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An Integrated Feasibility Study of Reservoir Thermal Energy Storage in Portland, Oregon, USA

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ABSTRACT

In regions with long cold overcast winters and sunny summers, Deep Direct-Use (DDU) can be coupled with Reservoir Thermal Energy Storage (RTES) technology to take advantage of pre-existing subsurface permeability to save summer heat for later use during cold seasons. Many aquifers worldwide are underlain by permeable regions (reservoirs) containing brackish or saline groundwater that has limited beneficial use due to poor water quality. We investigate the utility of these relatively deep, slow flowing reservoirs for RTES by conducting an integrated feasibility study in the Portland Basin, Oregon, USA, developing methods and obtaining results that can be widely applied to RTES systems elsewhere. As a case study, we have conducted an economic and social cost-benefit analysis for the Oregon Health and Science University (OHSU), a teaching hospital that is recognized as critical infrastructure in the Portland Metropolitan Area. Our investigation covers key factors that influence feasibility including 1) the geologic framework, 2) heat and fluid flow modeling, 3) capital and maintenance costs, 4) the regulatory framework, and 5) operational risks. By pairing a model of building seasonal heat demand with an integrated model of RTES resource supply, we determine that the most important factors that influence RTES efficacy in the study area are operational schedule, well spacing, the amount of summer heat stored (in our model, a function of solar array size), and longevity of the system. Generally, heat recovery efficiency increases as the reservoir and surrounding rocks warm, making RTES more economical with time. Selecting a base-case scenario, we estimate a levelized cost of heat (LCOH) to compare with other sources of heating available to OHSU and find that it is comparable to unsubsidized solar and nuclear, but more expensive than natural gas. Additional benefits of RTES include energy resiliency in the event that conventional energy supplies are disrupted (e.g., natural disaster) and a reduction in fossil fuel consumption resulting in a smaller carbon footprint. Key risks include reservoir heterogeneity and a possible reduction in permeability through time due to scaling (mineral precipitation). Lastly, a map of thermal energy storage capacity for the Portland Basin yields a total of 87,000 GWh, suggesting tremendous potential for RTES in the Portland Metropolitan Area.

1. INTRODUCTION

Storage of thermal energy in saline or brackish aquifers underlying freshwater aquifers (hereafter called Reservoir Thermal Energy Storage or RTES) would allow the use of largely undeveloped and relatively low-quality groundwater-resources for matching of peak energy production with peak energy demand. RTES can be coupled with deep direct-use. Direct use refers to energy consumption that is used at the source or transmitted without transformation. According to the United States Department of Energy (2019), typical direct-use operations utilize geothermal fluid capable of providing heat and cooling (via absorption chillers) to commercial or residential buildings. In the case of direct-use coupled with RTES, the energy produced, stored, and later extracted is delivered as hot or cold water. For example, summer solar energy might be stored and then extracted in the winter. Similarly, winter low temperatures might be stored for use during the summer.

Much of the physics of this technology has been historically researched, developed, and implemented, usually under the name Aquifer Thermal Energy Storage (ATES); and this technology is mature in some parts of the world, though most applications are restricted to shallow depths in the uppermost aquifers beneath metropolitan areas. For a systematic description and history, see Fleuchaus et al. (2018). A primary distinction between most ATES systems and RTES as defined herein, is that the target saline/brackish reservoirs for RTES have much in common with traditional geothermal reservoirs, except for having comparatively low temperatures and relatively shallow depths. Saline/brackish reservoirs have geochemically evolved fluids, a consequence of comparatively low groundwater flowrates and long residence times along flow paths that are poorly connected with shallower fresh groundwater systems. For ATES, regional groundwater flow may cause drift of stored heat in the direction of regional groundwater flow, and extraction wells need to be located to optimally intercept the stored heat. In contrast, the low groundwater flowrates within many brackish/saline systems ensures that most of the stored heat does not migrate away from the injection zone. Because the proposed brackish/saline storage zones share characteristics of traditional geothermal reservoirs (particularly in terms of chemistry, flowrate, and poor connection with shallow fresh aquifers), the term RTES is proposed to distinguish thermal energy storage using slow-moving geochemically-evolved aquifers from traditional ATES applications.

RTES may have advantages over ATES, and the disadvantages are seemingly tractable problems. In regions where freshwater supplies have largely been appropriated for other beneficial uses, the use of brackish/saline waters as a working fluid for heat exchange represents a new opportunity for beneficial use of these largely undeveloped groundwater resources. Deep storage of heat would prevent thermal plumes from easily reaching surface waters, greatly reducing the likelihood of adverse ecological impacts. While exploration risks and costs of development of RTES will likely be higher than for ATES, working with geochemically evolved waters is standard fare for the geothermal industry, so engineering solutions already exist or are the subject of active engineering research.

The remainder of this paper explores the feasibility (cost/benefit) of implementing RTES in the Portland Basin, Portland, Oregon, USA. We begin with a detailed study of the geologic framework (Section 2). Then, we employ a heat and fluid flow model to estimate the stored thermal resource available for heating an urban hospital, Oregon Health Sciences University (OHSU) using RTES technology. We also estimate the potential RTES resource if utilized throughout the Portland Basin (Section 3). We describe some anticipated risks and uncertainties related to RTES operations (Section 4). Lastly, the economics of implementing RTES in a new conventional building at OHSU are estimated, resulting in a levelized cost of energy (LCOE), which is compared to other sources of heating available to OHSU (Section 5). This, in addition to societal (non-fiscal) benefits are integrated into an interpretation of feasibility.

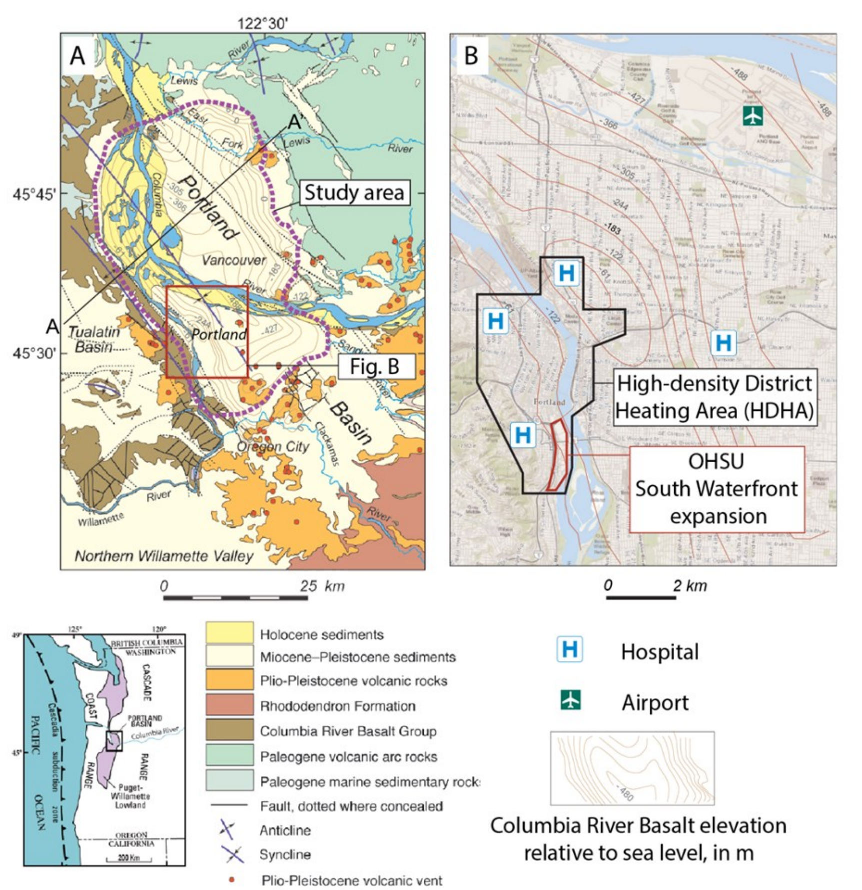

Figure 1: Location maps of study extents with elevation contours of the top of the Columbia River Basalt Group (CRBG). (A) Study area extent for resource map development. Geology is modified from Evarts et al. (2009). A-A' is an approximate location for the generalized cross-section in Figure 2. (B) Focus area inset map shows a high-density area where RTES might be used for district heating and the Oregon Health and Science University (OHSU) south waterfront expansion area used as the foundation for representative simulations.

