with UTES techniques is crucial in leveraging the potential efficiency gains and other benefits made possible by controlling the time of thermal energy discharge. On the city scale, these risks become even more urgent to address. 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 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. Risks other than those that could cause physical harm may include low adoption rates, competitive disadvantage, and misplaced subsidy. Misplaced subsidy may include the granting of dollars for air-source heat pumps at the same rate as UTES despite the fact that geothermal supported heating and cooling systems often require greater than 4 times less electricity to meet the same demand (Buonocore et al., 2022).

3. Case Study

The research team at the University of Calgary is engaged in research of geothermal and geoexchange systems that leverage many technologies ranging from deep drilling projects (>13,000', or >4km) to shallow heating and cooling systems (<500', or <150 m). This multipronged approach attracts industry partners ranging from standalone geothermal companies to oil and gas operators, real estate developers, and consulting engineers. All participants, including the research team, have an interest in the energy transition that seeks success, knowledge transfer, and advancement of sustainable subsurface applications. In recent years, more participants have been attracted to geothermal applications throughout Alberta because of pending emissions taxes (EnergyRates.ca, 2022). This regulatory signal has incentivized the growth of the geothermal industry across the province.

A joint venture real estate development team and the authors are seeking to implement new capital cost saving methods for geoexchange. Such a system may serve more than 5000 living units in southern Calgary (Figure 17). This includes the application of solar assisted GHX, thermal energy networks, and novel control systems. Data from experimental test platforms will be used by the developers, their engineering consultants, and the University to guide the potential construction of an integrated sustainable heating and cooling system. Two different locations for multifamily and mixed-use[1] communities, owned in part by Telsec Property Corporation, will incorporate novel geoexchange pilot projects.
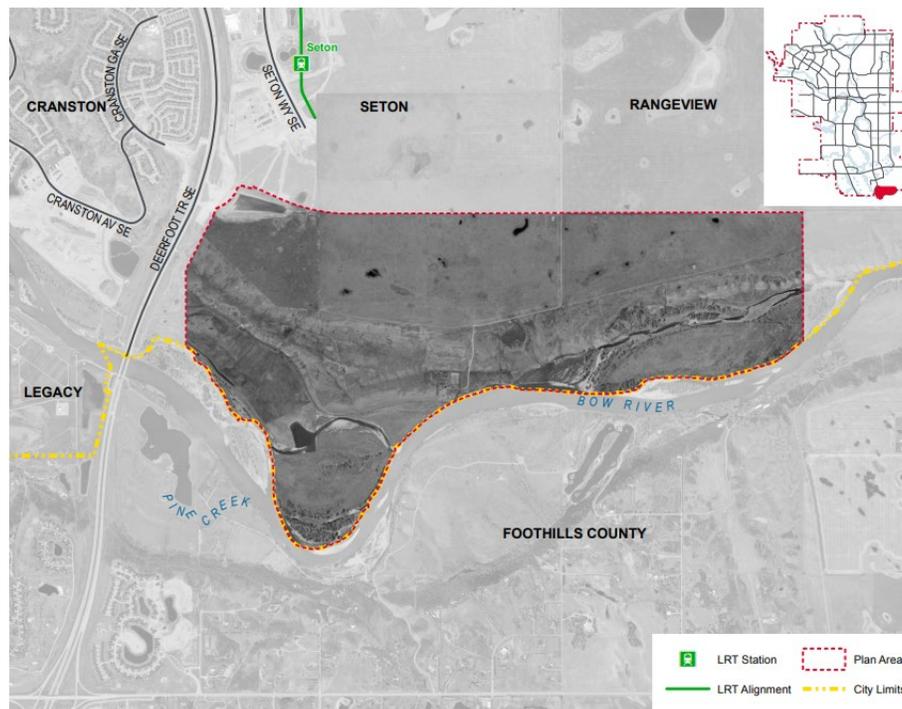

Figure 17 Real estate development concept where a TEN may eventually join more than 5000 living units and commercial spaces (The City of Calgary, 2019).

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[1] Mixed-use is a common phrase in real estate development referring to a combination of residential and commercial building uses.

