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Transported Low-temperature Geothermal Energy for Thermal End Uses

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ABSTRACT

Low-temperature geothermal resources (below 150°C), although abundant in the United States as stable renewable energy sources, are typically far away from major energy demands. The low temperature of the resource has limited the efficiency of electricity generation (i.e., with Organic Rankine Cycle) to below 15%, which is too low to achieve economic payback in typical system lifetime. Meanwhile, transporting this low-temperature thermal energy via hot water at an energy density of around 145 kJ/kg in current direct use heating (DUH) systems is not economically feasible over distances longer than 2 miles. Therefore, utilization of low-temperature geothermal energy has been largely limited to remote areas, and the abundant resources have remained quite under-developed so far. To overcome this distance barrier, an innovative two-step geothermal absorption (TSGA) system was proposed in previous studies to store the low-temperature geothermal energy in liquid desiccant at ambient temperature with an energy density of 405 kJ/kg. With TSGA system, strong solution of the liquid desiccant is used to provide space cooling in buildings, and the resulting weak solution is regenerated at the geothermal site. In this study, an enhanced design of the TSGA system using salt hydrate crystals (e.g. $LiBr\text{-}H_2O$), referred to as CTSGA, as well as two other alternative technologies (solid desiccant adsorption cooling and absorption ice making/storage) that can store and transport geothermal energy with an energy density higher than that of the conventional DUH were identified. Among all these technologies, CTSGA achieved the highest energy density (915 kJ/kg). However, it requires a higher geothermal resource temperature than that for typical TSGA system (100°C). Thermodynamic models of these technologies were developed and implemented into a screening tool that can calculate the energy consumption and efficiency of each potential technology under user-specified operating conditions. The screening tool can also estimate the investment and operation costs of the investigated systems. With all the costs calculated, the economics of the two-step geothermal cooling systems can be evaluated and compared with the conventional electric cooling system. Sensitivity analysis were carried out using the screening tool in a case study for utilizing an existing hydrothermal resource near Santa Rosa, CA, which has 4,447 L/min flow rate and bottom hole temperature (BHT) of 138°C, to provide space cooling to distant office buildings. The economics of applying the CTSGA and other two alternative technologies were investigated for the given geothermal resource under a range of conditions including distances, electricity rates, and cooling load profile (i.e., peak and total cooling load). The result demonstrated that the paybacks of the two-step geothermal cooling systems would be shorter with closer distance, higher electricity rate, lower peak load, and larger total cooling demand. Among all the investigated systems, the best payback is achieved by the CTSGA system, which yields less than 10-year payback for a 50-mile (80 km) distance between the hydrothermal resource and the office building.

1. INTRODUCTION

Geothermal resources produce thermal energy using heat in the earth crust, and therefore they can provide energy supply that is both sustainable compared with fossil fuels as well as stable regardless of the climate compared to other renewable energy sources such as solar and wind. While conventional geothermal energy applications have focused on power generation using high-temperature hydrothermal resources, there are abundant low-temperature (<150°C) geothermal resources across the U.S. It is estimated that the total potential of useful thermal energy in the U.S. from low-temperature hydrothermal resources was around 42,600 MW_{th} (Williams 2013). However, temperatures of these geothermal resources are not high enough to drive conventional power generation systems. While these geothermal resources can be utilized to generate electricity with Organic Rankine Cycle (ORC), the resulting thermal efficiencies of such systems are often lower than 15% (Hettiarachchi et al. 2007, Saleh et al. 2007). With such low efficiency, it is unlikely for these ORC systems to achieve payback within their typical lifetime.

While it is challenging from both technical and economic perspectives to convert the low-temperature geothermal energy into electricity, these low-temperature resources have the potential to displace electricity and natural gas consumption by directly satisfying thermal demands. Hot water from low-temperature geothermal reservoirs can be used to provide heat for industrial processes, agriculture/aquaculture, and to keep buildings warm. Such applications are usually called "direct use". Low-temperature geothermal energy can also be used to provide space cooling and refrigeration through absorption or adsorption cooling technologies (Holdmann 2005, Lech 2009, Luo et al. 2010, Kreuter 2012, Wang et al. 2013). However, due to the low energy density of hot or chilled water and

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the high cost of developing pipelines over long distances, utilization of geothermal energy for space conditioning is currently limited to places where the geothermal resources are available either at or very close (within 2 miles) to the demand site (GHC 2005). Such short-distance limitation has significantly hampered the widespread utilization of low-temperature geothermal resources. Of all the low-temperature hydrothermal resources in the U.S., only 624 MW_{th}—less than 2% —have been installed and utilized (GHC 2005). In addition to this severe under-development of the hydrothermal resources, 25 billion barrels of geothermal fluid (mostly water) at 80°C to 150°C are co-produced at oil and gas wells in the U.S. every year (USDOE, 2015), and the heat contained in the co-produced geothermal fluid is typically wasted, for the fluid is either disposed of on the surface or reinjected back underground without extracting the heat.