2. STUDY AREA

The 1,300 km^2 Portland Basin contains the cities of Portland, Oregon and Vancouver, Washington, separated by the Columbia River, which traverses the basin center on its way to the Pacific Ocean (Figure 1). The Portland Basin has low heat flow at ~50 mW/m^2 (Burns et al., 2018) and low traditional hydrothermal favorability (Williams & DeAngelo, 2008). Water quality within the target reservoir is likely poor, as residence time is relatively long resulting in geochemically evolved (saline or brackish) fluid (Svadlenak, 2019). Within this framework, there exist favorable conditions for RTES: a permeable low-flow aquifer system in the Columbia River Basalt Group (CRBG) that is hydraulically separated and thermally well-insulated from the overlying regional aquifer.

2.1 Geology

The Portland Basin (Figure 1) is a NW-SE trending part of the Puget-Willamette forearc trough, formed during oblique subduction of the Juan de Fuca plate beneath North America (Wells et al., 1998; Evarts et al., 2009). The forearc trough may be a flexural response of loading by the Cascade magmatic arc or Coast Range, with basin segmentation related to NW-striking dextral faults, which have been active since at least the mid-Miocene. The Willamette Valley region is seismically active with the largest historic event a M 5.7 earthquake that occurred in Scotts Mills in 1993 (Wong, 1997).

The Portland Basin stratigraphy (Figure 2) records a history of volcanism and sedimentation from the Eocene to present. The Eocene basement consists of oceanic basalt of the Siletzia terrane, accreted to North America about 50 million years ago (Wells et al., 2014). The basement is overlain by marine sedimentary rocks which interfinger with Cascade volcanics to the east. The Eocene basement within the Portland Basin is estimated (using gravity data) to be up to 2.5 km deep (McPhee et al., 2014). Marine sedimentation was followed by emplacement of more than a dozen CRBG lava flows arriving from eastern Washington via the ancestral Columbia River valley, filling in pre-existing topography with 300m or more of basalt (Beeson et al., 1985). Neogene subsidence and uplift of the Portland Hills followed CRBG emplacement. About 300 m of lacustrine, fluvial, and volcaniclastic rocks overlie the CRBG, forming the regional aquifer system. Eruption of the Boring volcanic field between 3 Ma and 50 ka produced cinder cones and associated lava flows, still visible on the east side of the basin (Evarts et al., 2009). Between about 18 and 15 ka, glacial outburst floods (Missoula floods) inundated the region to a depth of about 120m, mantling the basin with sediments derived from the continental interior (Waitt, 1985).

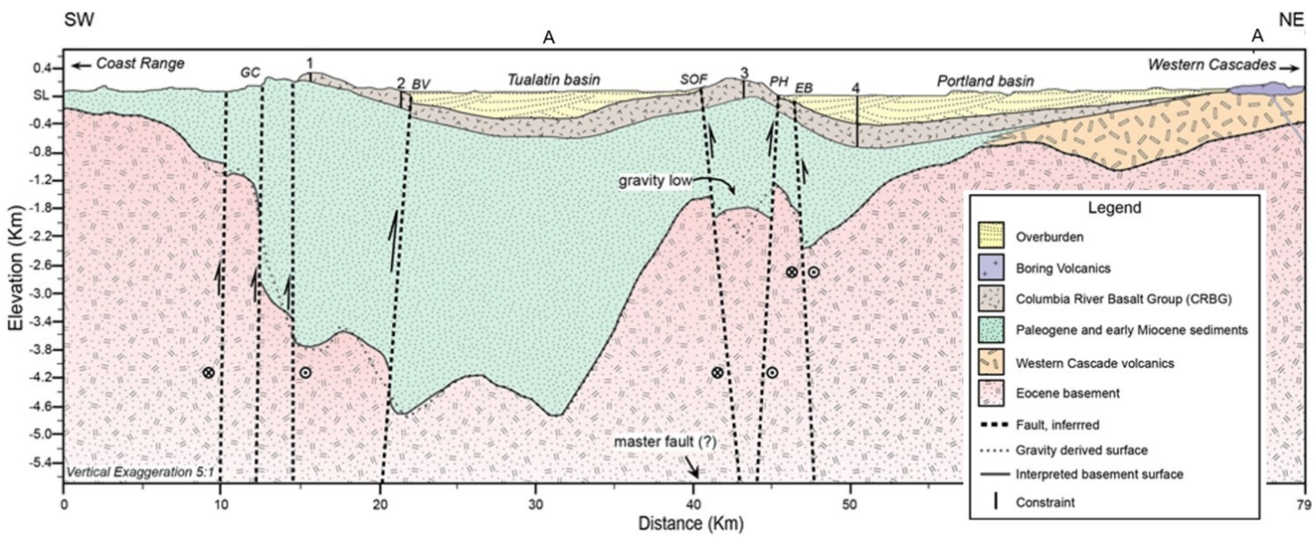

Figure 2: Geologic cross section A-A' including all modeled units down to Eocene basement. Basement offsets are interpreted from the residual gravity data (dotted line) of McPhee et al. (2014). Data constraints include (1) well - WASH 206, (2) well - WASH 633, (3) interpolation guide, and (4) - seismic profiles of Liberty (2002). Vertical exaggeration 5:1. Fault acronyms are GC – Gales Creek fault, BV – Beaverton fault, SOF – Sylvan-Oatfield fault, PH – Portland Hills fault, and EB – East Bank fault.

2.2 New 3D Geologic Model and Reservoir Geology

Three stratigraphic surfaces were mapped (top CRBG, base CRBG, and Eocene basement) to construct a 3D geologic model using well log, outcrop, seismic, aeromagnetic, and gravity data (Figure 2). The majority of available drilling logs for the southern Portland basin were accessed from the Oregon Water Resources Department (OWRD) Groundwater Site Information System (GWIS). Oil and gas exploration wells were accessed through the Oregon Department of Geology and Mineral Industries (DOGAMI) oil and gas index. Refer to Scanlon (2019) for a detailed explanation of the 3D geologic model methods and results.