3.1 Calgary Climate Zone

Calgary is a metro area of about 1.4 million people in the southern portion of Alberta (Government of Alberta, 2023a). Situated in the western part of the country, Calgary experiences a unique climate influenced by its proximity to the Rocky Mountains and its position on the prairies. The city's climate can be described as semi-arid with a mix of continental and mountain influences. It is located at 1045 m (3430') altitude, 51.0447° N latitude and 114.0719° W longitude with a total area of 825.3 km^2 (203,936 acre^2). The city has a significant temperature variation throughout the year, frequently ranging from +35°C to -35°C (95°F – -31°F) . Figure 18 shows the monthly minimum and maximum air temperature as well as the average air temperature and relative humidity for the year 2022. The average relative humidity fluctuated between 45% and 70%. Accordingly, even during the summer months, there is still a need for heating because the temperature can be as low as 5°C (41°F).
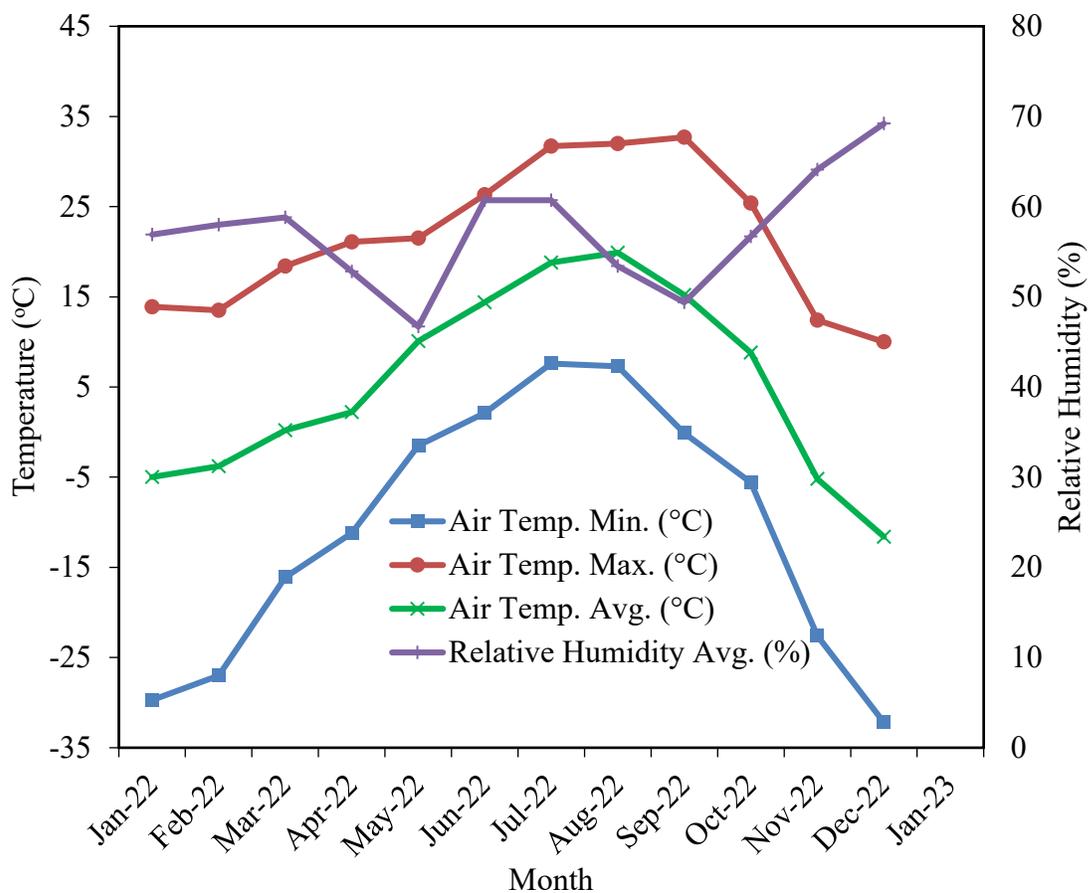
Figure 18 Temperature variations for Calgary (Government of Alberta, 2023b).

3.2 Thermal Loads

Thermal load balancing in Alberta's climate poses a technical challenge that can only be addressed through modifications to the energy system. This may be modifications to the building envelope, the subsurface exploitation method, mechanical operation of the system, among others. With a suite of technically suitable options, the University of Calgary research team will seek economically appropriate solutions in cooperation with industry partners.

