PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 16-18, 2021
SGP-TR-218

National-Scale Reservoir Thermal Energy Storage Pre-Assessment for the United States

Jeff D. Pepin, Erick R. Burns, Jesse E. Dickinson, Leslie L. Duncan, Eve L. Kuniansky, and Howard W. Reeves

U.S. Geological Survey, 6700 Edith Blvd. NE, Building B, Albuquerque, NM, 87113, USA

jpepin@usgs.gov

Keywords: Reservoir thermal energy storage (RTES), Geothermal, Direct-use cooling

ABSTRACT

The U.S. Geological Survey is performing a pre-assessment of the cooling potential for reservoir thermal energy storage (RTES) in five generalized geologic regions (Basin and Range, Coastal Plains, Illinois Basin, Michigan Basin, Pacific Northwest) across the United States. Reservoir models are developed for the metropolitan areas of eight cities (Albuquerque, New Mexico; Charleston, South Carolina; Chicago and Decatur, Illinois; Lansing, Michigan; Memphis, Tennessee; Phoenix, Arizona; and Portland, Oregon) so that computed metrics can be compared to evaluate RTES potential across diverse climates, geologic settings, and physiography. Permeable, semi-confined/confined units that underlie more-utilized aquifers and contain low-quality groundwater are selected for each city. Energy storage metrics are computed for the anticipated total thickness of stratigraphy for which RTES might be feasible, including estimated required well spacing, thermal storage capacity, and thermal recovery efficiency over time. Falta et al. (2016) showed that for a modern 25,000 square-foot (2,323 square-meter), two-story office building, cooling needs exceed heating demand for almost every region of the country. We therefore use Falta et al.'s cooling demand for each city as the representative RTES stress condition for metric computation, allowing comparisons across regions. Results indicate that favorable RTES conditions exist in each region, particularly in the Illinois Basin, Coastal Plains, and Basin and Range. Thermal recovery efficiencies are very high in all regions and increase over time. The thermal storage capacity metric is most informative in the pre-assessment and underscores the importance of mapping reservoir thicknesses and porosities to permit detailed mapping of thermal storage capacity per unit area as a key RTES resource classification standard. This assessment provides a basic understanding of the RTES potential in several metropolitan areas and geologic regions throughout the United States and will aid further evaluation of national RTES efficacy.

1. INTRODUCTION

Storage of thermal energy in aquifers that contain low-quality groundwater and underlie freshwater aquifers allows use of largely undeveloped groundwater resources for matching of peak energy production with peak energy demand. Both hot or cold water may be stored for later direct-use heating or cooling, respectively, or even the production of electricity (Neupane et al., 2020). The proposed storage zones share characteristics of traditional geothermal reservoirs, particularly in terms of chemistry, flowrate, and poor connection with shallow fresh aquifers. The term reservoir thermal energy storage (RTES) is therefore used in this case to distinguish thermal energy storage using slow-flowing, geochemically evolved aquifers from traditional aquifer thermal energy storage (ATES) applications (Burns et al., 2020).

The U.S. Department of Energy's (DOE) recent GeoVision report (DOE, 2019) considers a range of geothermal technologies, market conditions, and barriers to adoption – notably identifying both low-temperature geothermal resources and thermal energy storage as hugely underutilized. They project that district heating and cooling systems could grow to supply more than 320 Gigawatt-thermal (GW_{th}) of heating and cooling by 2050. The work described herein is an initial step towards understanding the extent to which RTES may supply part of the 2050 target. The U.S. Geological Survey (USGS), with support by the DOE Geothermal Technologies Office, is expanding national geothermal resource assessment and classification activities with a pre-assessment of RTES across a range of United States regions. Ultimately, activities are planned to be extended to include regional- and national-scale RTES resource assessments, driven by new model- and data-driven analyses. The pre-assessment is intended to further gauge RTES potential in the United States and aid in the development of new geothermal resource classification standards.

Herein, we summarize and analyze known or suspected reservoir conditions underlying eight selected cities that represent five generalized geologic regions. City selection considers metropolitan area population, hydrogeology, water quality, and climate (Figure 1). As part of this pre-assessment, 15 additional cities are identified as likely having favorable RTES conditions and may warrant consideration for future analysis (Figure 1). Using analytical estimates of required well spacing, thermal storage capacity, and thermal recovery efficiency over time, we evaluate local RTES efficacy and compare cities to understand conditions that will control regional potential. We use the cooling demand of a standardized office building from Falta et al. (2016) to compare how climate and reservoir properties will influence regional resources. Cooling was selected because commercial cooling needs exceed those of heating for almost every region of the country (Figure 2; Falta et al., 2016).