The focus area for RTES simulations (the OHSU south waterfront expansion) is on NE dipping strata, where the top of CRBG decreases from surface outcrop to ~500 m below sea-level in the center of the Portland basin (Figure 1B). The base of CRBG similarly decreases in elevation toward the center of the basin to a maximum depth of ~800 m below sea-level. The uncertainty of the base CRBG surface is higher than for the top CRBG surface, as it is derived from far fewer data points (i.e., PSU injection well and outcrop data from Wells et al., in press). The reservoir target for RTES is between top and base CRBG, which is ~300 m thick in the area of interest. RTES wells for the OHSU south waterfront expansion would be drilled to a measured depth (MD) of 125-250 m. Wells in this location may cross the inferred trace of the Portland Hills fault, which could cause reservoir heterogeneity and pose a seismic hazard (see Section 4). Motion on this fault is thought to be taken up in dextral strike-slip motion, with a component of dip-slip (Blakely et al., 1995).

3. HEAT AND FLUID FLOW MODELING

3.1 Hydrogeology

The thick sediments and volcanic deposits overlying the CRBG (Figure 2) form the primary aquifer system that transmits most of the groundwater to rivers and streams, and these overlying deposits are the main source of groundwater for the Portland Basin (McFarland and Morgan, 1996; Morgan and McFarland, 1996; Herrera et al., 2014). River and stream gains (including springs) are the primary discharge of groundwater, though groundwater is pumped for a variety of uses. All Miocene-age and older rocks, except for the CRBG, tend to have low permeability (McFarland and Morgan, 1996; Morgan and McFarland, 1996; Herrera et al., 2014). While the dense flow-interiors of CRBG lava flows tend to have very low permeability ($<10^{-18}$ m^2), the thin laterally connected interflow zones are productive, resulting in strongly anisotropic low-storage aquifers (porosity ~0.2-0.25) (Burns et al., 2016). Because the overlying aquifers are very productive, Miocene and older rocks are generally only used as aquifers in the uplands where recharge can enter exposed CRBG units (i.e., younger aquifers are absent). Lower in the basin, where CRBG is buried by the younger rocks, the low-permeability flow interiors form confining units, preventing CRBG groundwater from easily flowing out of the CRBG into the overlying aquifer system. As a result, CRBG reservoirs beneath younger rocks and sediments contain older groundwater that is slow moving or stagnant. Valley-bottom rivers and streams do not intersect the CRBG, except possibly the Willamette River, near the SW basin margin (Figure 1). The extent to which the Willamette River incises the CRBG is not well-understood.

CRBG aquifers can be connected over tens of kilometers, though the connectivity can be complex, and faults tend to form barriers where thin aquifers are juxtaposed against confining units (Burns et al., 2012, 2016; Ely et al., 2014). Bulk permeability (i.e., effective permeability of combined CRBG aquifers and confining units) from CRBG aquifer tests in the regional Columbia Plateau Regional Aquifer System (CPRAS) varies across seven orders of magnitude, with most tests in the range of 10^{-10}—10^{-13} m^2 and a mean value of ~$10^{-11.5}$ m^2 (Burns et al., 2015, 2016). Morgan and McFarland (1996) lumped all older-rock aquifer tests, documenting a range of 10^{-10}—10^{-16} m^2. Noting that the CRBG aquifers are the most permeable of the older-rocks, the range of permeabilities in the Portland Basin dataset is consistent with larger CRBG compilations. Further, calibrated CPRAS hydraulic conductivities are in good agreement with calibrated Portland Basin hydraulic conductivities, indicating the length scale of permeability is also similar. Permeable interflow thickness is typically ~10% of total CRBG thickness, indicating individual flow horizons will have ~10 times bulk permeability. Similarly, bulk porosity is estimated to be in the range 0.02-0.025 on average (Burns et al., 2016).

3.2 Ambient Geothermal Heat Flow

Subduction of the cold oceanic Juan de Fuca plate and associated sediments results in low regional geothermal heat flow beneath the Portland Basin. Heat flow increases to the east where subduction creates the Cascades magmatic arc. A preliminary analysis of the available twelve heat-flow measurements for the Portland Basin (Blackwell et al., 1978, 1990; Steele et al., 1982; and Blackwell and Steele, 1987), ranged from 33 to 77 mW/m^2, with a mean value of 52 mW/m^2. These values are relatively low, compared with much of the western United States, and are similar to those observed throughout much of the central and eastern United States (Blackwell et al., 2011).

3.3 Conceptual Model for the Portland RTES System

The target thermal storage zone for simulations is a single permeable interflow zone near the base of the CRBG (Figure 3). A well-doublet in this CRBG aquifer allows efficient distribution, storage, and retrieval of thermally regulated water, but requires little or no above-ground storage of water. The overlying CRBG promotes thermal and hydraulic separation from the regional potable aquifer system, allowing the CRBG and underlying low-permeability rocks to store heat. Low groundwater flow rates (assumed to be zero for simulations herein) in the CRBG and older rocks ensure that most injected heat will not be advectively transported away from the doublet. Heat that is conducted to the overlying primary aquifer above the CRBG is assumed to be removed advectively by the primary aquifer. The thermal plume is assumed to be well-mixed within the reservoir, and because the reservoir and plume are comparatively thin, most conductive heat loss is upwards towards the primary aquifer or downwards as the surrounding rocks are heated up. Initially heat loss will be high as the reservoir itself and the overlying and underlying rocks are heated up. As the surrounding geology is heated, conductive heat loss decreases over time, and annual recovery of injected heat will increase.

3.4 Model Sensitivity Analysis

A preliminary sensitivity analysis was performed to identify which features of an ATES system would be most important for controlling energy delivery in the Portland RTES system (Burns et al., 2018). Well-spacing, hydrogeologic heterogeneity, and operational schedule (i.e., timing and rate of injection and extraction of hot/cold water) dominated, with lesser effects attributed to the insulation thickness overlying the injection horizon and ambient groundwater flow within the CRBG. Well-spacing and insulation thickness over the injection horizon are engineering choices, and heterogeneity and ambient groundwater flow are conditions that cannot be controlled, but that can be assessed during resource exploration and accounted for during RTES system design and construction. Operational schedule is controlled by when and how much heating is required by the end-user, and when excess hot water is available to be injected. The total amount of heating required by the building and the temperature of stored water determine the necessary size of the RTES (i.e., the areal footprint of the RTES, and the well-spacing to prevent thermal breakthrough) and the RTES pumping rate.

3.5 Heating and Cooling Demand

Operational schedule of the RTES is driven by simulated hourly space-heating and cooling demand for the Knight Cancer Research Building (KCRB) in the OHSU South Waterfront Expansion area (Figure 1B). The KCRB is six stories, 10,400 m^2, and consists of office and laboratory space. During KCRB design, energy consumption for a typical year was simulated using the eQuest/DOE2.2 software, resulting in hourly estimates of heat exchanger temperatures and pumping rates (PAE, 2017). Though we only consider a conventional building as a base case (KCRB), a building could be customized for RTES, potentially improving energy use efficiency. The representative weather file used was the eQuest/DOE2.2 provided meteorological data for Portland International Airport (PDX).

Total annual space-heating is estimated to consume 1.88 GWh of thermal energy. Space-heating water is supplied to the building at ~50°C, and return temperatures for the loop generally fall within the range 20-45°C. The flow-weighted average return temperature is 32.2°C, so the thermal load to be supplied is to heat water from 32°C to 50°C on average (Figure 3).

