PROCEEDINGS, 48th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 6-8, 2023
SGP -TR-224

# City-Scale Geothermal Energy Everywhere to Support Renewable Resilience – a Transcontinental Cooperation

Gregor Goetzl[1], Erick R. Burns[2], Andrew J. Stumpf[3], Yu-Feng Lin[3,4], Amanda Kolker[5], Maciej R. Kłonowski[6], Cornelia Steiner[1], Ryan C. Cahalan[2] and Jeff D. Pepin[2]

[1]Geological Survey of Austria

2U.S. Geological Survey

3Illinois State Geological Survey

4Illinois Water Resources Center, University of Illinois at Urbana-Champaign

5National Renewable Energy Laboratory

6Polish Geological Institute – National Research Institute

Corresponding author

Geological Survey of Austria, Neulinggasse 38, 1030 Vienna, Austria

gregor.goetzl@geologie.ac.at

**Keywords:** urban geothermal, UTES, direct-use heating and cooling, energy resilience, geothermal heating and cooling

**ABSTRACT**

Cities have important and varying incentives to transform their energy sector to all-electric with low carbon emissions. However, they often encounter a number of impediments when attempting to implement such a change. For example, while urban areas have the highest energy demand density, cities often lack the space for installing additional energy generation and/or long-duration energy storage systems. Cities also have existing environmental issues from energy sources (e.g., pollution from dust, waste heat or noise) that make residents sensitive to energy infrastructure development. Utilizing power from conventional sources, such as natural gas, biomass and hydropower, which usually are distanced from urban areas, also make cities more vulnerable to supply disruptions. One promising de-carbonizing energy option for cities focuses on their heating and cooling needs, which constitutes around one-third of U.S. and one-half of European energy consumption (including industrial processes like drying, pasteurization, etc.; Jadun and others, 2017; EU Commission 2022). If heating and cooling loads can be met by geothermal direct-use technologies, then the need for new electric sources can be greatly lessened. Despite the proven efficacy of geothermal energy as a city/community -scale heating and cooling resource, it is currently only a niche resource in the heating and cooling sector, though has significant potential for future growth. Historically, emphasis has been placed on geothermal electricity generation potential that requires higher temperature (greater than 90 °C) resources at drillable depths, but potentially viable areas are geographically limited and typically well removed from urban centers. Key drivers for investments were represented by greater political interest in renewable electricity production, higher revenues and less effort in distributin g the produced energy via grids. In contrast, low-temperature (less than 90 °C) geothermal resources can be used directly for heating and cooling almost everywhere and are cost-effective in urban/suburban settings. In addition, the increased prominence of renewable electricity sources, such as wind and solar onto city-scale electric grids, has led to new urgency around questions of energy storage. Underground thermal energy storage (UTES), wherein surplus or waste heat is stored underground for later use, could present a long-duration energy storage solution.

From October 2022 through September 2024, a transcontinental consortium consisting of geological surveys, geoscience organizations, industry representatives and universities aims to develop an understanding of the global potential for city-scale geothermal energy, proposing guidelines to aid in promoting the economic utilization of low temperature geothermal resources. Efforts will focus on providing city managers and other decision makers with the information needed to evaluate and implement suitable city/community -scale geothermal technologies. Funded by the U.S. Geological Survey's John Wesley Powell Center for Analysis and Synthesis, this interdisciplinary consortium will showcase tools, datasets, and scientific recommendations to accelerate the broader understanding and adoption of renewable energy systems that access geothermal resources. The collaborative research activities include standardization of nomenclatures, resource description and characterization strategies globally. The results from these activities will be combined with a preliminary climate-driven, city-based energy needs related analysis to perform energy supply and demand matching analysis. The identification of city-specific applications that would benefit from the geothermal technologies provides the basis to up -scale city-specific determinations to regional and national assessments of resource estimates. The city -scale geothermal energy research initiative will ultimately provide the synergies and management analysis that can address benefits, environmental impacts, regulatory frameworks, sustainability, and suitability in retrofitted buildings or new as well as existing heating networks.

# 1. INTRODUCTION

## 1.1 Problem statement

Major policies related to climate and energy , such as the European Union (EU) Fit for 55 Package, EU Green Deal (Duscha and others, 2019; Bouzarovski and others, 2020), and the Paris Agreement's (COP 21) climate change mitigation and sustainable development goals, face major challenges. While significant efforts are underway towards decarbonizing the electricity sector and green transformation of the transportation sector, the heating and cooling (HC) sector still lags behind despite contributions to overall greenhouse gas (GHG) emissions at a global level of around 50% (IRENA, 2020).

Geothermal energy represents the heat stored in the Earth's interior as well as the ability of the subsurface to store heat. It is a proven, viable resource that can be a part of a global energy future that meets many critical needs (e.g., low-carbon, resilient, adaptive/responsive to energy gluts/scarcity) offering different technological concepts for exchanging heat with the subsurface (Van den Berg and others 2019) . However, compared with other renewables such as wind and solar, the range of geothermal technologies is poorly understood by decision and policy makers resulting in low adoption and low decarbonization of heat supply . In our understanding, relevant hurdles are:

- *A low level of knowledge and awareness on technological options to integrate the subsurface into urban heating and cooling supply concepts;*
- *Lower market readiness level of underground thermal energy storage solutions;*
- *Complexity in planning and specific investment costs compared to other renewable technologies*
- *Information gaps on available subsurface resources with regard to different heating and cooling demand profiles (e.g., required temperature and capacity levels);*
- *Information gaps on the environmental safety and sustainability of geothermal energy use;*
- *Lack of tools to facilitate geothermal energy into urban spatial energy planning.*

These hurdles hamper local decision makers' ability to consider geothermal as part of robust energy portfolios that might account for alternative socio-economic values. Knowledge gaps include a global lack of systematic characterization, quantification, and mapping of resource potential. Even if decision makers would like to consider geothermal options, uncertainties (e.g., regulations, environmental impact, and development costs) may make it difficult, leading to their selection of more 'tried-and-true' technologies.

## 1.2 The use of geothermal technologies for heating and cooling supply

Geothermal energy is a sustainable low-carbon renewable energy resource associated with a wide-range of geology -dependent technologies, many of which are actively being researched, developed, and refined (e.g., Fleuchaus and others, 2018; Burns and others, 2018, 2020; Pepin and others, 2021). Understanding of what constitutes a geothermal energy resource has evolved over time.