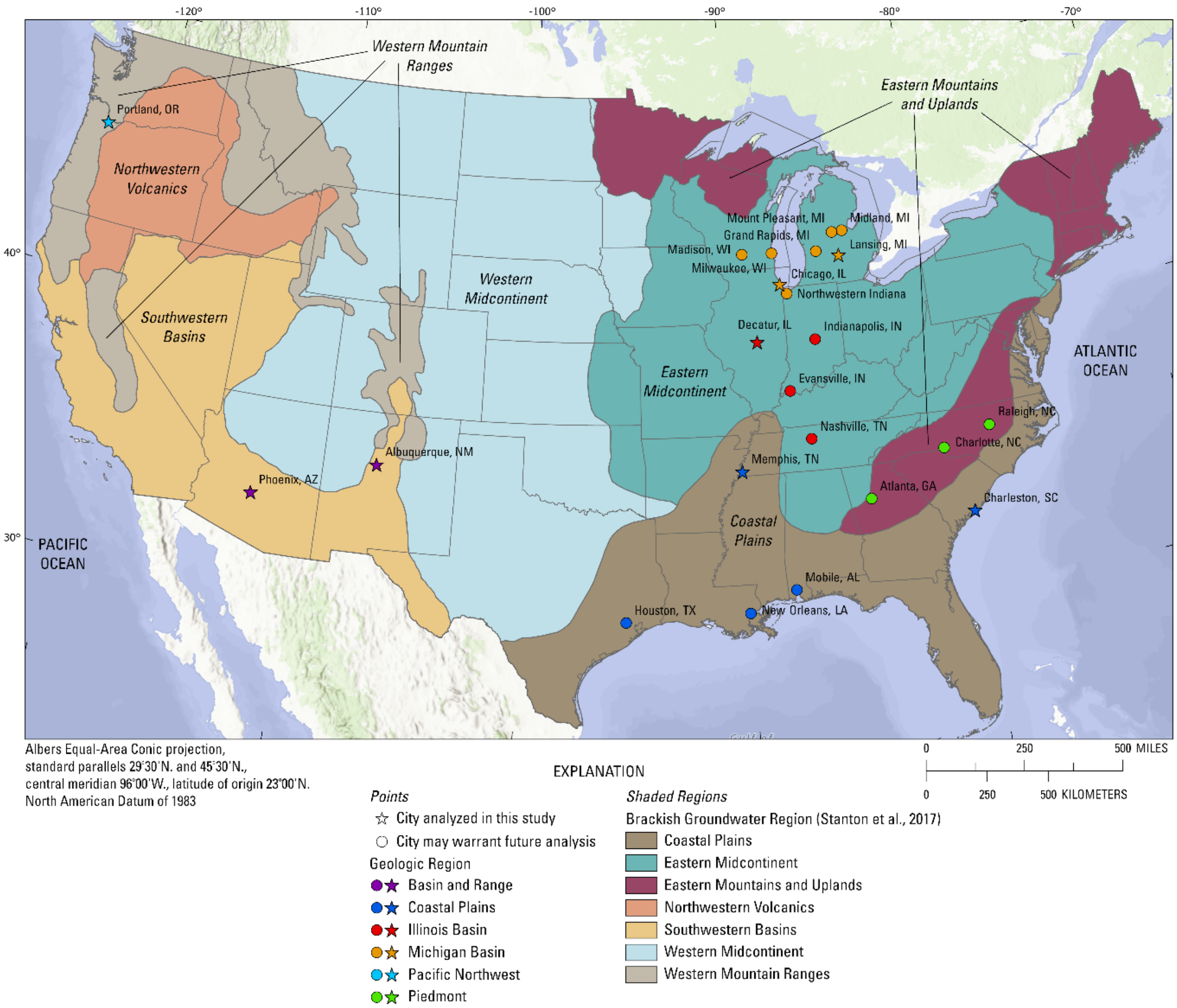

Figure 1: Cities used for the analyses herein (stars), grouped by geologic regions, and overlying brackish groundwater regions of the United States (Stanton et al., 2017). Additional cities (circles) represent nearby population centers with likely favorable RTES conditions that may warrant consideration for future analysis.

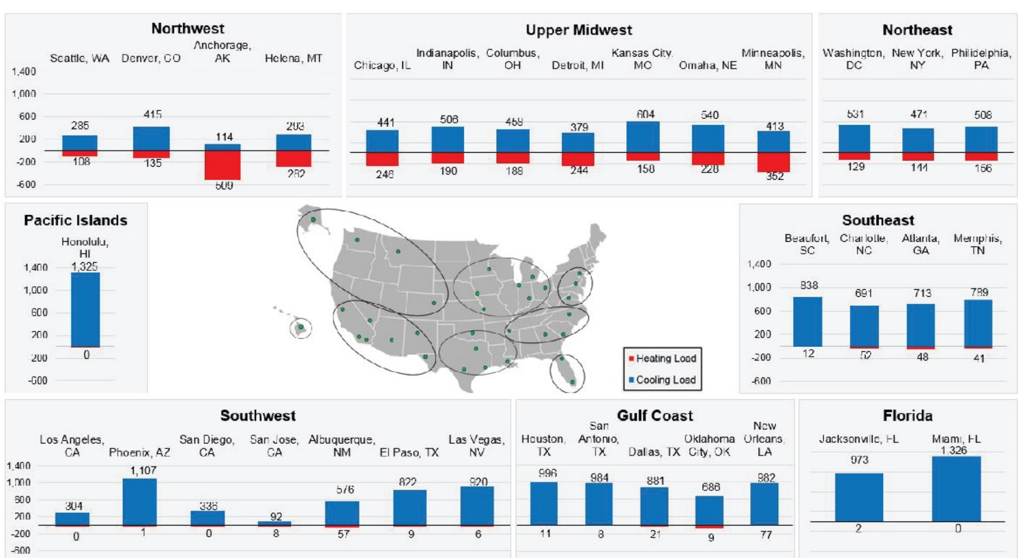

Figure 2: Estimated annual heating (red) and cooling (blue) loads in million BTUs (1 BTU= 1,055.06 J) for a representative 25,000 ft[2] (2,323 m[2]) two-story modern office building in select United States cities (figure used with permission from Falta et al., 2016).

2. SCOPE AND EVALUATED AREAS

We select cities where a basic literature review and researcher expertise indicate likely existence of favorable RTES conditions and provide enough hydrogeologic information to complete this pre-assessment. In short, favorable conditions include the presence of confined/semi-confined permeable strata saturated with relatively low-quality groundwater. Information for these less utilized units is limited, and because the nature of the study is preliminary, no attempt is made to exhaustively quantify likely reservoirs (e.g., number of permeable layers, range of parameters, uncertainty, etc.). Metropolitan area population and climate also factor into city selection so that results are applicable to areas of high-energy demand and cover a diverse set of climates, physiography, and geologic settings. An additional key criterion for pre-assessment inclusion is that USGS hydrogeologists (the study team) exist with local expertise about the hydraulic properties of at least part of the desired aquifer system, allowing a preliminary analysis.

A total of 23 cities are deemed to be of immediate interest, eight of which are further evaluated herein (Table 1, Figure 1). These eight cities represent a total of five generalized geologic regions across the United States including: Basin and Range, Coastal Plains, Illinois Basin, Michigan Basin, and the Pacific Northwest. Furthermore, four brackish groundwater regions from Stanton et al. (2017) are represented in the study, which include Coastal Plains, Eastern Midcontinent, Southwestern Basins, and Western Mountain Ranges. Three cities in the Piedmont geologic region and Eastern Mountains and Uplands brackish groundwater region are identified as favorable but are not yet incorporated into the pre-assessment; at least one of these cities is planned to be included in future assessment efforts.