3.3 Geologic Setting

The performance of geothermal systems is influenced by the soil type, the geothermal gradient as well as the moisture gradient (Jalaluddin et al, 2011). In the location of the pilot project, the topsoil is approximately 300 mm thick. The soil sample at the Ricardo Ranch consists of silty clay and silty sand from depth of 0 – 50' (0 – 16 m) as well as a water content that varies with the depth from 14% to 25%. From the depth of 51 – 114' (16 – 34 m), the soil sample consists of damped gravel with moisture content of about 19% while the soil from 114 – 140' (35 – 43 m) depth is made of sandy gravel, clay, and sandstone bedrock with an average moisture content of 10%. Shale bedrock was found from 141 – 158' (44 – 48 m) depth with an average moisture content of 8%. The study on the geological formation at Ricardo Ranch has only been reported up to a depth of 158' (48 m), from a geotechnical survey (Klassen, 2021). The geothermal gradient in Calgary has been reported to be within the range of 20 to 25°C/km (20.7°F – 23.5°F/1000') (Brasnett, 2022). Both conventional geothermal exploitation of warm aquifers at depth and shallow geoexchange is appropriate in Calgary. A variety of geologic conditions in the region may enable UTES across the entire spectrum, ranging from RTES to GHX.

3.6 Regional Implications

Single building borehole GHX is of less interest to the University and its partners as they seek to scale sustainable heating and cooling to the masses. Several example GHX supported TEN developments are either in operation throughout Canada or under development. If through the rigors of experimentation, multivalent, connected geoexchange systems are proven more robust than the single building borehole GHX, the regional implications are tremendous. Regardless of the outcomes, the data collected will be made publicly available, ideally alleviating one of the primary limitations to geoexchange improvement in cold climates.

4. Outlook and Challenges

4.1 Risk Mitigation

One of the many benefits of GHX is the absence of induced seismicity risk associated with conventional geothermal systems, or deep direct uses. While the peak load capabilities of such systems will never be comparable, GHX and BTES may serve as a developer's or authority's first interaction with subsurface applications, paving the way for broader geothermal system developments. Further, multivalent GHX reduces security of supply problems in cold climates, such as Alberta, reducing risk for adopters while decreasing capital costs.

4.2 Expected Outcomes

With the integration of solar thermal energy with geoexchange system, we expect an improvement in performance. Also, given the extreme weather in Calgary, it is expected that the solar collectors will remedy the load imbalance on the ground loop for the residential building stock across the demonstration sites. This will ensure consistent long-term system performance and allay the fear of ground temperature decline over long term use. The results from this case study may drive more widespread adoption of sustainable ground-source heating and cooling throughout the province.

4.3 Engagement

The City of Calgary, property developers, and the research team will continue to collaborate. This collaboration has led to the identification of several regulatory barriers, mostly relating to utility corridor allocation, underground utility crossings, and public space permitting, that may be improved. Such ongoing discussions are important for major projects as carbon taxes and emissions reduction targets loom large for regulators and business operators alike. This will also support regulations and policy for adopting geoexchange systems in the province. Through this engagement, there will be opportunities to encourage the adoption of this technology through education and showcasing the performance of the system.

5. Conclusion

This review examines different techniques for underground thermal energy storage application with particular attention to a case study in Calgary, Alberta. The GHX has been the most prevalent form of UTES. Mainly, GHX has a closed loop interaction with the geological formation in a given locale and reduces regulatory barriers when compared to other forms of UTES. There are numerous barriers to the implementation of UTES for sustainable heating and cooling including lack of awareness, capital costs, regulations. To improve the efficiency and reliability of GHX, there is a need for an integrated approach with other energy sources such as solar energy. This is often enabled by a TEN. The research team at the University of Calgary is currently partnering with building developers to increase understanding of geothermal and geoexchange technology, encouraging wider adoption. Sustainable heating and cooling is now a regulatory requirement set forth by the province so timely results from this work could not be more important.