Historically, much emphasis has been placed on geothermal electricity generation potential, higher temperature (>90 °C for electricity production) resources at drillable depths have geographically limited extents. Key drivers for investments were represented by greater political interest in renewable electricity production (Huttrer 2020), higher revenues and less effort in distributing the produced energy via grids. In contrast, low-temperature (<90 °C) geothermal resources can be used directly for heating and cooling in a wider range of geological settings. Heating and cooling using both electricity and fossil fuels accounts for more than one-third of the U.S. total energy consumption (including industrial processes like drying, pasteurization, etc.; Jadun and others, 2017). Although geothermal electricity production has been studied extensively over the past half-century, and the development of geothermal resources at temperatures <90 °C is technologically and scientifically viable, widespread evaluation/assessment and technology adoption for district - or city-scale uses are in their infancy (e.g., Fleuchaus and others, 2018).

Heating/cooling sources can either be natural ambient subsurface temperatures (hereafter, *AMBIENT* resources) or hot/cold water stored for later use (Underground Thermal Energy Storage [hereafter, *UTES*], an umbrella term referring to a suite of technologies (Sanner and others, 2003, 2005). Across the globe, low-temperature *AMBIENT* and *UTES* resources are both hugely under-utilized with regard to the identified resources (Lund and Toth 2020). Northern European and eastern Asian countries have seen many instances of successful implementation of these technologies over the past 10+ years (Snijders 2000; Tomigashi and Fujinawa, 2011; Bloemendal and others 2015; Fleuchaus and others, 2018), demonstrating that these resources are viable, though the method of utilization varies based on local conditions and heating/cooling demands. In comparison, the U.S. has seen limited development of these resources (~0.1 GWth; USDOE, 2019) with a clear focus on the high geothermal heat-flow areas of the western U.S. The U.S. Department of Energy (USDOE) has used existing U.S. Geological Survey (USGS) geothermal assessments of heating potential in the western U.S. to estimate that heating systems could grow to supply more than 320 GWth by 2050, but USGS assessments of cooling resources have not been completed, nor has heating potential been assessed for the central and eastern U.S. Early conjectures and crude estimates indicate that fresh and brack ish/saline aquifers of the U.S. could potentially supply thousands of GWth for district heating and cooling resources (e.g., Burns and others, 2020; Pepin and others, 2021). Despite the early successes of Europe and Asia, geothermal energy (both electricity and heating/cooling) supplies <3% of energy end-uses globally (Goetzl and others, 2020), far below the potential demand for these resources (e.g., >one-third of total energy end-use for heating/cooling alone).

1.2.1 Direct use of geothermal for heating applications

Direct-use refers to heating or cooling via heat extraction or heat exchange with the subsurface. Heat exchange technologies use a geothermal working fluid (e.g., native water circulated from underground to land surface, and typically reinjected into the same formation). Active hydrothermal circulation systems, leading to convective heat transport phenomena, were the first geothermal systems identified and developed to extract heat from the subsurface. Extracted heat was and is used directly or to generate electricity, taking advantage of natural groundwater circulation through porous or fractured rocks, which results in significant advective concentration and transport of heat to near-surface. The hydrogeological settings for hydrothermal systems are relatively sparse leading to clear spatial concentration of thermal resources. If hydrothermal circulation can be engineered via deep (typically 3-6 km) permeability enhancement (i.e., enhanced/engineered geothermal systems [EGS]), heat extraction for direct use or electricity production would be feasible in many active tectonic environments worldwide. For example, geothermal heat at drillable depths (<6 km) in the western U.S. is estimated to be capable of supplying~500 GWe, ~50% of the current U.S. electric power production capacity (Williams and others, 2008).

Under most natural geologic conditions, temperatures at economically viable drilling depths are insufficient for the generation of electricity, limiting geothermal resources to direct -use for heating and cooling. Unless care is taken to balance heating and cooling, *AMBIENT* resources may degrade over time as energy is utilized (e.g., extraction of heat cools the subsurface, reducing potential future heating), but proper seasonal balancing can increase efficiency over the years (Zhu and others, 2015). Also, if the working fluid is circulated inside an aquifer, then heat is swept away, helping to maintain a steady heating/cooling supply (e.g., Banks, 2014).

For low-temperature geothermal resources within regional and local groundwater-flow systems, the properties of the aquifer system are primary controls on heating/cooling potential (Fuji and others, 2005). If higher *AMBIENT* resource temperatures are desired (higher but still <90 °C), then the conductively dominated region beneath the regional aquifer may be used as the heat source, provided that permeability can be found or engineered at greater depths with higher temperatures (e.g., Schintgen 2015). Because the challenge at greater depth is to locate permeability for water circulation, exploration and characterization strategies used for conventional hydrothermal and EGS resources are applicable. While *AMBIENT* deeper direct-use heating resources have been assessed for the higher-heat-flow western U.S. (most recently by Williams and others, 2015), the remainder of the U.S. has not been assessed for *AMBIENT* heating or cooling potential.

1.2.2 Underground Thermal Energy Storage

Underground thermal energy storage (*UTES*) is a broad class of thermal energy storage methods that capitalizes upon the insulation capacity and thermal inertia of geologic units to limit thermal energy loss during a storage period (Lee, 2013). Heat is stored by two mechanisms: (1) the heat contained in the stored injected water (i.e., specific heat) and (2) conductive heat exchange via contact with solid materials in the subsurface. Subsurface materials can be natural geologic reservoirs or buried engineered materials with high heat capacity and high heat exchange rate surrounded by insulating geologic deposits (Burns and others, 2018).

Both heated and cooled water can be stored underground, and the source of both can be waste heat or any other ambient or generated source. For example, solar heating can supply summer heat, and heat exchange with rivers could cool injected water (Nordell and Hellström, 2000; Burns and others, 2020). Water exceeding boiling temperatures can be stored under pressure, but geochemical alteration can be rapid and significant when high-temperature water is stored in low-temperature reservoirs, degrading *UTES* performance (e.g. Bershaw and others, 2020). Due to the ubiquity of porous geologic materials, *UTES* can be used to supply a significant portion of U.S. energy end-uses, though the particular technologies applied may be geology-dependent.

*UTES* systems are varied, sometimes using different names for the same technology. A broad and preliminary classification used to start working group discussions includes (see also Figure 1):

i) Open loops using groundwater as a transport medium for storage and recovery of heat in aquifers, also defined as *Aquifer Thermal Energy Storage* [ATES], e.g., Bridger and Allen, 2005, Sommer and others, 2014;

ii) Open loops using permeable strata that are poorly connected to regional freshwater resources (e.g., below the potable water boundary), also defined as *Reservoir Thermal Energy Storage* [RTES], e.g., Burns and others, 2020, Pepin and others, 2021;

iii) Closed loops heat exchangers, not relying on permeable layers, are defined as *Borehole Thermal Energy Storage* [BTES], e.g., Welsch and others, 2016; Bar and others, 2017, having a myriad of operational configurations (Bloemendal and others, 2014);

The range of *UTES* technologies are variably well-developed and heterogeneously adopted worldwide (Gao and others, 2009; Bloemendal and others, 2015; Zhu and others, 2015; Fleuchaus and others, 2018). By far, the most common type of *UTES* is ATES with seasonal heat storage in relatively shallow aquifers beneath northern and northwestern European cities where groundwater flow velocities are low enough to allow capture of the thermal plume before it is swept away (Midttømme and others, 2017).