To overcome this distance barrier, an innovative two-step geothermal absorption (TSGA) system was proposed in previous studies to store the low-temperature geothermal energy in liquid desiccant solution at ambient temperature with an energy density of 405 kJ/kg (Liu et. al. 2016). With the TSGA system, strong solution of a liquid desiccant such as $LiBr/H_2O$ was transported to the target building to drive absorption process and provide space cooling, and then the resulted weak solution was transported back to the resource site to be regenerated using the low-temperature geothermal heat. A case study was discussed using TSGA with the geothermal heat of co-produced water from oil wells to provide space cooling for an office building 10-mile (16 km) away from an oilfield in the vicinity of Houston, TX. The simple payback of replacing a conventional electric chiller with the proposed TSGA system was calculated to be less than 11 years, with almost half of the total life cycle cost spent on transportation operations. To curtail the transportation cost, the best approach was concluded to be increasing the energy density of the transported energy storage material.

In this study, an enhanced design of the TSGA system referred to as CTSGA using salt hydrate crystals (e.g. $LiBr\text{-}H_2O$ and $LiBr\text{-}2H_2O$) instead of salty solution to store energy was introduced. Two other alternative technologies (solid desiccant adsorption for cooling and absorption ice making and storage) that can store and transport geothermal energy with an energy density higher than that of the conventional direct use (hot water) approach were also identified. Among all these technologies, CTSGA achieved the highest energy density (915 kJ/kg). However, it requires a higher geothermal resource temperature than that for typical TSGA system (100°C). Thermodynamic models of these technologies were developed and implemented into a technical and economic analysis tool that can calculate the energy consumption and efficiency of each potential technology under user-specified operating conditions. The analysis tool can also estimate the investment and operation costs (non-transportation and transportation-related) of the system, from which the economics of the entire system can be evaluated and compared with the conventional electric cooling system.

Case study and sensitivity analysis were carried out using the analysis tool for utilizing a hydrothermal resource near Santa Rosa, CA. The existing geothermal resource had a flow rate of 4,447 L/min and bottom hole temperature (BHT) of 138°C. In the case study this geothermal resource was utilized with different technologies to provide seasonal space cooling for buildings about 50 miles away. The economics of three geothermal cooling technologies were investigated under a range of conditions including distances, electricity rates, and cooling load profile (i.e., peak and total cooling load).

2. SUMMARY OF POTENTIAL TECHNOLOGIES

Following previous studies of the TSGA system, a comprehensive literature review was carried out to identify other technologies with potential for utilizing low-temperature geothermal energy for thermal applications (Yang et al. 2016). These technologies were originally developed for other purposes, such as industry waste heat recovery, compact thermal energy storage, and non-vapor compression cooling. The energy densities (i.e., the amount of heating/cooling energy provided by each unit mass of the transported energy storage media) of these technologies are compared in Table 1 along with other characteristics, including transported media, underlying technology, and advantages and limitations.

Table 1 Summary of technologies that has potential to utilize low-temperature geothermal energy for thermal applications

Transported medium	Application technology	Energy density		Advantages	Limitations
		Heating [kJ_{th}/kg]	Cooling [kJ_{clg}/kg]		
Water	Direct Use (DU)	146	23	Simplest technology	Only feasible for short distance
Solid desiccant	Adsorption (ADS)	202	526	High energy density	Need high charging temperature, slow charging/discharging, varying outputs
Salt solution/crystal	Two Step Geothermal Absorption (TSGA)	-	405	High energy density	Technical challenges to maintain vacuum at components and prevent air infiltration, need to prevent crystallization
	Crystal Enhanced TSGA (CTSGA)	-	915	High energy density	New technology and need to be customized for geothermal applications
	Crystal Enhanced Liquid Desiccant Dehumidification (LDD)	-	857	High energy density, ambient pressure operation	Only deals with latent cooling load, performance dependent on climate
Ice	Absorption Refrigeration (Ice)	-	355	Mature technology	Need heavy insulation when transporting ice in summer, varying charge/discharge rate

As shown in Table 1, all these technologies can provide space cooling but with different energy densities. TSGA, ADS, and Ice have similar energy densities for cooling application, which are more than 15 times higher than direct-use cooling and more than double the energy density of direct-use heating. The cooling energy density is nearly further doubled with CTSGA and LDD. However, the LDD systems can only deal with the latent cooling load (i.e., dehumidification) instead of replacing the entire electric chiller system like the TSGA systems, therefore, their applications are significantly limited. The Ice systems face another challenge when compared with TSGA systems: their energy density is lower. Therefore, they will cost even more to transport ice between geothermal resource and the building than the TSGA system. Meanwhile, only ADS can produce needed hot water for heating application and its energy density in heating is only slightly higher than that of direct-use heating. Therefore, this study focus on investigating the most promising technology—CTSGA system—in comparison with the TSGA and ADS technologies in cooling applications.