Acknowledgement

REFERENCES

Andersson, O., Hellström, G., & Nordell, B. (2003). Heating and cooling with UTES in Sweden : current situation and potential market development. In *Proceedings : Futurestock 2003, 9th International Conference on Thermal Energy Storage : Warsaw, Poland, September 1 - 4, 2003* (pp. 207–215). Warszawa: PW Publishing House. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-33209

Aranovitch, E., Hardacre, A. G., & Oefverholme, E. (1984). *Workshop on solar assisted heat pumps with ground coupled storage*. Commission of the European Communities, Ispra (Italy). Joint Research Centre.

Bloemendal, M. (2018). The hidden side of cities: Methods for governance, planning and design for optimal use of subsurface space with ATES. https://doi.org/10.4233/uuid:0c6bcdac-6bf7-46c3-a4d3-53119c1a8606

Boesten, S., Ivens, W., Dekker, S. C., & Eijdems, H. (2019). 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. *Advances in Geosciences*, *49*, 129–136. https://doi.org/10.5194/adgeo-49-129-2019

Borehole Thermal Energy Storage: DLSC. (n.d.). Retrieved May 25, 2023, from http://dlsc.ca/borehole.htm

Bowen, R. (1989). *Geothermal Resources*. New York, NY, USA: Elsevier Science Publishers.

Brasnett, G. (2022). *Mapping Techno-Economic Feasibility of Geothermal Energy Resources in Alberta*. University of Calgary, Alberta, Canada.

Buffa, S., Cozzini, M., D'Antoni, M., Baratieri, M., & Fedrizzi, R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*, *104*, 504–522. https://doi.org/10.1016/j.rser.2018.12.059

Buonocore, J. J., Salimifard, P., Magavi, Z., & Allen, J. G. (2022). Inefficient building electrification will require massive buildout of renewable energy and seasonal energy storage. *Scientific Reports*, *12*(1), 11931. https://doi.org/10.1038/s41598-022-15628-2

Burns, E. R., Bershaw, J., Williams, C. F., Wells, R., Uddenberg, M., Scanlon, D., et al. (2020). Using saline or brackish aquifers as reservoirs for thermal energy storage, with example calculations for direct-use heating in the Portland Basin, Oregon, USA. *Geothermics*, *88*, 101877. https://doi.org/10.1016/j.geothermics.2020.101877

Busato, F., Lazzarin, R. M., & Noro, M. (2013). Two years of recorded data for a multisource heat pump system: A performance analysis. *Applied Thermal Engineering*, *57*(1), 39–47. https://doi.org/10.1016/j.applthermaleng.2013.03.053

Catolico, N., Ge, S., & McCartney, J. S. (2016). Numerical Modeling of a Soil-Borehole Thermal Energy Storage System. *Vadose Zone Journal*, *15*(1), vzj2015.05.0078. https://doi.org/10.2136/vzj2015.05.0078

Chiasson, A., & Yavuzturk, C. (2003). Assessment of the viability of hybrid geothermal heat pump systems with solar thermal collectors. *ASHRAE Transactions*, *109*, 487–500.

Cullin, J. R., Spitler, J. D., Montagud, C., Ruiz-Calvo, F., Rees, S. J., Naicker, S. S., et al. (2015). Validation of vertical ground heat exchanger design methodologies. *Science and Technology for the Built Environment*, *21*(2), 137–149. https://doi.org/10.1080/10789669.2014.974478

De Hoe, J. M., Geeraert, B., Aranovitch, E., Hardacre, A. G., & Ofverholm, E. [eds.]. (1982). Heating of a laboratory hall by means of a soil heat pump combined with unshielded solar collectors. Commission of the European Communities, Ispra (Italy). Joint Research Centre.

DEEP.KBB GmbH. (n.d.). Cavern storage: Planning, construction, and operation. Retrieved June 10, 2023, from https://deep-kbb.de/Underground/CavernConstruction?en

EnergyRates.ca. (2022). Alberta carbon tax and rebates. Retrieved May 5, 2023, from https://energyrates.ca/alberta/alberta-carbon-levy-rebates/

Fleuchaus, P., Godschalk, B., Stober, I., & Blum, P. (2018). Worldwide application of aquifer thermal energy storage – A review. *Renewable and Sustainable Energy Reviews*, *94*, 861–876. https://doi.org/10.1016/j.rser.2018.06.057

Fox, D. B., Sutter, D., & Tester, J. W. (2011). The thermal spectrum of low-temperature energy use in the United States. *Energy & Environmental Science*, *4*(10), 3731. https://doi.org/10.1039/c1ee01722e

Frederiksen, S., & Werner, S. (2013). *District Heating and Cooling* (1st ed.). Lund, Sweden: Studentlitteratur.