The primary advantages of *UTES* over other thermal energy -storage technologies (e.g., phase-change-material and thermochemical storage at building-scale) is the long-duration storage/release cycle (weeks to years), the potential to store very large quantities of thermal energy (Kallesøe and Vangkilde-Pedersen, 2019; Shi and others, 2021; Aneke and Wang, 2016), and the independence of these technologies on critical minerals and other key supply chains. *UTES* is only limited by the "reservoir" size and the rate at which stored heat "leaks" away (Burns and others, 2020; Pepin and others, 2021). For example, for ATES, groundwater flow sweeps heat away, potentially reducing thermal energy recovery efficiency (e.g., Kangas and Lund, 1994; Bridger and Allen, 2005; Sommer and others,

2014), but RTES loses heat much more slowly via conduction due to low or entirely lacking hydraulic flow (Burns and others, 2020). In contrast to conventional direct use, recoverable thermal energy tends to increase over time as surrounding geologic materials are heated/cooled to operating temperatures while recovery efficiency decreases as storage-cycle time increases (Bloemendal and Hartog, 2018; Zanchini and others, 2012). This requires operational concepts tailored to the specific hydrogeological conditions to optimize the tradeoff between storage efficiency and storage-cycle times.

1.2.3 Ground source heat pump use

Geothermal heating and cooling are also regularly associated with single-family-homes supplied by ground-source heat pumps (GSHPs). As shown in Figure 1, these systems utilize the thermal energy of the shallow-subsurface (commonly <10 m for horizontal loops, or narrow vertical installations up to ~150 m). Large groundwater-filled reservoirs beneath typical GSHP depths (e.g., shallow groundwater bodies) are widely spread in basin areas, and these can also be engineered/constructed for district -scale heating and cooling (Self and others, 2013; Sarbu and Sebarchievici, 2014, Lucia and others, 2017). In low permeability geology, closed loop systems (borehole heat exchangers [BHE]) can be used and can be scaled up to large BHE fields or deep BHEs exceeding the typical lengths of around 150 meters by a significant amount. In both cases borehole heat exchangers may be operated as borehole thermal energy storage (BTES).

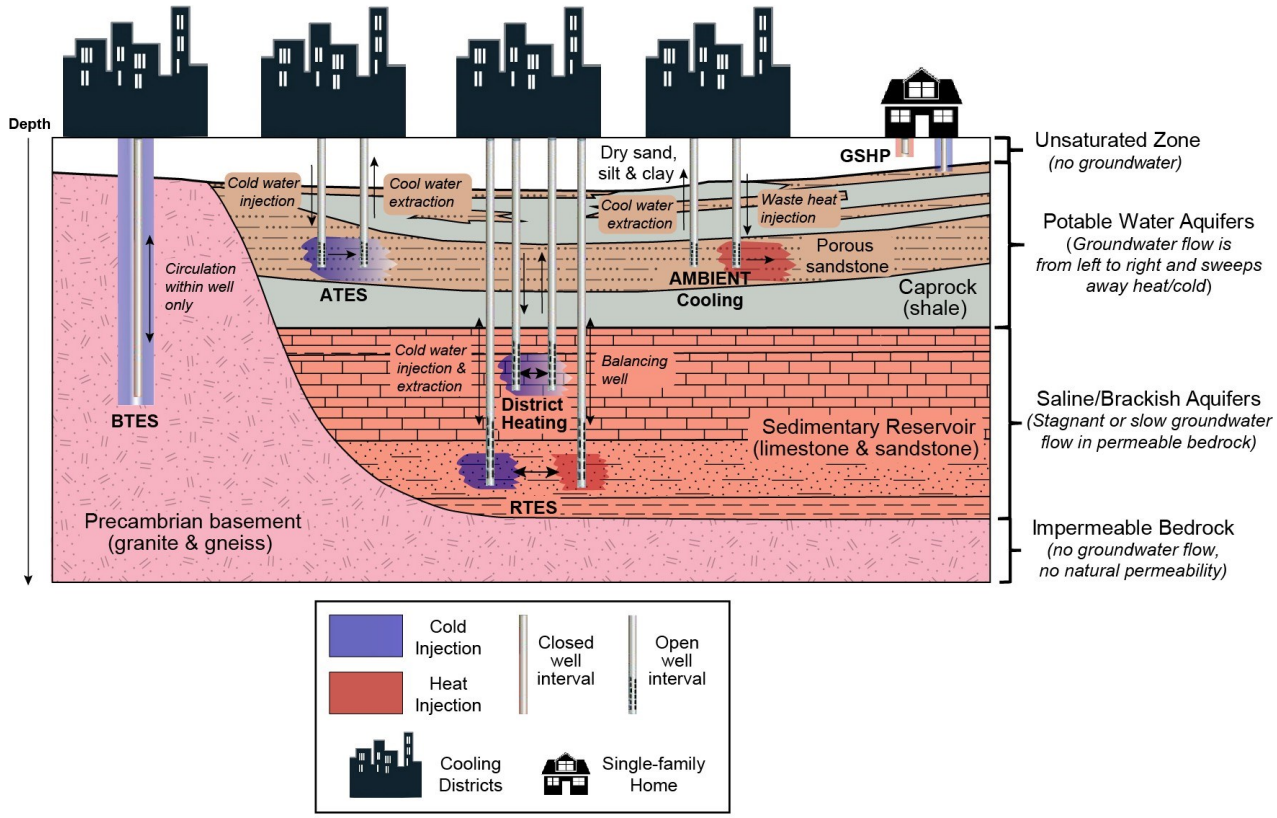


**Figure 1: Typical examples of cooling a single -family home and four high-density urban cooling districts (e.g., commercial and residential) using geothermal resources.** *Each district has a schematic representation of a viable underground thermal energy storage (UTES) resource based on hydrogeological* **conditions** *or AMBIENT cooling using an aquifer as the cooling source and heat sink. For all resource types, cooling is shown, but heating is also feasible. Geologic descriptions are provided to illustrate how geology creates a range of conditions for UTES technologies, but each technology is not restricted to the geology depicted here. [ATES, aquifer thermal energy storage; BTES, borehole thermal energy storage; GSHP, ground source heat pump; RTES, reservoir thermal energy storage]*

### 1.3 The Energy Transition for Urban Areas

In 2020, more than 55% of the global population (more than 75% in Europe) lived in urban environments, and global urban populations are predicted to rise to more than 65% of total population by 2050 (more than 85% in Europe [United Nations, 2018]). In contrast to electricity and fossil fuels, thermal energy cannot be efficiently transported over long distances (Kavvadias and Quoilin 2018). Effective low carbon solutions for the built environment need to be locally available sources and storage. Geothermal heating and cooling solutions in high-density urban areas can replace both electric and fossil fuel supplied loads.