While an RTES can be operated in either continuous or cyclic modes for heating or cooling (Burns et al., 2018), for simplicity, only cyclic operations of a doublet for heating purposes are considered here. Cyclic operations have reversal of pumping direction when switching between heat storage and extraction, typically providing the highest temperatures first and declining temperatures during the heat extraction period. Continuous operations are unidirectional flow, requiring heat to break through at the downgradient well before it can be utilized. Under cyclic operations, one well is the *thermal storage well*, where heat is injected for later extraction, and the second well, is the *balancing well*, where water is injected or extracted at the same rate but opposite direction as the thermal storage well. Use of a doublet prevents the need to store significant amounts of water above ground by balancing flow rate at the thermal storage well with the balancing well.

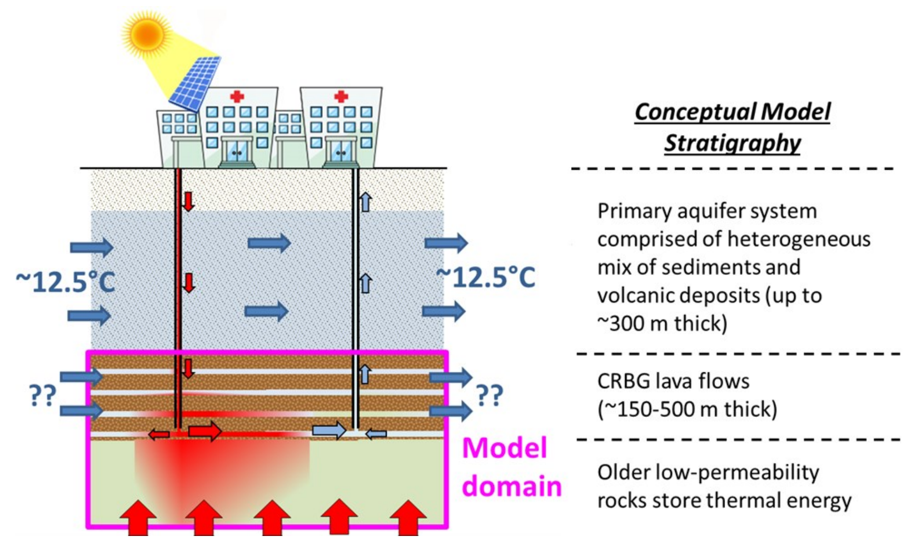

Figure 3: Conceptual model of Reservoir Thermal Energy Storage (RTES) for the OHSU study area. Heat can be injected into the *thermal storage well* (left) in the summer, and flow will be reversed in the winter to extract heat from the thermal storage well. The *balancing well* (right) maintains the same flowrate as the thermal storage well and injection temperature is determined by heat exchange with the building heating system. Dark blue arrows show regional groundwater flow above and within the CRBG. Large red arrows represent background geothermal heat. Heat is conducted away from the injection horizon down into older rocks and up into overlying CRBG aquifers. The overlying CRBG promotes hydraulic and thermal separation between the thermal energy storage zone and the overlying primary aquifer system.

3.6 Seasonal Sources of Energy to be Stored

Thermal energy can be taken from a variety of sources, including solar, heat exchange with ambient natural conditions (e.g., summer heat and winter cold), or using heaters/chillers during periods when electricity surpluses provide low-cost electricity. Here, it is assumed that the solar energy delivery pattern can be estimated using standard solar design criteria, that the solar array can be linearly sized to deliver any desired percentage of heat, and that this scaled solar source will first supply any building thermal load. Excess solar heat is injected into the reservoir as hot water at a prescribed fixed temperature.

The solar supply pattern was estimated hourly for 2018 using solar incidence data at Portland International Airport. The magnitude of energy supplied by solar heating per square meter of installed solar collector is a function of desired production temperature, type of collector, etc. Solar water heating can be used to heat water to a desired injection temperature. This temperature may be chosen based on desired RTES operational considerations.

3.7 RTES Simulations

The simulation tool of Burns et al. (2018) was altered to simulate reservoir operations that would result from use of a solar array to provide building heating demand (see Burns et al., in press, for a comprehensive description of the modeling and the conditions evaluated). Each 30-year simulation was divided into a series of approximately week-long simulations where boundary conditions representing average conditions for the week are held constant. Environmental variables that change on a timescale of less than a week (e.g., hourly, daily, etc.) will average out on the timescale of months to years, so upscaling to weekly simulations results in increased computational efficiency. Weekly average building heat load and solar source can be divided into energy components that determine model stresses (Figure 4). Summer heat in excess of building heat demand (red) is injected into the reservoir, and winter heating need is supplied by a combination of solar (yellow) plus hot water from the reservoir. The heat demand placed on the reservoir (blue) is partially or fully satisfied from the reservoir, only if reservoir temperatures are sufficiently high to heat the hourly building return flows from the hot water loop.

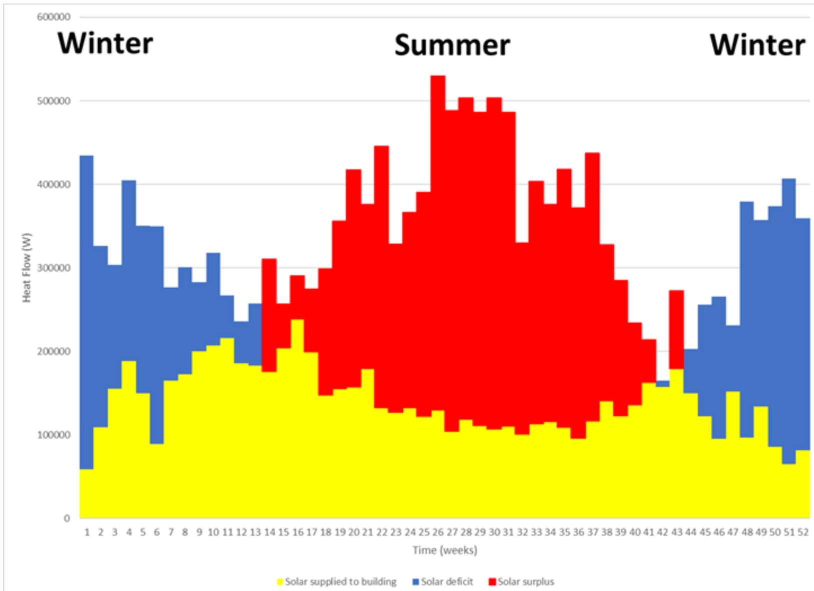

Figure 4: Energy that can be supplied directly to the building (yellow), the solar energy excess (red), and the winter heating deficit (blue).

System design depends on both size of the solar source and reservoir injection temperature from the solar array. If the combined solar/RTES system will eventually meet the full building heating load, then the solar source must be sized larger than the full load, because heat will be lost to the surrounding geology.

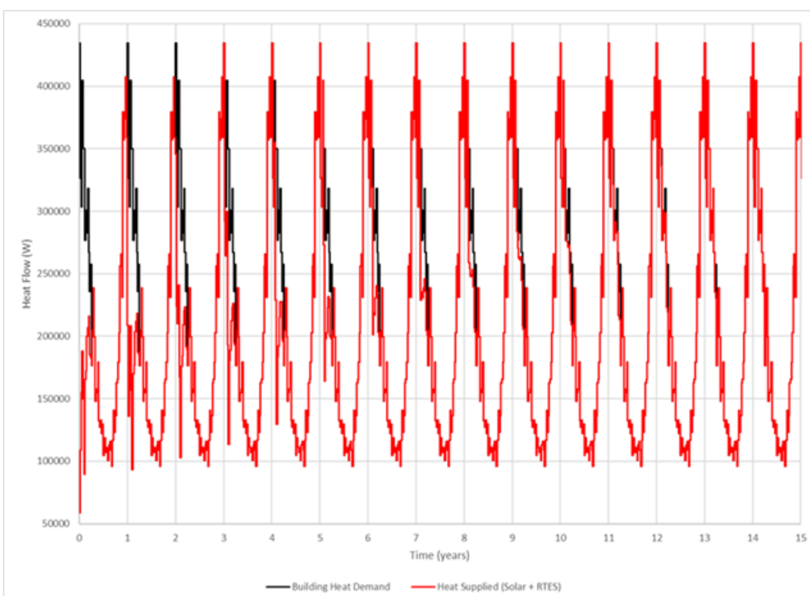

Figure 5: Simulated heat delivered from the combined solar/RTES system for the 125% solar/80°C scenario (base case). When the heat supplied to the building line covers the building heat load line (i.e., no black curve is visible), the full heat demand is being satisfied from the combined solar/RTES system.