Gao, Q., Li, M., Yu, M., Spitler, J. D., & Yan, Y. Y. (2009). Review of development from GSHP to UTES in China and other countries. *Renewable and Sustainable Energy Reviews*, *13*(6), 1383–1394. https://doi.org/10.1016/j.rser.2008.09.012

Government of Alberta. (2023a). Calgary population. Retrieved June 26, 2023, from https://regionaldashboard.alberta.ca/region/calgary/population/#/?from=2018&to=2022

Government of Alberta. (2023b). Current and historical Alberta weather station data viewer [Data set]. Retrieved from https://agriculture.alberta.ca/acis/weather-data-viewer.jsp

Government of Canada, N. R. C. (2023, April 25). Residential Sector Alberta1 Table 2: Secondary Energy Use and GHG Emissions by End-Use. Retrieved May 1, 2023, from https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/showTable.cfm?type=CP&sector=res&juris=ab&year=2020&rn=2&page=0

Grobe, M., Richardson, R. J. H., Johnston, K., Quibell, J., Scillereff, H. S., & Tsang, B. (2009). *Importance of geoscience information in the implementation of closed loop ground-source heat pump systems (geoexchange) in Alberta* (p. 56). Alberta. Retrieved from https://static.ags.aer.ca/files/document/OFR/OFR_2009_09.pdf

Hanova, J., Dowlatabadi, H., & Mueller, L. (2007). *Ground source heat pump systems in Canada: Economics and GHG reduction potential*. Washington, D.C.: Resources for the Future. Retrieved from https://www.rff.org/publications/working-papers/ground-source-heat-pump-systems-in-canada-economics-and-ghg-reduction-potential/

IAPMO. (2022). *BEST methodology: Fundamentals*. International Association of Plumbing and Mechanical Officials. Retrieved from https://www.iapmo.org/media/29471/best-methodology_fundamentals.pdf

IEA. (2019). *Heat – Renewables 2019 – Analysis*. Paris: International Energy Association. Retrieved from https://www.iea.org/reports/renewables-2019/heat

Ivanova, I. (2023, February 2). Oil companies in 2022 had their most profitable year in history. *CBS News*. Retrieved from https://www.cbsnews.com/news/exxon-chevron-shell-conocophillips-record-profits-earnings-oil-companies-most-profitable-year/

Jalaluddin et al. (2011). Experimental study of several types of ground heat exchanger using a steel pile foundation.

Kantrowitz, T. (2009, May). Geoexchange and quality. *Canadian Consulting Engineer*. Retrieved from https://www.canadianconsultingengineer.com/features/geoexchange-quality/

Kavanaugh, S. P., & Rafferty, K. D. (2014). *Geothermal heating and cooling: design of ground-source heat pump systems*. ASHRAE.

Kemler, E. N. (1947, September). Methods of earth heat recovery for the heat pump. *Heating and Ventilating*, *44*(9). Retrieved from https://archive.org/details/sim_energy-engineering_1947-09_44_9/page/68/mode/2up

Kitz, K. (2021). Grid energy storage in shallow geothermal boreholes as a higher-performing and lower-cost solution to grid and building decarbonization. *GRC Transactions*, *45*. Retrieved from https://publications.mygeoenergynow.org/grc/1034434.pdf

Klassen, N. (2021). *Geotechnical Report Ricardo Ranch* (p. 4). Calgary, Alberta: McIntosh Lalani Engineering.