Geothermal is not only beneficial for decarbonization of heating/cooling demand, but it is complimentary to other green solutions (Goetzl and others 2022). It may create grid stability in a situation where there is a lot of intermittent electricity availability by balancing of loads. By replacing electric resistance heating, it also frees up scarce renewable electricity for other uses. Moreover, it has advantages over other options due to real or perceived shortcomings of other technologies. For example, biomass has been one of the largest growing segments

of renewable heating, but is limited in future growth due to potential capacity shortcomings and environmental impacts caused by dust emissions, especially in densely settled environments (Brack, Hewitt and Marchand 2018).

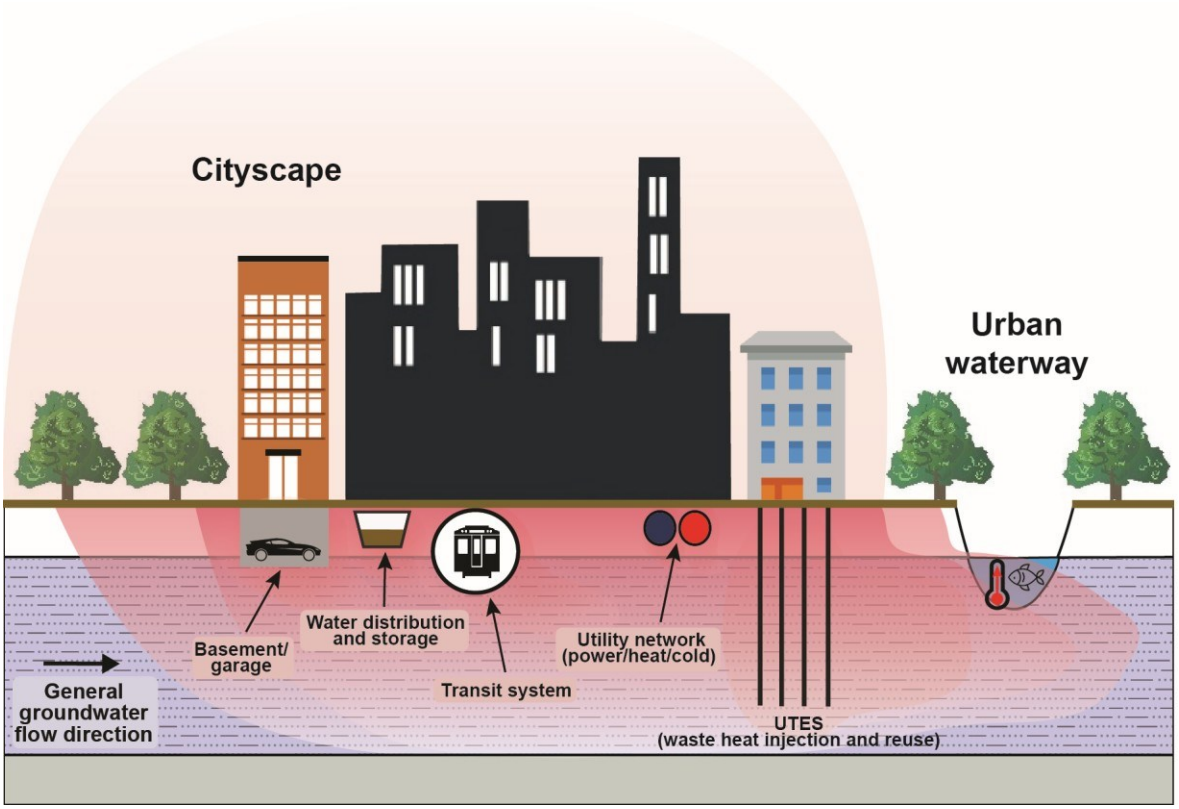


**Figure 2: Urban heat island (UHI) effects can have negative impacts on groundwater resources and receiving waterways and their ecosystems.** ***UHI's are often conceptualized as regions of diffuse widespread heating, but within the larger island, there may be localized heat sources related to anthropogenic infrastructure. A generic underground thermal energy storage (UTES) installation is shown as adding heat, but storage of cold water (e.g., Figure 1) would result in local cooling within the UHI.***

Urban areas have a range of unique supportive aspects for effective low-carbon energy portfolio development, including: 1*) short supply distances, 2) elevated household income levels and 3) availability of inter-sectoral synergy options*. Conversely, decarbonization of the urban heating and cooling sector faces major challenges (Figure 2) that include: i) *high sensitivity towards environmental impacts* such as waste heat (e.g., urban heat islands), dust and noise, ii) *lack of space for installations* and iii) *complex summation effects and interference phenomena above and below the surface*. Triggered by global warming and human interference, such as the sealing of natural surfaces or subsurface installations, urban heat islands [UHI] provide a significant risk to health and livability of cities (Heaviside, Macintyre and Vardoulakis 2017). Moreover, the excess heat at the surface continuously transfers to the subsurface leading to so called subsurface heat islands [SHI], which in turn provide risks to the ecological quality of shallow groundwater bodies as well as to the drinking water supply, respectively (Menberg and others 2013). Including geothermal technologies in urban heating and cooling supply strategies may provide a clear win-win situation by 1) providing clean cooling combined with *UTES* and 2) harvesting excess heat in the subsurface to enhance the biological quality of springs and seeps. The challenge is to get access to sound geoscientific data to evaluate potentials and include them into sustainable urban energy planning strategies. The goal of the 'City-scale Geothermal Energy ' project is to aid in meeting this challenge from a global perspective.