Table 1: Evaluated cities with their corresponding metropolitan area population, geologic region, and brackish groundwater region. Energy loads from the nearest city in Falta et al. (2016; Figure 2) are provided in gigajoules. Population estimates are from United States census data (U.S. Census Bureau, 2012).

City	Metro Area Population	Geologic Region	Brackish Groundwater Region	Nearest City in Falta et al. (2016)	Cooling Load	Heating Load
Albuquerque, NM	887,077	Basin and Range	Southwestern Basins	Albuquerque, NM	608	60
Charleston, SC	664,607	Coastal Plains	Coastal Plains	Beaufort, SC	884	13
Chicago, IL	9,461,105	Michigan Basin	Eastern Midcontinent	Chicago, IL	465	260
Decatur, IL	110,768	Illinois Basin	Eastern Midcontinent	Indianapolis, IN	534	200
Lansing, MI	464,036	Michigan Basin	Eastern Midcontinent	Detroit, MI	400	257
Memphis, TN	1,316,100	Coastal Plains	Coastal Plains	Memphis, TN	832	43
Phoenix, AZ	4,192,887	Basin and Range	Southwestern Basins	Phoenix, AZ	1,168	1
Portland, OR	2,226,009	Pacific Northwest	Western Mountain Ranges	Seattle, WA	301	114

2.1 RTES Conceptual Models and Conditions

The evaluated generic RTES cooling conceptual model (Figure 3) uses an injection well and extraction well pair (doublet). Cooled water (4°C) is injected into the reservoir during winter and then extracted in the summer for direct-use cooling, returning 14°C water. Well flow rates are balanced in this configuration, leading to little or no above-ground water storage. Well spacing needs to be large enough to avoid thermal interference between wells and is determined by local cooling needs and reservoir conditions. The storage reservoir is a permeable zone located between less-permeable strata, and in the case of the selected cities, underlies a more utilized or primary aquifer system. The low-permeability units thermally insulate the reservoir, while also impeding vertical groundwater flow. This restriction of vertical energy movement causes the lateral spreading of stored energy within the reservoir. Groundwater flow rates in the overlying aquifer system are anticipated to be much greater than those of the reservoir, though this is not required. High flow rates in the overlying aquifer system provide an essentially constant overlying groundwater temperature through time that leads to enhanced vertical conductive energy flux to or from the reservoir (depending on reservoir storage temperatures and overlying aquifer temperature). Slower ambient groundwater flow in the reservoir minimizes advective energy loss within the reservoir itself. Target reservoirs have low-quality groundwater compared to the overlying aquifer system, which naturally discourages competing anthropogenic uses like municipal groundwater production, thereby further limiting advective energy losses. In other words, the targeted conditions favor stored energy remaining in place throughout storage durations. Vertical conductive energy losses are greatest early on but diminish over time as the reservoir and surrounding rocks equilibrate with mean annual injection temperatures. Annual recovery of thermal energy will therefore increase with time.

The RTES conditions of the selected geologic regions are diverse (Tables 1 and 2). Cooling loads are greatest in the Basin and Range and Coastal Plains, while the lowest cooling loads are found in the Pacific Northwest and Michigan Basin. This climatic influence is also evident in estimated overlying primary aquifer and initial subsurface temperatures. The extensional tectonic environment of the Basin and Range yields the highest ambient geothermal heat flux estimates, while the lowest are in Memphis and Portland. Target reservoirs are basin-fill and coastal sediments in the Basin and Range and Coastal Plains, respectively. The target reservoirs of the Illinois and Michigan Basins are sandstones, whereas a sequence of basalt flows is targeted in the Pacific Northwest. Thicknesses of reservoirs and surrounding strata vary from city to city. In all cases, except Phoenix, estimated horizontal permeabilities ($k_{horizontal}$) in the reservoir are several orders of magnitude greater than the vertical permeabilities ($k_{vertical}$) of the bracketing units; yielding ratios of the $k_{vertical}$ of the bracketing units to $k_{horizontal}$ of the reservoir on the order of 10^2 to 10^6. The overlying unit in Phoenix restricts vertical groundwater flow but not to the extent of the units in other cities ($k_{vertical}$ overlying unit to $k_{horizontal}$ reservoir ratio of 9), while the underlying unit strongly limits vertical flow ($k_{vertical}$ underlying unit to $k_{horizontal}$ reservoir ratio of 7,190). Overall, the wide range of evaluated conditions is intended to make this pre-assessment relevant to many cities in the United States.