Representative reservoir properties (e.g., geometry and thermal and hydraulic properties) were used in a model that was stressed with a range of conditions, with the base case stresses being defined as having a solar array sized at 125% of annual average building heat demand with an injection temperature of 80°C. Because the desired temperature on the building supply side is 50°C, the effect of lowering the injection temperature to 55°C was also considered. Because space may be limited for installation of a solar array, the effect of having a smaller solar array sized at 75% of the annual average building heat demand was also considered (75% is approximately the amount that could be supplied if the entire roof of the KCRB was covered with a solar array). To aid in sizing and design of infrastructure, Burns et al. (in press) develops and summarizes a range of tools that can be used to estimate

well spacing and the size of the external heat source necessary to meet full building thermal demand after the reservoir is heated up. Well spacing is a function of volume of water to be stored, and the same amount of heat can be stored in a smaller volume if water temperatures are higher. For all simulations, well-spacing was fixed at 500 m, though for higher temperature simulations, a spacing of ~100 m might be possible (assuming a homogeneous system). Heterogeneity would require larger well spacing.

For the base case where we assume a system lifespan of 30 years, the 15th year of operations is the first year when 100% of building thermal demand is met from the combined solar/RTES system (Figure 5), but this time can be shortened considerably by increasing the early-time heat addition (e.g., using nearby heating infrastructure, oversizing the solar array, having a period of operation where all solar is injected rather than being used for the building, etc.). If all solar heat (i.e., 125% at 80°C) is injected for 1-2 summers, then 100% of KCRB heating demand can be met by the combined solar/RTES system thereafter (Burns et al., in press). After full-heat demand is met, the reservoir continues to heat, building a surplus that can provide additional heat in the future (e.g., new buildings, or particularly cold years, etc.).

Time until full heat demand can be satisfied is a function of heat recovery, and Burns et al. (in press) provide analytic estimates of minimum heat recovered as a function of years of operation. Heat recovery depends on the reservoir surface area to volume ratio, with a higher surface area losing more heat to surrounding rock. Because the CRBG reservoirs are thin, they have a relatively high surface area to volume ratio, and heat recovery starts low compared with what might be expected in thicker reservoirs. For the base case, first year thermal recovery efficiency (i.e., the fraction of injected heat that could be extracted to meet building heat demand) was ~30%, and in year 15, when 100% of building heat demand was satisfied, recovery was ~60%. The long-term thermal recovery is estimated to asymptotically approach 93%.

3.8 Resource (Heat) Estimates for the Portland Basin

Seasonal heat storage and delivery capacity can be mapped as a function of hot water storage capacity per °C (Figure 6). To generate this map, typical values for density and specific heat capacity of water are combined with bulk porosity of CRBG units (estimated to be 0.025) and the reservoir geometry extracted from the 3D geologic model of Scanlon (2019). To represent a thermal and hydraulic separation from the overlying aquifer, the uppermost CRBG lava flow interior was not included (estimated to be the upper 27 m of CRBG). Only parts of the reservoir beneath the regional water table were used so that the reservoir contains water to transport heat. The total area of the reservoir is estimated to be 1,596.5 km^2, yielding a total potential energy storage capacity of 8,679 GWh of energy per °C of stored energy that can be later extracted. If the system were fully developed to store and release 10°C annually, then annual energy budget would be ~87,000 GWh of thermal energy. Because computation of the thermal energy storage map (Figure 6) is proportional to thickness of CRBG reservoir, the map also shows areas where thermal recovery efficiency would be higher as more CRBG injection horizons are developed. Recall that the annual heating load for the building is on the order of 2 GWh, so the total heat storage capacity of the reservoir could conceivably supply heating for more than 40,000 large research hospital buildings, far in excess of the current need in Portland.

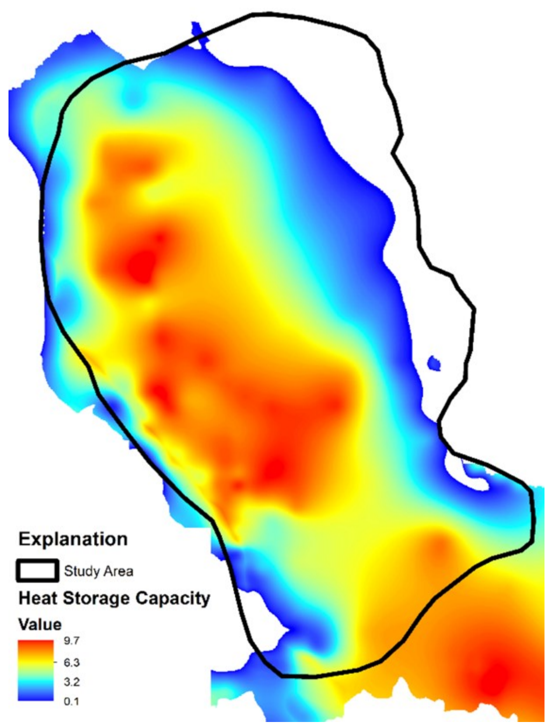

Figure 6: Map of estimated thermal energy storage capacity in the CRBG in the Portland Basin (units: KWh/m^2/°C). The study area extent is the same as in Figure 1A.

4. RISKS AND ADDITIONAL CONSIDERATIONS

Complicating factors in implementing RTES in the Portland Basin include:

(1) *Reservoir heterogeneity* that might result in preferential fluid flowpaths and early heat breakthrough during injection/extraction
(2) Faults may act as horizontal barriers to flow in the CRBG or fluid migration pathways into the shallow aquifer.
(3) *Hydrothermal alteration* may adversely affect the porosity and permeability of the reservoir over time.
(4) *Seismicity* (both induced and natural) may pose a hazard to RTES operations.

The analyses summarized herein are a proof of concept, and (1) and (2) would need to be addressed during and after field testing, with new simulations being performed to incorporate information gained. In the following sections, we consider risks associated with hydrothermal alteration (3) and seismicity (4).

4. 1 Hydrothermal Alteration of the Reservoir

Heating of brackish waters and rocks of the reservoir during cyclical hot water injection and extraction can result in chemical changes that form scale in piping and heat exchange components, and mineral deposits that change aquifer porosity and permeability. This has been documented in laboratory, modelling, and field-based experiments (Bonte et al., 2013; Garcia-Gil et al., 2016; Rosenbrand et al., 2013). Groundwater chemistry data analyzed for this project was compiled from published literature, well logs, and local, state, and federal water quality reports, including >200 wells in and around the Portland Basin.