## 2. THE JOINT TRANSCONTINENTAL APPROACH

### 2.1 Key research questions and objectives

In general, the concepts behind direct-use geothermal energy are well-understood, and *AMBIENT* and *UTES* systems have been implemented successfully , at least at the level of pilot and demonstration sites and early business movers around the globe. Although older geothermal technologies were geology -dependent, recent concepts, e.g., by integrating heat pumps and networked thermal energy configurations, are less dependent and can be implemented under a wide range of operational and geologic settings. However, this message has not been clearly communicated to policy and decision makers, leaving gaps in the knowledge base and in public awareness . Improved accessibility of high- and low-temperature geothermal energy can contribute to diversification of energy sources and improve energy security as well as independency. The 'City-scale Geothermal Energy' project therefore seeks an acceleration of understanding that could lead to increased adoption of geothermal technologies in urban areas to mitigate possible future shortcomings of other renewable technologies (e.g., intermittency, vulnerability, supply chain dependencies, critical mineral demands).

In particular, 'City-scale Geothermal Energy' addresses the following key research questions, grouped into different technological and societal domains:

*UNDERGROUND RESOURCE OPTIONS*: Can early lessons learned across the involved continents guide effective and efficient resource assessment and development of city-scale multi-resource (e.g., *AMBIENT*, ATES, BTES, RTES, etc.) evaluation tools? Can these tools help cities develop robust energy portfolios as well as energy plans that meet local goals (e.g., reduce carbon emissions, provide natural-disaster resilience, etc.)?

*ENERGY DEMAND*: What are the heating and cooling needs of each physiographic setting (e.g., geography, geology, climate, etc.), and can geothermal resources and technologies be paired with needs under all or just under certain conditions? How does need/supply matching vary in time? Are there local social or economic incentives that value green-energy solutions, and do these incentives extend to geothermal energy?

*UNDERGROUND THERMAL ENERGY STORAGE AS PART OF LOCAL ENERGY PORTFOLIOS*: How can *UTES*, with energy storage timescales of days to months, compliment short term storage options (timescales of seconds to days)?

*RESOURCE ASSESSMENT*: What constitutes a geothermal resource considering the wide range of geothermal heating and cooling and UTES technologies now available? Are there categories of resources or resource types that must be defined? How much of each resource type exists globally/locally (assessment)? Can maps be constructed for use by municipalities or other large energy users? How to translate complex geoscientific and technologic expert knowledge to non-technical decision makers and planners without loss of information?

*RESOURCE DEVELOPMENT IMPACTS*: What are the impacts of resource development? Are there significant water demands? Is there potential for pollution or degradation of natural resources (e.g., groundwater)? What are the environmental footprints of these systems? Is there potential to contribute to natural disasters (e.g., induced seismicity due to construction or operation of district -scale heating systems)? What do these perceived impacts imply for regulatory oversight (e.g., permits, monitoring, etc.)? Are t here additional governance considerations (e.g., zoning or regional reservoir management)? Does diversification improve energy security?

By systematically addressing these five domains with a knowledgeable international team, we seek to create a state-of-the-science summary that facilitates collaboration and accelerates informed and appropriate adoption of geothermal technologies worldwide.

### 2.2 Organizational structures and approach to support transnational cooperation

#### 2.2.1 The transcontinental consortium

John Wesley Powell grants are awarded to foster collaboration across diverse groups to advance understanding of critical scientific questions (https://www.usgs.gov/centers/john-wesley -powell-center-for-analysis-and-synthesis), and the 'City-scale Geothermal Energy' project aims to accomplish this by establishing a diverse and talented international working group with a wide range of relevant experience. It currently includes experts in different disciplines (e.g., geosciences, engineering and environmental research), different career levels (mentorship by pairing teams of early stage and established researchers) and geographical as well as cultural background to foster mutual learning on relevant societal aspects in deploying geothermal for urban heating and cooling supply. The core team, led by the U.S. Geological Survey, covers 15 participants (maximum limit) from three different continents, engaged at national geological surveys, industrial representatives and universities from *Austria, Germany, Poland, the Netherlands, Greece and Colombia*.

#### 2.2.2 Short introduction to the international working groups

In 'City-scale Geothermal Energy', the international collaboration is organized via working groups, which address the five domains of the above outlined key questions. Each working group is coordinated by a team consisting of an early-stage scientist working with a senior scientist.

*Underground Resource Options working group*: In the beginning, this working group will focus on developing a systematic technical dictionary for categorizing the investigated geothermal application schemes, allowing clear and accurate communication. Using the new dictionary, the working group will elaborate a rubric of underground geothermal-energy-resource types related to close-to-market *AMBIENT* and *UTES* concepts. In a next step, the defined rubrics will be linked to geoscientific characteristics, which need to be translated to the technical language of the addressed end-users (e.g., energy planners, city managers, real estate developers etc.). Once this characterization has been accomplished, suitable mapping and modelling schemes will be assessed in existing international repositories, and gaps in knowledge will be identified. Finally, a conceptual multi-resource evaluation tool will be formulated for end-users to offer sound and understandable resource models for the purposes of energy-portfolio planning (e.g., cost-benefit estimates). For example, existing groundwater flow models may provide the basis for characterizing ATES resources, and geologic carbon sequestration studies and potable water boundary and depth maps may be used to constrain and estimate reservoir thermal energy storage (RTES) resources. Such tasks will be a joint effort with the *Underground Thermal Energy Storage working group.*

*Energy Demand* working group: While national-scale end-use energy -source distributions are commonly prepared by national energy agencies, district-scale or city-specific energy -demand summaries are generally not compiled in many regions worldwide. Because, unlike electricity, thermal energy cannot be efficiently transmitted over long distances (due to excessive heat loss from pipelines) , district-heating/cooling systems need to be sized to deliver heating/cooling at spatial- and temporal-scales that may be unique to each district served. For that reason, this working group aims to compile energy demand estimates from published reports and databases for at least 20 urban centers across Europe, South America and the U.S. The same applies to currently existing energy sources, whilst estimates and proxies, e.g., via building age and density of settlements, will fill prevailing data gaps in the selected case studies. The selection criteria

for case studies will be jointly defined during an initial workshop. Combining energy demand with the availability of existing sources will allow for analyses whether conversion to geothermal resources would lower electricity demand or fossil fuel consumption (e.g., coal or natural gas heating). Energy estimates will be integrated over high-density energy districts and summarized by city. Cities used for these analyses will be critically examined to evaluate the potential value of developing similar datasets for other cities. Finally, a preliminary analysis of energy -demand/resource matching, using results from the *Resource Options* working group, will be accomplished for these cities. For example, in tropical climates with low heating demand, ambient groundwater temperatures are unlikely to provide sufficient cooling, possibly making *UTES* technologies the more likely viable options.