3. CRYSTAL-ENHANCED TWO STEP GEOTHERMAL ABSORPTION SYSTEM

The CTSGA system was developed based on the two-step absorption system design of the TSGA system that was introduced and discussed in previous studies. The most important difference between a CTSGA system and the TSGA system is that it allows crystals of salt hydrate to be formed in the storage tanks, and it uses the crystals as the energy storage media to achieve a higher energy density. A concept design of the CTSGA system is shown in Fig. 1. The desorber at geothermal site generates strong solution at high temperature using the hot geothermal fluid. This strong solution is then cooled in a storage tank (i.e., the tanker-trailer) until it crystallizes into salt hydrate. Since the mass fraction of salt in the crystals is higher than the strong solution, more energy is stored in the crystals. The remaining saturated solution in the tank is re-circulated into the desorber to have more water content driven off and become strong enough to be able to crystallize in the storage tank. At the building site, weak solution leaving from the absorber goes into a storage tank filled with the mixture of crystals and saturated solution. After dissolving some crystals, the weak solution becomes strong again, and then flows back into the absorber to generate more chilled water. With the CTSGA system, the same tank load of energy storage material can provide twice as much cooling compared to the TSGA system.

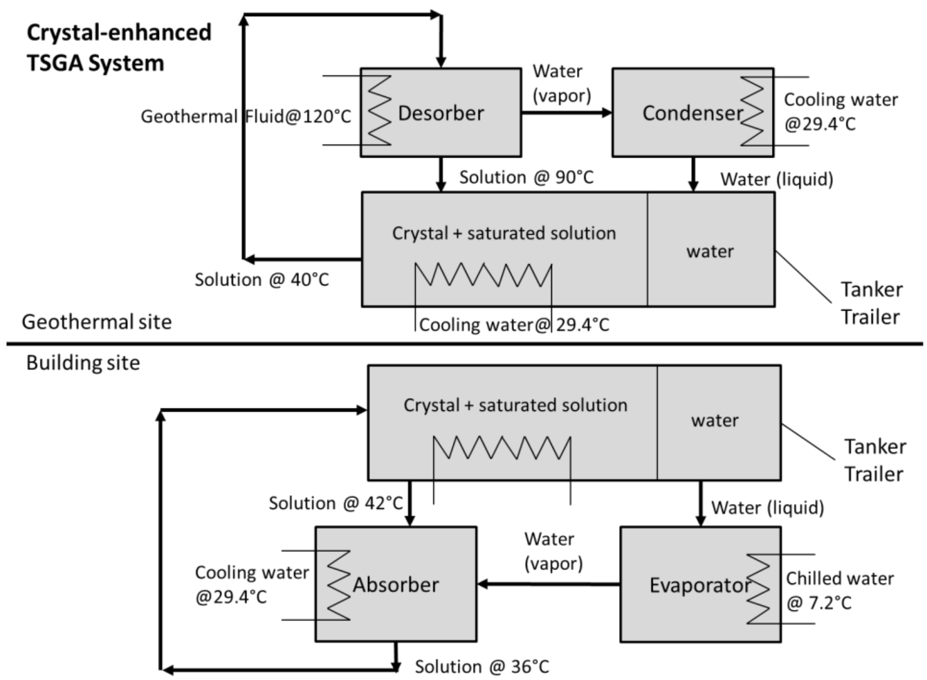

Figure 1 Crystal enhanced TSGA (CTSGA) system operation cycle

To evaluate the energy, economic, and environmental footprint of the CTSGA systems and compare them with the TSGA and ADS systems, the correlations between the performance of these systems under various operation conditions, as well as equations for calculating the initial cost, annual operation cost, and the energy density of the transported energy storage media are generalized based on similar work done in the previous study (Liu et al. 2015). The initial cost to purchase the system (IC_{CTSGA}) is calculated with Eq. (1), which includes the costs of the absorption chiller ($IC_{Abs_{chiller}}$), cooling towers ($IC_{Abs_{CT}}$), and the circulation pumps ($IC_{Abs_{pump}}$).

$$IC_{CTSGA} = IC_{Abs_{chiller}}\left(peakLoad/CF_{Cap}\right) + IC_{Abs_{CT}}\left(peakLoad * (1 + \frac{1}{COP_d})\right) + IC_{Abs_{pump}}(peakLoad * (1 + \frac{1}{COP_d})) \quad (1)$$