RTES will likely source its water from deeper CRBG aquifers present in the Portland Basin. Because there is little published data regarding the water composition in the lower CRBG, and because groundwater compositions may vary depending on depth, proximity to structures, and location within the basin, a range of potential native water compositions were simulated with geochemical reaction models (details provided in Svadlenak, 2019).

Silica precipitation is likely to occur at the cooling / mixing front in the RTES reservoir. However, the volumes precipitated are unlikely to cause significant porosity loss and over time the cooling front and associated mineral buildup may migrate with expansion of the hot water storage zone. However, because many CRBG groundwaters are near saturation with respect to calcite and because the solubilities of calcite and other carbonates, such as siderite, decrease with temperature and with loss of $CO_{2(g)}$, carbonate scaling is of primary concern during heating of groundwaters. Our modeling confirms that elevated temperatures may result in extensive mineral precipitation. Reaction rates for carbonate precipitation are typically orders of magnitude faster than for clays, so precipitation of carbonate minerals (chiefly, calcite and siderite) has the potential to form extensive scale deposits within pipes and heat exchange systems upon heating. Precipitation of these phases in the aquifer, or transfer of suspended precipitates to the aquifer, could result in significant declines in porosity and permeability, likely at or near the injection site when injected waters are heated to 70°C. Such loss is minimized, though not necessarily eliminated, when waters are heated to ~50°C.

Under the most optimistic conditions (less evolved waters, ample reactive silicate surfaces, lower temperatures, and or low to modest flow rates), a slight increase in porosity near the injection point may occur (Figure 7). Under the worst-case scenarios (mature waters that are saturated or oversaturated with respect to calcite, an absence of reactive silicates as in calcite-lined fracture porosity, higher temperatures, and higher flow rates), a loss of >50% of total porosity (from 20% to <10%) may occur near the injection well within one seasonal cycle, which would likely be accompanied by a loss in permeability. Modeling the recycling of waters between two reservoirs maintained at 70°C and 40°C suggests porosity loss in both reservoirs, but that some porosity may be recovered in the 70°C reservoir over multiple cycles (Figure 7).

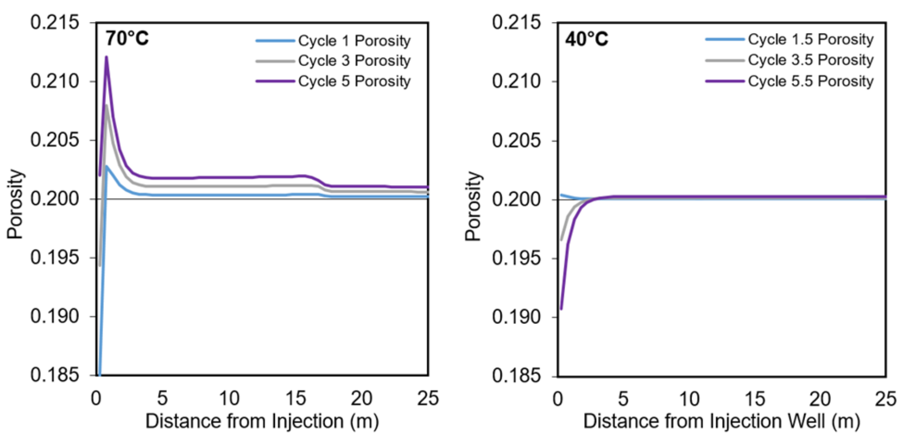

Figure 7: Changes in porosity after 5 successive annual cycles of pumping/recovery/pumping in a) primary aquifer (70°C) and re-injection of cooled water into b) separate reinjection zone (40°C).

Modeling the extent to which mineral precipitation and dissolution reactions occur is complicated by uncertainties with respect to phases exposed in pore spaces, their reactive surface areas, and kinetic rates. Expanding what is known about the target zone in terms of its water chemistry, the nature of porosity, and the extent of secondary minerals, will allow for more accurate modeling of geochemical impacts from RTES cycles. This information could be gleaned through exploratory drilling and water quality sampling.

4.2 Seismicity

A preliminary analysis of past seismicity in and near the Portland Basin indicates that the potential to induce seismicity from RTES operations is relatively small. We evaluate geologic conditions and model parameters for injection rates, volume, and water injection depth to understand risk from induced seismicity resulting from the injection and production of fluids during RTES operations. We compiled rates, volumes and depths of injection for local injection activities (e.g., CRBG aquifer storage and recovery wells in the adjacent Tualatin basin) and also for Oklahoma, and compared injection activities to published seismic activity for these areas. We compare proposed depths and rates of injection for the proposed RTES in Portland, Oregon with compiled values and find the proposed system falls below the range of values for nearby operating aquifer storage and recovery wells which are shallow, have low injection and withdrawal rates, and have not been historically associated with occurrences of induced seismicity in the Portland region.

Two injection wells located < 2 km northwest of the proposed RTES site inject water to depths less than 1,200 feet and have injection rates that reach 1,500 gallons per month, similar to our proposed wells. No historical seismicity is associated with water injection in these or aquifer storage and recovery (ASR) wells nearby (https://pnsn.org/pnsn-data-products/earthquake-catalogs, last accessed 4/2019). For ASR systems in the Tualatin Basin, ~30 km west of the proposed site, in the same regional stress regime, fluid injection depths are generally shallower than our proposed wells and injection rates are much higher.

While there is little to no evidence that injection into CRBG results in induced seismicity, there is evidence that fluid injection has triggered earthquakes in other settings, where pore pressure at a fault increases beyond a critical pressure threshold (Keranen et al., 2013). Wastewater in Oklahoma is being injected at greater depths (>6,000 ft / 1,825 m) into crystalline basement, and as a result induces slip on basement faults causing seismicity. In recent decades, there has been an increase in earthquakes in the central United States, which has been linked with oil and gas wastewater fluid injection in these regions (Rubinstein and Mahani, 2015). In Oklahoma, three > M 5 earthquakes have occurred in injection areas that experienced an increase in both the number of injection wells and injection rates (Hincks et al., 2018). Injection rates and depths are typically higher in Oklahoma compared to this study. Also, in contrast to wells in Oklahoma, the RTES system proposed here cycles water in and out of the same reservoir, minimizing increases in pore pressure. Based primarily on the fact that higher injection rates into CRBG in the Tualatin basin have not historically induced seismicity, proposed RTES operations are deemed low-risk for inducing seismicity within the Portland Metropolitan area. Current research at Lawrence Berkeley National Laboratory is using the Portland Basins geologic model and RTES properties to simulate the effects of heating and cooling near faults on potential seismicity (Eric Sonnenthal, personal communication).

Seismicity associated with a naturally occurring earthquake poses a risk to RTES operations, but also provides the basis for a potential benefit to implementing RTES as a form of energy resiliency in the event that an earthquake were to disrupt conventional energy supplies to critical infrastructure. In addition to induced seismicity, we reviewed existing ground shaking maps for the Portland Metropolitan region for both local crustal fault rupture and a subduction zone earthquake to constrain this seismic hazard. For a crustal fault rupture like a scenario M 6.8 earthquake on the nearby Portland Hills fault, the proposed RTES study site is expected to experience between 0.5 to 0.75 g acceleration and Severe to Violent shaking (Wong et al., 2000; Bauer et al., 2018). There are no geophysical investigations near the proposed study area that image the Portland Hills fault at depth, nor are there nearby geological investigations that evaluate displacement on the Portland Hills fault in the last 12,000 years. Our compilation of existing geotechnical studies and seismic source characterization suggests a sub-vertical Portland Hills fault (Figure 2). Given the short distance of the proposed site from the Portland Hills fault, < 500 m, further investigation of this fault is warranted prior to development of the RTES system.