*Underground Thermal Energy Storage working group*: Whereas the *Underground Resource Options* working group will focus on the geologic properties that control heat content and energy delivery, the *Underground Energy Storage* working group will focus on the potential value added when *UTES* is used in combination with other sources of heat and sector coupling. In a first step, this working group will link diverse energy -portfolio options with complementary *UTES* technologies that flatten energy demand cycles to prevent peak-demand energy shortcomings. For each of the urban centers selected by the *Energy Demand* working group, the *Underground Thermal Energy Storage working group* will apply the *Resource Options* rubric to the *Energy Demand* summaries to identify energy storage options that may pair well with current and planned local energy portfolios. This step will require interaction with local stakeholders, which are anticipated to be involved with the international collaboration by means of virtual focus group workshops.

*Resource Assessment working group*: This working group will seek to identify methods for and barriers to the creation of reliable estimates of geothermal resource potential, including maps of suitability and resource estimates. Collaboration will primarily focus on existing methods and the identification of remaining gaps following the learning network approach. The anticipated activities include identifying concepts to upscale district-scale *Resource Options* methodologies to regional- or national-scale maps linked to quantitative estimates of resource potential (including uncertainty). This also includes the identification of relevant regional datasets that can be used as the foundation for construction of resource assessment maps. For case studies showing shallow groundwater systems, special attention will be paid on mapping thermal summation effects linked to the UHI effect as well as on the resulting implication on geothermal energy use. If data are available in a sufficient extent, the working group may demonstrate sample elaborated workflows to provide resource assessment maps. Special attention will be given to identifying data gaps, leading to recommendations for future survey strategies.

*Resource Development Impacts working group*: This complementary working group seeks to broadly identify implications of geothermal energy development. The working group will define a diverse set of relevant topics, which will be refined during the collaborative process, based on input from team members and external connections made during the project. In a next step, the identified relevant impacts will be compared with the current regulations in the countries and states involved in 'City -scale Geothermal Energy' to identify good practices and possible gaps. Finally, the working group concludes on possible trade-offs between different energy options in the selected case studies and derives scientific goals for resource managers based on the international experiences gained. A preliminary list of key impacts has been identified as a starting place for discussions by the working group (Table 1).

**Table 1: Overview of anticipated key impacts related to the deployment of geothermal energy at city-scale.**

| Anticipated key impact | Explanations |
|---|---|
| **Groundwater quality** | Safety and sustainability requirements for the construction and operation of identified geothermal technologies in urban environments (e.g., hydraulic shortcuts between different aquifers, additional heat injection by sole cooling applications or freshwater consumption related to the installment and operation of geothermal technologies). |
| **Environmental impacts** | Thermal pollution of groundwater bodies through insufficient planning and management of ATES applications.<br><br>M utual thermal or hydraulic negative interference of neighboring geothermal installations in densely settled environments.<br><br>Prevailing gaps in environmental impact assessment methodologies linked to novel geothermal utilization schemes.<br><br>Reduced sustainability of existing geothermal resources due to overexploitation.<br><br>Increased health and livability conditions in cities in the light of global warming due to the use of geothermal technologies (e.g., climate friendly geo-cooling, use of excess surface and subsurface heat in combination with *UTES*).<br><br>Ecological benefits of applying geothermal technologies in cities with attention paid to the possible consumption of excess heat due to UHIs. |

| | |
|---|---|
| **Technological impacts** | Bottlenecks in retrofitting existing infrastructure (e.g., heating network pipelines) for the integration of geothermal applications. |
| **Societal and regulatory impacts** | Competing interests in using the subsurface with regard to the deployment of geothermal applications (e.g., subsurface traffic lines, carbon or non-thermal energy storage).<br><br>Regulatory bottlenecks and unwanted rebound effects in the light of balancing environmental protection and deployment of renewable energies.<br><br>Social perceptions and unwanted socio-economic rebound effects (e.g., social inclusiveness, tax policies) linked to a deployment of geothermal applications in cities. |

### 2.3 Anticipated tasks and timeline

The funds provided by the John Wesley Powell Center for Analysis and Synthesis includes two in-person workshops for the fifteen core team-members as well as access to data processing infrastructure during the two years lifetime of the 'City-scale Geothermal Energy' project. Funding is limited to participant travel and a part-time post-doctoral technical fellow, so all additional participant costs for collaboration are provided by voluntary contributions of individuals or employers of working group team members.

For that reason, the anticipated work structure of this initiative is de-centralized, comprising key in person workshops marking critical milestones, which are complemented by remote collaboration within each working group and sub-group. Joint external communication activities will focus on between-meeting goals and ultimately, the resulting scientific publications that are linked to the outcomes of each working group . In addition, dedicated focus group workshops involving stakeholders from the selected case studies as well as a series of webinars will complement the anticipated communication activities.

The 'City-scale Geothermal Energy' collaboration has already kicked off, with the first in-person workshop planned for February 2023 at the John Wesley Powell Center for Analysis and Synthesis, Colorado, U.S. Apart from team building activities, the first workshop will aim at positioning and identifying collaboration means of working group s. The first workshop will conclude in a set of working steps to be fulfilled in preparation for the second workshop, scheduled for February 2024.

The second and final in-person meeting at John Wesley Powell Center for Analysis and Synthesis targets alignment with next year's Stanford Geothermal Workshop , which will offer an excellent dissemination opportunity of the results achieved so far. The second workshop will focus on the critical interfaces between the individual working groups and foster to exchange the outcomes achieved so far in order to develop an updated work plan for the closing phase of 'City -scale Geothermal Energy'. Moreover, the final workshops will offer dedicated sessions to the working groups to discuss and work on manuscripts comprising the key outcomes.

In between the two key in-person workshops, a general framework will be put in place for each working group, which consists of proposed internal collaboration and external cooperation measures (e.g., virtual progress meetings, publicly accessible webinars related to the focus of each working group , joint digital work environments, and required joint working group leaders' meetings). However, the working groups will have the freedom to organize the collaboration inside each group independently inside the given framework.

## 3. EXPECTED OUTCOMES OF THE COLLABORATION

Considering the voluntary contributions of its participants, 'City-scale Geothermal Energy' aims at creating a community-of-practice that benefits from the strengths and experiences of a diverse multi-national, multi-cultural, and multi-generational working group. The collaboration is expected to lead to a set of specific outputs, which are outlined below.

*Technical/scientific reports and manuscripts*: Each working group will prepare a technical summary on the achieved outcomes at the end of the project. Technical summaries will be linked to joint publication in the peer-reviewed open access literature. Special attention will be paid to key topics such as *state-of-the-science/technology*, *trans-continent comparison of cities' potential for geothermal energy use*, and *identification of major challenges or research needs*.

*Events and seminars*: The project will organize at least five publicly accessible summary webinars and will target organization of an urban geothermal energy use session at the World Geothermal Congress 2026, where key results will be presented to a global audience of scientists, engineers, and industry. All materials created, including internal workshops and meetings , will be linked to a John Wesley Powell Center for Analysis and Synthesis hosted project webpage.