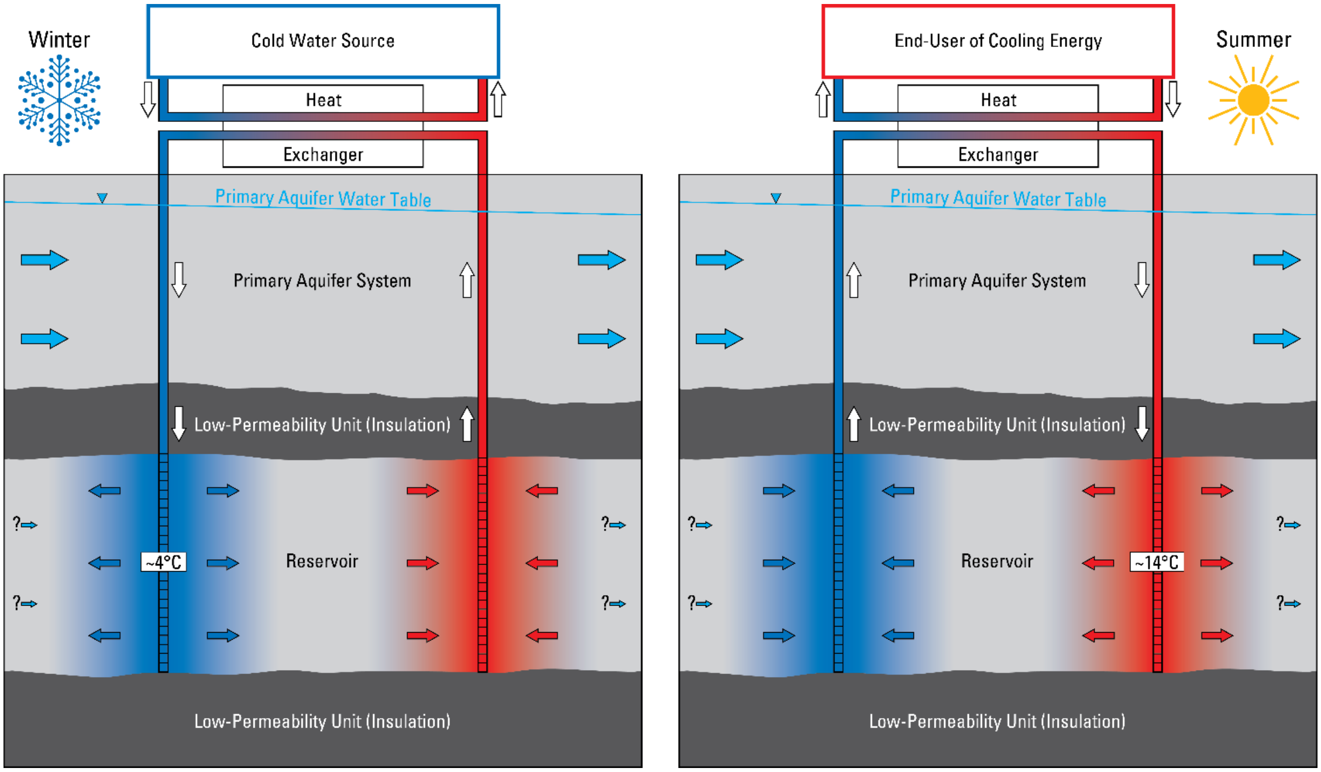

Figure 3: Conceptual model for cooling with a reservoir thermal energy storage (RTES) doublet. Cooled water is injected into the reservoir in the winter (left) and then extracted from the reservoir in the summer (right) via flow reversal. Flow rates in the extraction and injection wells are balanced to minimize above-ground storage of water. Shaded arrows show subsurface groundwater flow patterns resulting from injection and extraction (blue and red) along with ambient regional groundwater flow (light blue). White arrows depict flow directions within the RTES piping system. Question marks near small arrows in the reservoir indicate ambient groundwater flow may occur, but magnitude is expected to be small and assumed negligible herein.

Table 2: Estimated local hydrogeologic properties of conceptualized reservoir thermal energy storage stratigraphy in each city. *Abbreviations:* $\dot{q}_{geo}$ = geothermal heat flux in milliwatts per square meter, T_{aq} = overlying primary aquifer and initial subsurface temperature in degrees Celsius, b = thickness in meters, n = effective porosity, $k_{horizontal}$ = bulk horizontal permeability in square meters, $k_{vertical}$ = bulk vertical permeability in square meters. Geothermal heat fluxes are from the most recent USGS heat flow map (Williams and DeAngelo, 2015). Subsurface conditions are estimated from previously published literature (Pepin et al., 2021).

			RESERVOIR				OVERLYING UNIT			UNDERLYING UNIT	
City	$\dot{q}_{geo}$	T_{aq}	Unit	b	n	$k_{horizontal}$	Unit	b	$k_{vertical}$	Unit	$k_{vertical}$
Albuquerque, NM	70	21.5	Middle Santa Fe Group sediments	150	0.20	1.4E-12	Atrisco Member of Ceja Formation	150	1.1E-15	Lower Santa Fe Group sediments	5.5E-15
Charleston, SC	51	31.0	Gramling aquifer sediments	152	0.35	6.6E-13	Gramling confining unit	61	5.6E-17	Basement	6.6E-17
Chicago, IL	59	10.0	Mount Simon Sandstone	300	0.05	1.2E-12	Eau Claire Formation	416	4.8E-17	Basement	7.5E-17
Decatur, IL	54	24.5	Mount Simon Sandstone	457	0.14	3.7E-10	Eau Claire Formation	152	1.4E-15	Basement	1.3E-15
Lansing, MI	48	10.0	Marshall Sandstone	64	0.05	1.5E-11	Michigan Formation	188	4.8E-17	Coldwater Shale	2.0E-18
Memphis, TN	43	21.5	McNairy Sand	176	0.30	2.4E-11	Midway confining unit	183	4.2E-18	Demopolis Formation	2.4E-15
Phoenix, AZ	70	24.0	Lower alluvial unit	564	0.07	7.2E-13	Middle alluvial unit	201	7.9E-14	Basement	1.0E-16
Portland, OR	41	12.5	Columbia River Basalt Group	273	0.025	1.0E-11	Columbia River Basalt Group flow interior	27	1.0E-15	Basement	1.0E-15

3. METHODS

Three RTES metrics are computed for each city by using analytical tools developed by Burns et al. (2020). The metrics include required well spacing to store a full season of cooling water, thermal storage capacity, and thermal recovery efficiency over time. These metrics were chosen because they are primary components of RTES feasibility and potential. The analyses herein are not comprehensive but are intended to permit evaluation of RTES efficacy across a range of conditions, while demonstrating key concepts and providing a foundation for future research to build upon.

While RTES systems can be used for cooling or heating (Burns et al., 2018), only cooling applications are considered in this work, because commercial cooling demand is typically greater throughout the United States (Figure 2; Falta et al., 2016). To consider the influence of differing climates and cooling needs, the annual cooling load for each city, or nearest city, in Falta et al. (2016) for a modern 25,000 square-foot (2,323 square-meter) two-story office building is applied in the well-spacing calculation. A 10°C injection/extraction temperature differential in the reservoir (4 to 14°C; ΔT = 10°C) is assumed in order to be consistent with typical radiant slab cooling systems (Figure 3; Tian and Love, 2006; Tang et al., 2018; Woolley et al., 2018). This temperature differential is an engineering choice in practice and computed metrics are applicable to other end-users, while thermal storage capacity estimates are independent of this assumption. A cooled water storage temperature of 4°C is presumed obtainable but specific sources of cold water are not determined for each city. Cooled water delivery at this temperature might be difficult in some cities, particularly in warmer climates, depending on the nature of the cooled water source. In practice, injection schemes, storage temperatures, and/or energy delivery could be modified as appropriate to accommodate for these local engineering obstacles.