Alternatively, a scenario M 9.0 subduction zone earthquake would generate > 3 to 6 minutes of shaking and would result in peak horizontal acceleration of 0.25 to 0.30 g classified as Severe (Bauer et al., 2018). For this scenario earthquake, the likelihood of permanent ground deformation for saturated soil is very high, from 0.1 – 1.18 m of permanent deformation (Bauer et al., 2018). Deformation at the proposed area of the RTES thermal storage injection well locations on Willamette waterfront OHSU property would include liquefaction and lateral spread. Permanent ground deformation throughout the Portland Metropolitan area should be anticipated in the event of either a crustal fault or subduction zone earthquake, and appropriate well shut-off systems should be in place in the event of ground failure. RTES operation could be restored once shaking stops and if no substantial localized ground deformation was present.

5. COST / BENEFIT ANALYSIS

In addition to technical feasibility, a goal of this paper is to analyze the economic feasibility of RTES for district (or large critical infrastructure) heating needs in the Portland Basin. In particular, we focus on understanding the market potential for application of RTES in the high population-density Portland downtown area, using an OHSU building on the south waterfront expansion (Figure 1) as a case study to investigate the possible advantages and disadvantages. This analysis considers not only the costs of existing energy options in comparison to RTES, but also the potential environmental benefits/impacts and resiliency and reliability characteristics related to natural catastrophes.

Our findings suggest a general framework on the types of buildings with possible efficiency improvements that could be met with a RTES system. In particular, building types with high energy demand to keep occupants comfortable, namely hospitals, colleges, and grocery stores, appear to be good candidates for geothermal projects. Buildings or campuses over 500,000 square feet in size may also benefit, considering the cost of improvements may be smaller relative to the value of the building(s). Economies of scale may further benefit campuses or groups of buildings where one geothermal system (or a district geothermal system) can supply heat to multiple buildings, sharing large fixed costs.

5.1 Levelized Cost of Energy (LCOE)

First, we compare RTES in the Portland Metro area with the current most common methods of building heating and cooling using a common metric for energy cost comparisons - levelized cost of energy (LCOE). This calculation allows decision makers to compare lifetime costs of different types of energy generation systems (coal, nuclear, solar, natural gas, wind, etc.). The most basic form of an LCOE calculation is the sum of all of the costs of installing and operating a system over the expected life of the system divided by the lifetime energy generation of a system. We use a general LCOE equation from GEOPHIRES v2.0 (Beckers and McCabe, 2018), which assumes that all capital costs occur in the first year. LCOE and levelized cost of heating (LCOH) are present value calculations to evaluate the per unit cost of energy or heat for a generation system over the course of an assumed lifetime. Here, we report both LCOE ($/MWh) and LCOH ($/MMBtu).

Table 1 summarizes the required input variables and assumptions used to calculate LCOE for a new conventional building at OHSU. Capital costs include two production wells ($1.3 million total), pumps ($127,184), piping ($53,000), and a solar array ($1.8 – 3.0 million). Solar array costs vary significantly depending on the engineered heat desired. We include pricing that reflects a solar array that can accommodate model conditions at 75% and 125% of building heat load. In addition, there are variations in operating costs depending on the heat available, as water pumping quantities and flow rates vary, resulting in a range of pumping electricity costs. However, we find this variation is relatively minor, as it does not contribute significantly to LCOE (approximately 0.10% to 0.13% of capital costs). In our estimate of a baseline LCOE for OHSU, we are including the costs of the solar array (engineered heat) in addition to the costs of RTES infrastructure and maintenance, so these should be considered estimates of RTES plus solar heating, as the costs and benefits of both are included. We also assume a two-year period of "priming", where the reservoir is heated without extraction to establish the thermal mass necessary for efficient RTES operations. In addition, the base case assumes a solar array that can provide 125% of building heat demand, which comes to **$34.08 / MMBtu ($116.28 / MWh)**. According to unsubsidized LCOE of other energy sources, this is within the range of coal ($60-143 / MWh), nuclear ($112-189 / MWh), solar ($73-267 / MWh), and fuel cell ($103-152 / MWh), but more expensive than combined cycle natural gas ($41-74 / MWh) and wind ($29-56 / MWh)[1] (Lazard, 2018).

Table 1: Levelized Cost of Energy (LCOE) Calculation Input Variables. Where there is a range of values, a sensitivity analysis was performed. Nominal Capital Costs include 2 wells, 2 pumps, piping, and a solar array.

Variable	Units	Assumption	Source
Construction Time	Years	1	Team experts
System Lifetime	Years	25-35	Team experts
Nominal Discount Rate	%	3.00%	Li and Pizer (2019)
Expected Annual Inflation	%	2.20%	Federal Reserve 10-year inflation forecast (as of 11-2018)
Real Discount Rate	%	0.80%	Real Discount Rate = Nominal Discount Rate – Expected Annual Inflation
Base Energy Output	kWh per year	1,212,735 – 1,845,164	Solar providing 75% and 125% of building load
Nominal Operating Costs	$ / year	$34,764	Pumping rates vary according to flow rates. Assumes $0.10/kWh electricity cost
Nominal Capital Costs	$	$3,310,824 - $4,529,543	Varies based on solar capacity assumptions (75%-125% of heating)
Capital Cost Dispersion	Years	1	Team experts

Table 2: OHSU Case Study LCOE Estimates with System Lifetime and Nominal Capital Sensitivity Analysis.

System Lifetime	**Nominal Capital Cost**	
	$3.311 million (75% Energy Supply via Solar)	$4.530 million (125% Energy Supply via Solar)
25 years	$46.17 ($157.54)	$39.25 ($133.94)
30 years	$40.38 ($137.77)	**$34.08 ($116.28)**
35 years	$36.27 ($123.76)	$30.41 ($103.77)

[1] Note that LCOE estimates do not include transmission costs, which can be significant for conventional heating (electric and natural gas), but is negligible for RTES as it is generated on site.

A sensitivity analysis indicates that the key variables affecting LCOE are system lifetime (25-35 years which affects LCOE up to 15%) and nominal capital costs which vary significantly based on the size of the solar array providing summer heating. A summary of this variation and its effect on LCOE is shown in Table 2. Generally, the economics are better for long-lived systems and one large enough to supply all of a building's heat.

5.2 Portland RTES Market Potential

The base case LCOE for RTES geothermal system in the OHSU case study is equal to $116.28 per MWh. Natural gas rates (as of April, 2019) are $0.82281 per therm for residential and $0.77852 per therm for commercial customers, equivalent to $28.08 and $26.56 per MWh. Electricity rates (also as of April, 2019) in in the Portland region depend on the utility provider, ranging between $0.0685 per kWh for Portland General Electric residential customers to $0.1115 per kWh for residential customers served by Pacific Power. Commercial electricity rates are $0.07572 per kWh for Portland General Electric and $0.092 per kWh for Pacific Power. These electricity rates are equivalent to a range of $68.50 to $111.50 per MWh. While these rates are not the same as LCOE estimates, they provide useful proxies for us to understand the relative cost of these energy sources.