*Datasets:* While 'City-scale Geothermal Energy' mainly relies on published data and available models, the team will likely create complementary datasets for specific analyses. Any new datasets will be published in publicly available repositories. At a minimum, datasets will include urban-center specific energy demand compilations, current energy supply portfolios, and if available, geologic evidence for types of geothermal resources will be provided for each key case study. These datasets will be published along with interpretive science reports at the end of the collaboration and made accessible to the public.

*Software*: No specific software development is planned throughout 'City -scale Geothermal Energy'. Instead, the team will likely use available USGS and USDOE National Renewable Energy Laboratory (NREL) software to evaluate resources or estimate costs. This may include adding a module or functionality, and all models will be archived and published.

*Spin-off activities and uptakes*: The internal meetings and workshops will have dedicated sessions on identifying measures and opportunities to capitalize upon the network created beyond the duration of the project.

**ACKNOWLEDGEMENTS**

This work was conducted as a part of the 'City-scale Geothermal Energy' working group supported by the John Wesley Powell Center for Analysis and Synthesis, funded by the U.S. Geological Survey.

**REFERENCES**

Aneke, M., and Wang, M., 2016, Energy storage technologies and real life applications – A state of the art review, Applied Energy, v. 179, issue C, 350-377.

Banks, D, 2014, A review of the importance of regional groundwater advection for ground heat exchange. Environmental Earth Sciences 73(6): 2555–2565.

Bar, K., Welsch, B., Schulte, D., Ruhaak, W., and Sass, I., 2017, Seasonal High Temperature Heat Storage with Middle Deep Borehole Heat Exchangers – a Coupled-Modeling Study, Proceedings: 42nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA.

Bershaw, J., Burns, E.R., Cladouhos, T.T., Horst, A., van Houten, B., Hulseman, P., Kane, A., Liu, J.H. Perkins, R.B., Scanlon, D.P., Streig, A.R., Svadlenak, E.E., Uddenberg, M., Wells, R., and Williams, C.F., 2020, An Integrated Feasibility Study of Reservoir Thermal Energy Storage in Portland, OR, USA, PROCEEDINGS, 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 10-12, 2020

Bloemendal, M. and Hartog, N., 2018. Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. Geothermics, 71, pp.306-319.

Bloemendal, M., Olsthoorn, T., and Boons, F., 2014, How to achieve optimal and sustainable use of the subsurface for Aquifer Thermal Energy Storage, Energy Policy, 66, 104-114.

Bloemendal, M., Olsthoorn, T., and van de Ven, F. (2015). Combining climatic and geo-hydrological preconditions as a method to determine world potential for aquifer thermal energy storage. Science of The Total Environment, 538:621–633

Bouzarovski, S., Thomson H., Cornelis M., Varo A. and Guyet R., 2020, Towards an inclusive energy transition in the European Union: Confronting energy poverty amidst a global crisis. Publications Office of the European Union, Luxembourg, (2020) DOI: 10.2833/103649, EU Energy Poverty Observatory.

Bridger, D.W., and Allen, D.M., 2005, Designing Aquifer Thermal Energy Storage Systems, Building for the Future; A Supplement to ASHRAE Journal, (2005), S32-S38.

Burns, E.R., Bershaw, J., Williams, C.F., Wells, R., Uddenberg, M., Scanlon, D., Cladouhos, T.T., and van Houten, B., 2020, Using Saline or Brackish Aquifers as Reservoirs for Thermal Energy Storage, with Example Calculations for Direct-Use Heating in the Portland Basin, OR, USA, Geothermics, v. 88, 101877, 17 p. https://doi.org/10.1016/j.geothermics.2020.101877

Burns, E.R., Cladouhos, T.T., Williams, C.F. and Bershaw, J., 2018, Controls on Deep Direct-Use Thermal Energy Storage (DDU-TES) in the Portland Basin, Oregon, USA, GRC Transactions, Vol. 42.

Brack D., Hewitt J. and Marchand T.M., 2018, Woody Biomass for Power and Heat, Demand and Supply in Selected EU Member States, The Royal Institute of International Affairs, London, United Kingdom, ISBN: 978-1-78413-277-5.

Duscha V., Denishchenkova A. and Wachsmuth J. 2019. Achievability of the Paris Agreement targets in the EU: demand-side reduction potentials in a carbon budget perspective, Climate Policy, 19:2, 161-174, DOI: 10.1080/14693062.2018.1471385.

EU Commission, DGE ENER/C1/2018-494 (2022), Renewable Space Heating under the Revised Renewable Energy Directive, European Comission, Brussels.

Fleuchaus, P., Godschalk, B., Stober, I., and Blum, P., 2018. Worldwide application of aquifer thermal energy storage – a review, Renewable Sustainable Energy Rev. 861–876.

Fujii, H., R. Itoi, J. Fujii, Y. Uchida 2005. Optimising the design of large-scale ground-coupled heat pump systems using groundwater and heat transport modelling. Geothermics, 34 (2005), pp. 347-364

Gao, Q., Li, M., Yu, M., Spitler, J.D. and Yan, Y.Y., 2009. Review of development from GSHP to UTES in China and other countries. Renewable and Sustainable Energy Reviews, 13(6-7), pp.1383-1394.

Goetzl G., Milenic D. and Schifflechner C., 2020, Geothermal-DHC, European Research Network on Geothermal Energy in Heating and Cooling Networks, Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020

Goetzl G., Milenic D., Mandrone G., Chicco J.M ., Gemeni V., Haslinger E., Rman N., Singh R.M ., Vranjes A. and Zosseder K, 2022, COST Action Geothermal-DHC – Roadmaps for integrating geothermal energy in its full technological spectrum into heating and cooling networks across Europe, Proceedings European Geothermal Congress 2022, Berlin, Germany, 17-21 October 2022.

Heaviside C., Macintyre H. and Vardoulakis S., 2017, *The Urban Heat Island: Implications for Health in a Changing Environment*, Curr Envir Health Rpt, Springer, DOI: 10.1007/s40572-017-0150-3

Huttrer G.W, 2020, *Power Generation in the World 2025-2020 Update Report*, Proceedings World Geothermal Congress 2020+1 Reykjavik, Iceland, April – October, 2021.

IRENA 2020. Renewable capacity statistics 2020 International Renewable Energy Agency (IRENA), Abu Dhabi, ISBN 978-92-9260-239-0.

Jadun, P., McMillan, C., Steinberg, D., Muratori, M ., Vimmerstedt, L., and Mai, T., 2017, Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050, Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-70485. https://www.nrel.gov/docs/fy18osti/70485.pdf.