Representative fluid and solid properties are used in the analytical tools. In all cases, except for the basalts in Portland, solid thermal conductivity, solid density, and solid specific heat capacity values were selected as 2.5 W/(m °C), 2,640 kg/m^3, and 775 J/(kg °C), respectively (Waples and Waples, 2004; Konakova et al, 2013; Eppelbaum et al., 2014). For Portland, 1.59 W/(m °C), 3,000 kg/m^3, and 850 J/(kg °C) from Burns et al. (2020) are used for those same parameters, respectively. A common value of 1,000 kg/m^3 was used for water density along with a water specific heat capacity of 4,187 J/(kg °C) in all cities. Remaining applied parameters are provided in Table 2. Porosities, permeabilities, overlying primary aquifer and initial subsurface temperatures, and unit information are representative values estimated based on previously published literature (Pepin et al., 2021). All properties are assumed to be constant over time and space in each city for this pre-assessment; future assessments will ideally consider local spatial heterogeneity and temporal variation.

3.1 Required Well Spacing

To ensure that most energy stays in the reservoir during injection, doublet wells need to be completed sufficiently far apart to store the needed volume of cooled water to meet cooling demand, while also minimizing the amount of injected energy that is withdrawn by the balancing extraction well (thermal breakthrough). The volume of injected cooled water will fill part of the reservoir, so well spacing needs to be greater than the distance that injected water will travel between the wells. Required well spacing (d [m]) is estimated based on thermal equilibrium conditions by using the following equation from Burns et al. (2020):

$$d = \sqrt{\frac{3E_{th}}{\pi b n \rho_w c_w \Delta T}} \quad \text{[Eqn. 1]}$$

where E_{th} [J], b [m], n [-], ρ_w [kg/m^3], c_w [J/(kg °C)], and ΔT [°C] are annual building cooling load, reservoir thickness, reservoir porosity, water density, water specific heat capacity, and the RTES injection/extraction temperature differential, respectively.

This solution assumes fully penetrating wells, piston flow, no energy conduction to or from the reservoir, and negligible ambient groundwater flow (i.e. no groundwater flow in the reservoir other than that produced as a result of RTES operations). Equation 1 also neglects thermal exchange between liquid and solid phases within the reservoir. In practice, more accurate required well spacing will need to be estimated with a more sophisticated analysis following exploratory drilling and hydraulic testing.

3.2 Thermal Storage Capacity

Thermal storage capacity per unit area (E'_{th} [J/m^2]) in each city is estimated following Burns et al. (2020). This metric is cast in terms of an energy flux per square meter of reservoir of a given thickness:

$$E'_{th} = b n \rho_w c_w \Delta T \quad \text{[Eqn. 2]}$$

This approach accounts for energy stored only in the liquid phase (pore space) of the reservoir and neglects energy stored in the solid phase. Because subsurface temperatures near the RTES wells will equilibrate with storage temperatures through time, it is appropriate to neglect solid phase energy, as little to no temperature difference between the two phases will exist to facilitate conductive energy recovery from the solid phase. In cases of close well spacing, this equilibrium may be seasonally disrupted due to thermal breakthrough, giving rise to temperature gradients that permit solid-phase energy recovery. In this sense, Equation 2 is conservative because actual thermal storage capacity may be higher when energy can be recovered from the solid phase. However, thermal breakthrough would also adversely affect recovery temperatures, which may counteract the benefits of solid phase energy recovery.

3.3 Thermal Recovery Efficiency over Time

An RTES system's ability to recover stored thermal energy over time is expressed by Burns et al. (2020) in terms of energy flux balance:

$$\dot{q}_{stor}^{in} + \dot{q}_{geo} - \dot{q}_{up} - \dot{q}_{down} = \dot{q}_{stor}^{out} \quad \text{[Eqn. 3]}$$

and:

$$\lambda > \frac{\dot{q}_{stor}^{in} + \dot{q}_{geo} - \dot{q}_{up} - \dot{q}_{down}}{\dot{q}_{stor}^{in}} \quad \text{[Eqn. 4]}$$

where the energy added to the reservoir over half the year ($\dot{q}_{stor}^{in}$), energy removed from the reservoir over the other half of the year ($\dot{q}_{stor}^{out}$), geothermal heat flux ($\dot{q}_{geo}$), and conductive energy flux to geologic strata overlying ($\dot{q}_{up}$) and underlying ($\dot{q}_{down}$) the reservoir are accounted for in watts per square meter [W/m^2]. Vertical conductive energy fluxes ($\dot{q}_{up}$ and $\dot{q}_{down}$) are estimated by using time-dependent 1-D solutions, which are described in detail in Burns et al. (2020). Solving for upward energy flux ($\dot{q}_{up}$) requires approximating an infinite sum by truncating some of its terms, for which a truncation error threshold of 0.01% is utilized. Horizontal energy fluxes are ignored in this approach, implicitly assuming these fluxes are negligible relative to vertical energy fluxes; this simplification is most valid when storage zones are wider than tall, or storage temperatures are similar to ambient reservoir temperatures. Geothermal heat flux ($\dot{q}_{geo}$) estimates are from the most recent USGS heat flow map (Williams and DeAngelo, 2015). The energy added to the reservoir over half the year ($\dot{q}_{stor}^{in}$) is approximated as one half of the thermal storage capacity calculated in Equation 2. Thermal recovery efficiency (λ [-]) of the RTES system over time (Equation 4) is then estimated as the ratio of recovered ($\dot{q}_{stor}^{out}$; Equation 3) to stored energy ($\dot{q}_{stor}^{in}$).

Equation 4 is expressed as an inequality to indicate that actual thermal recovery efficiency should be higher than estimates made with this approach; this is because vertical conductive energy fluxes are overestimated by their respective 1-D solutions at early time. These fluxes decrease over time as the contrast between surrounding subsurface temperatures and storage temperatures diminishes. Thermal recovery efficiency therefore increases over years of RTES operation. In this study, thermal recovery efficiencies are reported after 5, 10, 20, and 100 years of operation to provide insight over a large time window, while attempting to avoid the elevated uncertainties that accompany this approach near RTES initialization. The upper limit on recovery efficiency is controlled by the difference between mean reservoir injection temperature and the temperature of the overlying aquifer system.