Lazzarin, R. (2020). Heat pumps and solar energy: A review with some insights in the future. *International Journal of Refrigeration*, *116*, 146–160. https://doi.org/10.1016/j.ijrefrig.2020.03.031

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th generation district heating (4GDH): Integrating smart thermal grids into future sustainable energy systems. *Energy*, *68*, 1–11. https://doi.org/10.1016/j.energy.2014.02.089

Lund, H., Østergaard, P. A., Chang, M., Werner, S., Svendsen, S., Sorknæs, P., et al. (2018). The status of 4th generation district heating: Research and results. *Energy*, *164*, 147–159. https://doi.org/10.1016/j.energy.2018.08.206

Maltha, N. (2021). *Advancing adoption of aquifer thermal energy storage: A new evaluation method to support local decision-makers*. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3Aaced5542-1687-457b-b36c-88a061ef8e22

Matos, C. R., Carneiro, J. F., & Silva, P. P. (2019). Overview of Large-Scale Underground Energy Storage Technologies for Integration of Renewable Energies and Criteria for Reservoir Identification. *Journal of Energy Storage*, *21*, 241–258. https://doi.org/10.1016/j.est.2018.11.023

McDaniel, B., & Kosanovic, D. (2016). Modeling of combined heat and power plant performance with seasonal thermal energy storage. *Journal of Energy Storage*, *7*, 13–23. https://doi.org/10.1016/j.est.2016.04.006

Noreskar, F. (2022, December 8). Using CO_2 to heat and cool urban areas. Retrieved June 11, 2023, from https://exergo.com/using-co2-to-heat-and-cool-urban-areas-2/

Pepin, J. D., Burns, E. R., Dickinson, J. E., Duncan, L. L., Kuniansky, E. L., & Reeves, H. W. (2021). National-scale reservoir thermal energy storage pre-assessment for the United States.

Rabbimov, R. T., Umarov, G. Y., & Zakhidov, R. A. (1971). Storage of solar energy in a sandy-gravel ground. *Appl. Solar Energy (USSR) (Engl. Transl.); (United States)*, *7:5*. Retrieved from https://www.osti.gov/biblio/5180121

Rees, S. J. (2016). 1 - An introduction to ground-source heat pump technology. In Simon J. Rees (Ed.), *Advances in Ground-Source Heat Pump Systems* (pp. 1–25). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100311-4.00001-7

von Rhein, J., Henze, G. P., Long, N., & Fu, Y. (2019). Development of a topology analysis tool for fifth-generation district heating and cooling networks. *Energy Conversion and Management*, *196*, 705–716. https://doi.org/10.1016/j.enconman.2019.05.066

Ross, S. (2022, April). What's the average profit margin for a utility company? *Investopedia*. Retrieved from https://www.investopedia.com/ask/answers/011915/what-average-profit-margin-utility-company.asp

Sarbu, I., & Sebarchievici, C. (2018). A comprehensive review of thermal energy storage. *Sustainability*, *10*(1). https://doi.org/10.3390/su10010191

Sommer, T., Sulzer, M., Wetter, M., Sotnikov, A., Mennel, S., & Stettler, C. (2020). The reservoir network: A new network topology for district heating and cooling. *Energy*, *199*, 117418. https://doi.org/10.1016/j.energy.2020.117418

Spitler, J. D., Javed, S., & Ramstad, R. K. (2016). Natural convection in groundwater-filled boreholes used as ground heat exchangers. *Applied Energy*, *164*, 352–365. https://doi.org/10.1016/j.apenergy.2015.11.041

Stauffer, F., Bayer, P., Blum, P., Molina-Giraldo, N., & Kinzelbach, W. (2014). *Thermal Use of Shallow Groundwater* (1st ed.). Boca Raton, Florida: CRC Press. Retrieved from https://www.routledge.com/Thermal-Use-of-Shallow-Groundwater/Stauffer-Bayer-Blum-Giraldo-Kinzelbach/p/book/9781138077850

The City of Calgary. (2019, November 18). Ricardo Ranch Area Structure Plan. Retrieved from https://engage.calgary.ca/RicardoRanch

Tsang, C. F. (1978). Aquifer Thermal Energy Storage. Presented at the Institute of Gas Technology Symposium on Advanced Technologies for Storing Energy, Chicago, Illinois: Lawrence Berkeley National Laboratory.

Underground Energy. (2023). *BTES Summer operation - cooling*. Retrieved from https://underground-energy.com/our-technology/btes/

Wei Victor, L. (2019). *Refining the design approach for GeoExchange system*. Alberta Innovates.