Kallesøe, A.J. & Vangkilde-Pedersen, T. (eds). 2019: Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 130 p.

Kangas, M.T., and Lund, P.D., 1994, Modeling and simulation of aquifer storage energy systems, Solar Energy, 53, (1994), 237-247.

Kavvadias K.C. and Quoilin S., 2018, Exploiting waste heat potential by long distance heat transmission: Design considerations and techno-economic assessment, Applied Energy 216, pp 452-465, Elsevier, https://doi.org/10.1016/j.apenergy.2018.02.080.

Lee K (2013) Underground thermal energy storage. In: Aquifer thermal energy storage, Springer London, pp 59–93, doi: https://doi.org/10.1007/978-1-4471-4273-7_2

Liang, B., Chen, M. and Orooji, Y., 2022. Effective parameters on the performance of ground heat exchangers: A review of latest advances. Geothermics, 98, p.102283.

Lucia U., Simonetti M ., Chiesa G. and Grisolia G., 2017, Ground-source pump system for heating and cooling: Review and thermodynamic approach. Renewable and Sustainable Energy Reviews 70, 867–874.

Lund J.W. and Toth A. K., 2020, Direct Utilization of Geothermal Energy 2020 Worldwide Review. Proceedings World Geothermal Congress 2020+1, Reykjavik, Iceland, April - October 2021.

Menberg K., Bayer P., Zosseder K., Ruohr S. and Blum P., 2013, Subsurface urban heat islands in German cities, Science of the Total Environment 442, pp 123-133, Elsevier, https://doi.org/10.1016/j.scitotenv.2012.10.043.

Midttømme, K., Kocbach, J., Ramstad, R.K. and Henne, I., 2017. Aquifer thermal energy storage (ATES). Technika Poszukiwań Geologicznych, 56.

Nordell, B.O. and Hellström, G., 2000. High temperature solar heated seasonal storage system for low temperature heating of buildings . Solar energy, 69(6), pp.511-523.

Pepin, J.D., Burns, E.R., Dickinson, J.E., Duncan, L.L., Kuniansky, E.L., and Reeves, H.W., 2021, National-scale reservoir thermal energy storage pre-assessment for the United States, in Workshop on Geothermal Reservoir Engineering, 46th, Stanford, Calif., February 16–18, 2021, Proceedings: Stanford, Calif., Stanford University, SGP–TR–218, 10 p., https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2021/Pepin.pdf

Sanner, B., Kabus, F., Seibt, P., and Bartels, J., 2005, Underground Thermal Energy Storage for the German Parliament in Berlin, System Concept and Operational Experiences, Proceedings of the World Geothermal Congress, Antalya, Turkey, April 24-29, 2005, 8 p.

Sanner, B., Karytsas, C., Mendrinos, D., and Ryback, L., 2003, Current status of ground source heat pumps and underground thermal energy storage in Europe, Geothermics, v. 32, 579-588, https://doi.org/10.1016/S0375-6505(03)00060-9.

Sarbu I., Sebarchievici C., 2014. General review of ground-source heat pump systems for heating and cooling of buildings, Energy and Buildings 70, pp. 441–454, DOI: 10.1016/j.enbuild.2013.11.068.

Schintgen, T. Exploration for deep geothermal reservoirs in Luxembourg and the surroundings - perspectives of geothermal energy use. Geotherm Energy 3, 9 (2015). https://doi.org/10.1186/s40517-015-0028-2

Self S.J., Reddy B.V., Rosen M.A. 2013. Geothermal heat pump systems: Status review and comparison with other heating options. Applied Energy 101, 341–348, doi:10.1016/j.apenergy.2012.01.048.

Shi, L., Liu, X., Qu, M ., Liu, G., and Li, Z., 2021, Potential of Utilizing Thermal Energy Storage Integrated Ground Source Heat Pump System to Reshape Electricity Demand in the United States. ASME. J. Eng. Sustain. Bldgs. Cities. August 2021; 2(3): 031003. https://doi.org/10.1115/1.4051992

Snijders, A.L., 2000, Lessons from 100 ATES projects: The developments of aquifer storage in the Netherlands. In: Proceedings Terrastock. 8th International Conference on Thermal Energy Storage, Stuttgart, Germany

Sommer, W.T., Doornenbal, P.F., Drijver, B.C., van Gaans, P.F.M ., Leusbrock, I., Grotenhuis, J.T.C., and Rijnaarts, H.H.M ., 2014, Thermal performance of and heat transport in aquifer thermal energy storage, Hydrogeology Journal, 22, 263-279.

Tomigashi, A., K. Fujinawa, 2011, Enhanced aquifer thermal energy storage for cooling and heating of Shinshu University building using a nested well system, Sustainable Development and Planning V, pp.871-882.

United Nations, Department of Economic and Social Affairs, Population Division (2018). World Urbanization Prospects: The 2018 Revision, Online Edition

USDOE (U.S. Department of Energy), 2019, GeoVision: Harnessing the Heat Beneath Our Feet, 218 p., https://www.energy.gov/sites/default/files/2019/06/f63/GeoVision-full-report-opt.pdf.

Van den Berg B., Breemboek G., Ramsak P., Schreiber S., Richter M. and Siddiqi G, 2019, Barriers, Opportunities and RD&D needs for geothermal energy , Update 2018/2019, GEOTHERM ICA D7.2, GEOTHERM ICA Office, Reykjavik, Iceland, ISBN: 978-9979-68-498-5.

Welsch, B., Ruhaak, W., Schulte, D.O., Bar, K., and Sass, I., 2016, Characteristics of medium deep borehole thermal energy storage, International Journal of Energy Research, 40, 1855-1868.

Williams, C.F., DeAngelo, J., and Reed, M.J., 2015, Revisiting the Assessment of Geothermal Resources <90 ºC in the United States, GRC Transactions, Vol. 39.

Williams, C. F., Reed, M .J., Mariner, R.H., DeAngelo, J., and Galanis, S.P., 2008, Assessment of M oderate-and High-Temperature Geothermal Resources of the United States: U.S. Geological Survey Fact Sheet 2008-3082, U.S. Geological Survey Fact Sheet 2008-3082, pp. 1–4. Available at: http://pubs.usgs.gov/fs/2008/3082/.

Zanchini, E, Lazzari, S, Priarone, A, 2012, Long-term performance of large borehole heat exchanger fields with unbalanced seasonal loads and groundwater flow. Energy 38(1): 66–77.

Zhu, JL, Hu, KY, Lu, XL., 2015, A review of geothermal energy resources, development, and applications in China: Current status and prospects. Energy 93: 466–483.