The influence of initial reservoir temperatures and seasonal reheating of the injection zone by ambient-temperature groundwater during cool-water extraction are assumed negligible for this pre-assessment. These simplifying assumptions make the results most representative of applications where the reservoir has been precooled (i.e. primed) by initial cooling cycles. Reservoir priming could be done by implementing longer initial injection periods (possibly before the building becomes operational) or lower initial injection temperatures.

4. RESULTS

The three metrics computed in this study are presented below in Table 3 and Figure 4. Values that are scaled relative to the maximum estimate for any of the eight cities [maximum-normalized; e.g. $d/maximum(d)$] are provided to ease relative comparison.

4.1 Required Well Spacing

Estimated required well spacing varies moderately over the study area. Lansing has the largest well spacing of 53.4 meters, while Decatur has the smallest well spacing of 13.8 meters. The remaining cities have similar well-spacing estimates that range from 19.0 to 31.7 meters. Spatial patterns in well spacing show similar distances for the targeted sediments in the Coastal Plains and Basin and Range geologic regions (normalized d = 0.36 to 0.49). The basalts of the Pacific Northwest yield a slightly larger well spacing estimate (normalized d = 0.59). Well spacing increases in a northward pattern from Decatur through Lansing in the geologically similar sandstones of the Illinois and Michigan Basins (normalized d = 0.26 to 1.00). The sandstone of the Michigan Basin has the largest required well spacing.

4.2 Thermal Storage Capacity

The thermal storage capacity (E'_{th}) estimates have the most contrast between cities of all considered metrics. Lansing has the smallest value at 134 MJ/m^2, while Decatur has the greatest value of 2,680 MJ/m^2. Mean thermal storage capacity across all cities is exceedingly large at 1,384 MJ/m^2 (median = 1,454 MJ/m^2). The Coastal Plains and Illinois Basin geologic regions have the greatest estimated thermal storage capacity (normalized E'_{th} = 0.82 to 1.00). The cities in the Basin and Range have about half of the storage capacity of the Illinois Basin (normalized E'_{th} = 0.47 to 0.62). Like well spacing, thermal storage capacity estimates decrease in a northerly pattern starting at the Illinois Basin through the Michigan Basin (normalized E'_{th} = 0.05 to 1.00). Lansing in the Michigan Basin and Portland in the Pacific Northwest have relatively small, but still very large, storage capacities (normalized E'_{th} = 0.05 to 0.11).

4.3 Thermal Recovery Efficiency over Time

Both early and long-term RTES system thermal recovery efficiencies (λ) for each of the selected cities are very high. Thermal recovery efficiency after 5 years of operation (λ_5) in all cities ranges from 96.3 to 99.3%. This range improves even more spanning 97.8 to 99.6% after 20 years of operation (λ_{20}), with a maximum evaluated efficiency of 99.7% in Chicago after 100 years (λ_{100}). Computed thermal recovery efficiencies improve over time and are very similar across all geologic regions (mean and median normalized λ_5 = 0.98).

Table 3: Results for each city. Maximum-normalized results are provided to ease relative comparisons. *Abbreviations: d* = well spacing in meters; E'_{th} = thermal storage capacity in megajoules per square meter; λ_i = thermal recovery efficiency in percent, where subscript *i* denotes the elapsed time since RTES system initiation in years (5, 10, 20, and 100 years are presented).

							NORMALIZED		
City	*d*	E'_{th}	λ_5	λ_{10}	λ_{20}	λ_{100}	*d*	E'_{th}	λ_5
Albuquerque, NM	21.5	1,256	96.7	97.7	98.3	99.2	0.40	0.47	0.97
Charleston, SC	19.5	2,227	96.8	97.7	98.4	99.0	0.36	0.83	0.97
Chicago, IL	26.6	628	99.3	99.5	99.6	99.7	0.50	0.23	1.00
Decatur, IL	13.8	2,680	98.1	98.7	99.0	99.6	0.26	1.00	0.99
Lansing, MI	53.4	134	97.0	97.7	98.2	98.9	1.00	0.05	0.98
Memphis, TN	19.0	2,211	98.2	98.7	99.1	99.6	0.36	0.82	0.99
Phoenix, AZ	26.0	1,653	97.0	97.9	98.5	99.3	0.49	0.62	0.98
Portland, OR	31.7	286	96.3	97.2	97.8	98.2	0.59	0.11	0.97