We use the commercial cost for natural gas ($26.56 per MWh) and electricity (average $84.86 per MWh) to roughly estimate that commercial buildings in the City of Portland spend approximately $12.97 million on natural gas and $35.17 million on electricity for heating, totaling $48.14 million annually. Suppose that it is geologically, technically and economically feasible to expand systems such as the OHSU case study RTES system to all commercial buildings in the City of Portland, this translates to approximately $62.53 million in overall cost, which is approximately 30% more than current spending on heating. It is likely that the cost of RTES will decrease in the future as the cost of solar continues to decrease (Lazard, 2018). The question for urban planners and government officials is whether this additional cost is worth the environmental, reliability and resiliency benefits.

5.3 Non-economic Benefits of RTES

Geothermal is a renewable, low-carbon, environmentally friendly method of generating heat compared to conventional systems. In Oregon, most heating systems run on direct natural gas, electricity, or some combination of the two. And while natural gas is often touted as a cleaner alternative to coal, and the largest portion of Oregon's electricity comes from hydro, a renewable resource, the Northwest Power and Conservation Council (2018) conclude that both sources of heat energy still create negative environmental impacts. While natural gas for direct use and for electricity generation may be an improvement from coal, it still emits 120 pounds of CO_2 equivalent per MMBtu (Jaramillo et al., 2007) and there are significant environmental impacts from its production (UCS, 2014). While hydropower in the Pacific Northwest does not emit greenhouse gases, it does impact the environment in adverse ways, including the construction of dams that have submerged fisheries and land used by Native Americans for centuries (Beschta, 2000). Environmental concerns have been levied against wind power as well, as hundreds of thousands of birds and bats die annually from accidental collision with wind turbines (Erickson et al., 2014).

Solar energy has all of the commonly cited advantages over fossil fuel, and more within the renewable energy sector itself. Photovoltaic energy is derived from an abundant free source that can't be exhausted, it has minimal environmental impacts (including noise pollution), and entails relatively low costs of operation and maintenance (Sampaio and Gonzalez, 2017). Solar, like RTES, is a local source of energy that can be generated on site, but solar arrays can take up large amounts of ground area in comparison to other renewable energy sources.

Geothermal environmental impacts are significantly lower than natural gas and the average electricity generation mix in Oregon. While geothermal projects have occasionally been associated with releasing small amounts of harmful gasses from drilling as well as minor earthquakes, Fridleifsson (2003) finds that their environmental impacts are drastically less severe than other forms of energy used for heating and cooling. In addition to being less detrimental, the environmental impacts associated with RTES may be easier to control than other systems. This is consistent with OHSU's goal of being the "greenest campus in North America." In their strategic plan, they specifically mention geothermal heating and cooling as a component towards reaching this goal.

Other potential benefits of RTES are increased reliability and resiliency. Reliability includes measures of performance and risk management - do systems produce to the capacity they were built for on a consistent basis when conditions are typical? Common inputs that negatively affect the reliability of an energy system are fuel, energy leakages, and equipment failure. The reliability of RTES coupled with solar may be higher than other energy sources due to its local production and nearly unlimited fuel source. Geothermal systems in general are also known to have some of the most predictable costs.

Resiliency, on the other hand, includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents. Geothermal is the one of the most resilient sources of heating and cooling during and after a natural disaster. Gerner and Hansen (2011) provide evidence for the World Bank that further development of geothermal systems in the Caribbean will be vital for increasing the region's resilience to climate change-related disasters citing its ability to remain online after severe storms and in isolation. Achieng Ogala (2013) discusses how its ability to provide baseload power and its low maintenance requirements make it a resilient resource when compared to others. This also applies to the risk of an earthquake in the Pacific Northwest. Because RTES generates and stores energy locally, supply is less likely to be disrupted compared to conventional natural gas and electricity which require functioning pipelines and transmission lines, often over long distances. This is particularly important for critical infrastructure (like hospitals) directly after an event that could result in significant injuries and loss of life.

While RTES is an environmentally friendly method of heating, with significant resiliency benefits, it has yet to become mainstream in North America, due partly to markets dominated by electricity and natural gas, and high capital costs. Despite having a competitive

LCOE, RTES systems in the Portland area will have high upfront costs (Table 1). We did not explicitly account for the cost of financing, but did perform a sensitivity analysis on discount rate and found its impact to be relatively minor. High fixed capital costs are compounded by a lack of commercial availability. However, these barriers can be overcome as the technology matures and research or pilot projects similar to this one are conducted.

6. CONCLUSIONS

RTES is shown to be a viable option for heating buildings at Oregon Health Sciences University (OHSU) along the South Waterfront expansion district, suggesting significant potential for large facilities (e.g., the Portland International Airport) or district heating across the Portland Basin. The simplifying assumptions applied to our analysis of RTES are robust, and paired with other low-carbon sources of energy like solar, RTES holds tremendous promise for many large cities in the USA that overlie brackish reservoirs at depth.

In summary, we find that the most important factors to consider when evaluating RTES efficacy are operational schedule, well spacing, the amount of summer heat stored (in our model, a function of solar array size), and longevity of the system. Key risks (future research needs) in implementing RTES in the Portland Basin include reservoir heterogeneity (e.g. faults and fractures) and scaling (mineral precipitation) due to high temperatures involved (in this study, up to 80 C). We find that preheating of the reservoir and higher injection temperatures shorten the period until thermal loads can be met, with heat recovery efficiency continuing to increase over time. Our base case LCOE estimate ($34.08 per MMBtu or $116.28 per MWh) suggests RTES is comparable to unsubsidized solar and nuclear, but more expensive than natural gas, with additional benefits in reducing our carbon footprint and energy resiliency, particularly for critical infrastructure in the event of a natural disaster. Simulations herein assume steady storage and use of heat, but the reservoir might also be operated to store heat for use during emergency conditions (e.g., earthquake, volcanic eruption, etc.). To handle this contingency, the reservoir could be sized larger with hotter temperatures to store a significantly larger volume of heat. Even when the solar array is smaller than necessary to supply 100% of annual loads, having a larger reservoir would allow receiving other episodic sources of heat (e.g., low-cost electricity during peak wind) for regular or emergency heating.

We also find that the Portland Basin has a large thermal energy storage capacity (reaching ~87,000 GWh) for both heating and cooling, suggesting tremendous potential to expand RTES throughout the Portland Metropolitan Area. Though we do not focus on it here, cooling is also likely viable, but specially constructed building cooling systems may need to be utilized to allow for efficient transfer of heat using RTES. Heating and cooling in the same vicinity would result in a reduction in thermal recovery efficiency. But if other renewables (e.g., wind, solar, ambient air/water temperature, etc.) were used as the reservoir heating/cooling sources, the tradeoff with thermal recovery could be evaluated.

Buildings can be engineered to use lower temperatures and lower temperature differentials, so while RTES is viable as a resource for a new conventional building at OHSU, new buildings or retrofits might consider heating options for use in RTES systems operated at lower temperatures. Future work could focus on the development of non-conventional building designs that are optimized for RTES (e.g., radiant floor heating, above-ground water storage, etc.) to improve the economics (lower LCOE). Cooling needs are more significant than heating in most cities across the USA (including Portland), with cooling demand anticipated to grow in the coming decades as buildings become better insulated and global climate continues to warm. Compared to heating, using RTES for cooling may also reduce risk associated with scaling. This presents a great opportunity to evaluate the potential for RTES to provide building cooling for critical infrastructure.

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