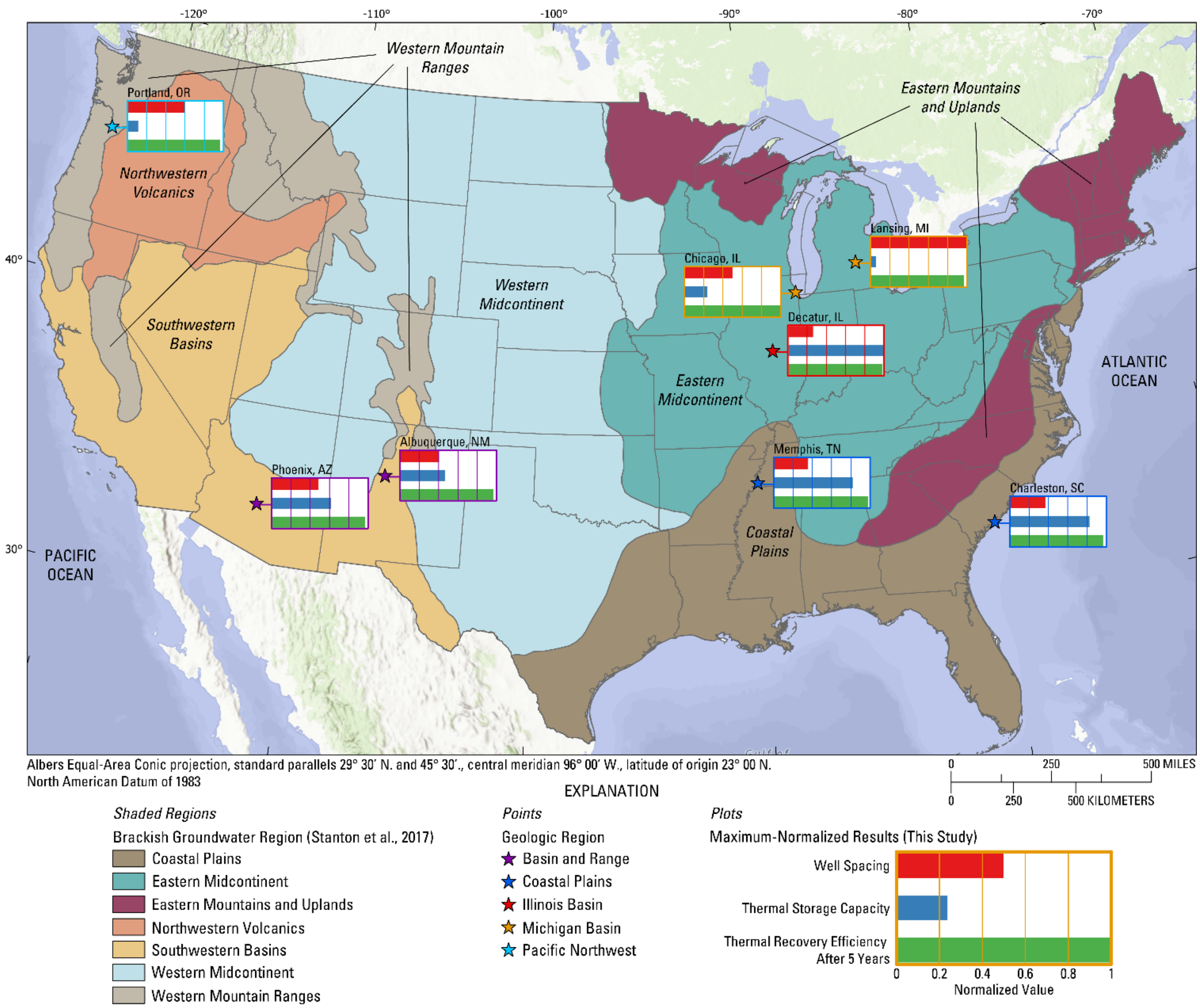

Figure 4: Maximum-normalized results for well spacing, thermal storage capacity, and thermal recovery efficiency after 5 years for each analyzed city. Results are grouped by geologic region and are overlain on the brackish groundwater regions of the United States of Stanton et al. (2017).

5. DISCUSSION

The most favorable geologic regions for RTES development in this pre-assessment are those with consistently large thermal storage capacities and thermal recovery efficiencies but small required well spacing. These regions include the Basin and Range (Phoenix, Albuquerque), Coastal Plains (Memphis, Charleston), and Illinois Basin (Decatur). The Coastal Plains and Illinois Basin have slightly larger thermal storage capacities and smaller well spacing than the Basin and Range, with Decatur having the largest thermal storage capacity and smallest required well spacing. Thermal recovery efficiencies are very high at all cities. The favorability of Decatur is linked to its below average cooling demand and thick reservoir of moderate porosity. The Decatur conceptual model considers injection into the full thickness (457 m) of the Mount Simon Sandstone, though the most permeable lowermost 200 meters of this unit may be best suited for RTES. All well-spacing estimates (13.8 to 53.4 meters) in this work are considered practical relative to the modeled office building size (2,323 square-meters or approximately 48 meters x 48 meters in footprint). Overall, this pre-assessment indicates that there is substantial RTES potential throughout the United States and all evaluated areas are considered viable for RTES.

While not dominantly controlled by one characteristic, the results of this pre-assessment strongly emphasize the importance of reservoir thickness and porosity on RTES potential; these two characteristics are also more influential than climate for the evaluated regions and building size. Required well spacing in Equation 1 is non-linearly and inversely related to reservoir thickness and porosity, meaning well spacing increases drastically as these parameters decrease. Even though climate, in terms of cooling load, is mathematically more influential in the well-spacing equation, its contrast across evaluated regions is less than that of the reservoir characteristics. As a result, the thermal storage capacity, controlled by reservoir thickness and porosity, plays a more important role than climate in this study. For instance, Lansing and Portland require the largest well spacing, despite having the lowest cooling loads, as a result of them also having the smallest thermal storage capacities. Additionally, thermal storage capacity varies the most of all three metrics over the study area. This indicates that maps of reservoir thickness and porosity that can be used to map thermal storage capacity per unit area are critical for evaluating RTES efficacy throughout the country.

Local favorability will change based on the evaluated RTES conceptual model. This study considers the full development of the target reservoir thickness in each city; however, system design and regulatory considerations may prevent this full development in practice and thereby reduce favorability. In contrast, favorability will improve if several storage strata are considered. For example, there are multiple potential reservoirs in layered sedimentary regions like the Coastal Plains, Michigan Basin, and Illinois Basin that might be used for RTES; incorporating these additional units will effectively increase local thermal storage capacity and decrease required well spacing, thus improving RTES favorability. Identifying all viable RTES layers was not in the scope of this pre-assessment but could be pursued in future assessments.

RTES cooling applications are more efficient than similar heating applications, because storage temperatures are typically more like initial and overlying subsurface temperatures. The results herein show that thermal recovery efficiencies over time for this cooling scenario are consistently very high, even at early time (96.3 to 99.3% after 5 years of operation). Portland has the lowest thermal recovery efficiency at 96.3% and 98.2% after 5 and 100 years of operation, respectively. Burns et al. (2020) evaluated an RTES doublet heating scenario in Portland with an injection/extraction reservoir temperature differential of 36°C. Using their temperature differential, Equation 4 produces thermal recovery efficiencies of 90.4% after 5 years and 95.8% after 100 years for Portland. In both scenarios, the initial subsurface and overlying primary aquifer temperatures are specified as 12.5°C, which is much closer to the cooling storage temperature range of 4 to 14°C than that of the heating scenario (34 to 80°C). The improved recovery efficiency with the cooling application is a result of substantially smaller vertical temperature gradients, and thereby reduced conductive energy losses, between the reservoir and its surroundings. Assuming many cooling applications will include storage temperatures that are closer to initial and overlying subsurface temperatures than those used in heating applications, RTES cooling systems are more efficient at recovering stored thermal energy and take less time to equilibrate compared to typical RTES heating systems.

5.1 Limitations

The simplified approaches used herein have limitations. The most likely complicating factors are related to neglecting:

(1) hydrogeologic heterogeneity that may result in preferential groundwater flow paths and early thermal breakthrough during injection/extraction;

(2) the possibility of faults acting as horizontal barriers to flow or as vertical conduits;

(3) temporal dependence of porosity as a result of hydrothermal alteration;

(4) spatial variation of hydrologic conditions such as reservoir thickness, porosity, fracturing, and groundwater salinity;

(5) ambient groundwater flow and horizonal conductive energy flux within the reservoir; and

(6) density-driven flow due to temperature or geochemistry contrasts.

This pre-assessment is not intended to be comprehensive but is instructive about the potential to use RTES for cooling nationally. All results presented herein can be improved upon with a more detailed analysis that follows exploratory drilling and ensuing site-specific characterization.

6. CONCLUSIONS

In this pre-assessment, evaluation of required well spacing, thermal storage capacity, and thermal recovery efficiency through time shows the efficacy of RTES in five generalized geologic regions dispersed throughout the United States. A realistic RTES conceptual model based on the local cooling demand for a modern office building is considered at eight cities within these regions. The following findings are supported:

(1) All evaluated regions and cities are favorable for RTES development, indicating substantial national RTES potential. This is underscored by immense local thermal storage capacities (134 to 2,680 MJ/m^2, mean = 1,384 MJ/m^2). In descending order, the most favorable evaluated geologic regions in terms of mean thermal storage capacity are Illinois Basin, Coastal Plains, Basin and Range, Michigan Basin, and Pacific Northwest;

(2) Thermal storage capacity, which is controlled by reservoir thickness and porosity, is the most informative metric considered and is more influential than climate variations for the evaluated regions and building size. This emphasizes the importance of mapping these basic reservoir properties to facilitate construction of spatially varying thermal storage capacity per unit area maps as a cornerstone RTES geothermal classification standard;

(3) Typical cooling configurations have higher thermal recovery efficiencies than similar heating RTES configurations, because of a smaller temperature contrast between storage and pre-RTES subsurface temperatures. This yields less vertical conductive energy loss from the reservoir and shorter rock-water thermal equilibration durations, producing very high thermal recovery efficiencies that improve with time (96.3 to 99.3% after 5 operational years in this study); and

(4) More research is needed to consider local spatial heterogeneity, temporal dependence of subsurface conditions, horizontal energy loss in the reservoir, density-driven flow, and additional RTES conceptual models in each region.

This pre-assessment is not comprehensive and has limitations; however, the results presented herein indicate the presence of extensive RTES resources spanning a diverse set of geologic, physiographic, and climate conditions throughout the United States.

ACKNOWLEDGEMENTS

This manuscript is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Geothermal Technologies Office, under Inter-Agency Agreement Number 89243419SEE000022/P00001. Additional support for Jeff Pepin and Erick Burns was provided by the U.S. Geological Survey (USGS) Energy Resources Program.

REFERENCES

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*, 42, 37 p.

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*, 88, 101877, 17 p. https://doi.org/10.1016/j.geothermics.2020.101877

Eppelbaum, L., Kutasov, I., and Pilchin, A., 2014, Thermal properties of rocks and density of fluids. In: *Applied Geothermics*. Lecture Notes in Earth System Sciences. Springer, Berlin, Heidelberg, 99-149. https://doi.org/10.1007/978-3-642-34023-9_2

Falta, R.W., Molz, F., and Newell, C.J., 2016, Subsurface thermal energy storage for improved heating and air conditioning efficiency, *U.S. Department of Defense Final Report*, ESTCP Project EW-201013, 94 p.

Konakova, D., Vejmelkova, E., and Cerny, R., 2013, Thermal properties of selected sandstones, *Advances in Modern Mechanical Engineering*, Proceedings of the 4th International Conference on Fluid Mechanics and Heat & Mass Transfer, Dubrovnik, Croatia, 100-104.

Neupane, G., Smith, R.W., McLing, T.L, McLaughlin, J.F., Spycher, N., and Dobson, P.F., 2020, Geochemistry of geologic thermal energy storage (GeoTES) systems: assessment of the Weber Sandstone, western Wyoming, USA, *GRC Transactions*, 44, 13 p.

Pepin, J.D., Burns, E.R., Dickinson, J.E., Duncan, L.L., Kuniansky, E.L., and Reeves, H.W., 2021, Compiled reference list to support reservoir thermal energy storage research, *U.S. Geological Survey data release*, https://doi.org/10.5066/P90GOJNK

Stanton, J.S., Anning, D.W., Brown, C.J., Moore, R.B., McGuire, V.L., Qi, S.L., Harris, A.C., Dennehy, K.F., McMahon, P.B., Degnan, J.R., and Böhlke, J.K., 2017, Brackish groundwater in the United States, *U.S. Geological Survey Professional Paper 1833*, 185 p. https://doi.org/10.3133/pp1833

Tang, H., Raftery, P., Liu, X., Schiavon, S., and Woolley, J., 2018, Performance analysis of pulsed flow control method for radiant slab system, *Building and Environment*, 127, 107-119.

Tian, Z., and Love, J.A., 2006, Radiant slab cooling: A case study of building energy performance, *SimBuild 2006*, Second National IBPSA-USA Conference, Cambridge, MA, 238-244.

U.S. Department of Energy [DOE], 2019, Geovision: harnessing the heat beneath our feet, *U.S. Department of Energy Report*, DOE/EE-1306, 218 p., accessed December 3, 2020: https://www.energy.gov/eere/geothermal/geovision

Waples, D.W., and Waples, J.S., 2004, A review and evaluation of specific heat capacities of rocks, minerals, and subsurface fluids. Part 1: minerals and nonporous rocks, *Natural Resources Research*, 13, 2, 97-122.

Williams, C.F., and DeAngelo, J., 2015, Developing improved methods for the assessment of enhanced geothermal systems, *Proceedings*, 40^{th} Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, 9 p.

U.S. Census Bureau, 2012, Patterns of metropolitan and micropolitan population change: 2000 to 2010, C2010SR-01, U.S. Government Printing Office, Washington, DC, 102 p.

Woolley, J., Schiavon, S., Bauman, F., Raftery, P., and Pantelic, J., 2018, Side-by-side laboratory comparison of space heat extraction rates and thermal energy use for radiant and all-air systems, *Energy & Buildings*, 176, 139-150.