The cost for purchasing and installing each component is estimated based on its size/capacity using the national average values from 2011 RSMeans mechanical cost data (Mossman 2010). The nominal size of the absorption chiller is determined based on the peak cooling demand and the operating condition of the chiller (i.e., the heat source temperature and the cooling water temperature). A single effect absorption chiller was modeled with SorpSim (Yang et al. 2014) to predict the cooling capacity at various operating conditions. A brief summary of the assumptions of the operating conditions used in the analysis is listed in Table 2, and the details of the assumptions can be found in the previous study (Yang et al. 2016). Instead of using monthly or even daily weather data, the average ambient wet-bulb/dry-bulb temperature of the selected location is used to calculate the overall performance of the entire cooling season. This simplified computation provided results that proved to be accurate compared to monthly or daily cumulative simulation. A capacity correction factor (CF_{Cap}), which is the ratio of the chiller's capacity at a given operating condition to that at the standard rating condition, assuming constant solution flow rate, is used to determine the nominal capacity of the absorption chiller. Since crystals are used, the strong solution concentration at the building is decoupled from the geothermal source temperature.

Table 2 Brief summary of assumptions used in the analysis

Temperature approach in wet cooling tower	Temperature approach in dry cooler	Chilled water supply temperature	Design COP of single-effect absorption system	Design COP of water-cooled electric chiller	Design COP of air-cooled electric chiller	Standard absorption chiller rating condition (AHRI, 2000)
5.6°C	11 °C	7.2°C	0.7	5.5	2.8	Hot water: 100°C Cooling water: 29.6°C

Assuming the chilled water temperature is kept at 7.2°C, the capacity correction factors can be plotted as a function of the cooling water temperature, as shown in Fig. 2. The correction factor at the standard rating condition (AHRI, 2000) is 1. With higher wet bulb temperature, the correction factor is smaller, which means a chiller with a larger nominal size is needed to provide the needed cooling capacity at the actual operating condition.

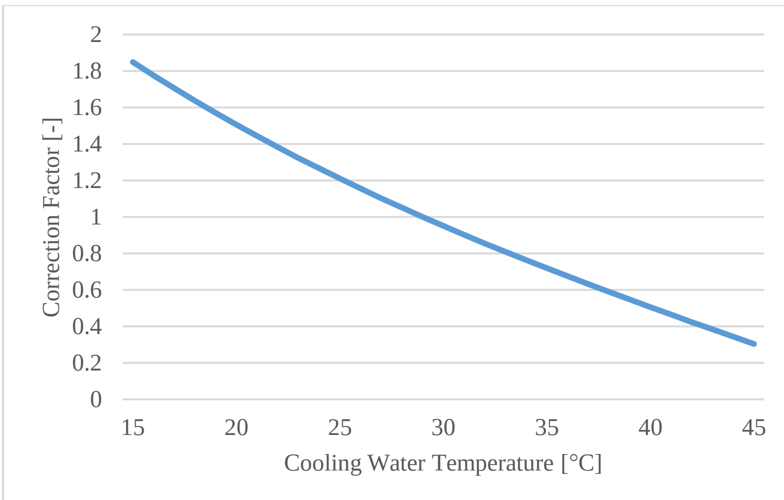

Figure 2 Capacity correction factor of CTSGA system at various cooling water temperatures

The capacity of the cooling towers and circulation pumps are determined based on $peakLoad$ and the thermal coefficient of performance (COP_d, the ratio of cooling output to the heat input) of the absorption chiller. For a single effect absorption chiller at the standard rating condition, the typical value of COP_d is 0.7 (Herold et al. 2016).

The operation cost of the system (OPC_{CTSGA}) is calculated with Eq. (2), which includes the costs of electricity consumption of the cooling towers and circulation pumps. These electricity consumptions are calculated based on the electricity consumptions of the cooling towers and circulation pumps of the baseline electric chiller cooling system, which is calculated with a ratio between the annual power consumption of the cooling towers or circulation pumps to that of the electric chiller. The ratio is determined based on computer simulation results of a conventional water-cooled electric chiller system serving a building of interest in this study. The power consumption of cooling towers and circulation pumps in the CTSGA system are calculated by multiplying the baseline power consumption of cooling towers and circulation pumps with the ratio of the heat rejection load of the CTSGA system to that of the baseline cooling system.

$$OPC_{CTSGA} = ElePrice * \frac{totalLoad}{COP_{a_{baseline}}} * (PowerRatio_{CT} + PowerRatio_{pump}) * \frac{1 + \frac{1}{COP_{a_{absChiller}}}}{1 + \frac{1}{COP_{a_{baseline}}}} \tag{2}$$

In Eq. (2), $COP_{a_{absChiller}}$ is the thermal COP of the absorption chiller, $COP_{a_{baseline}}$ is the electric COP of a baseline electric chiller. $COP_{a_{absChiller}}$ at various operating conditions are determined with the SorpSim model and shown in Fig. 3.

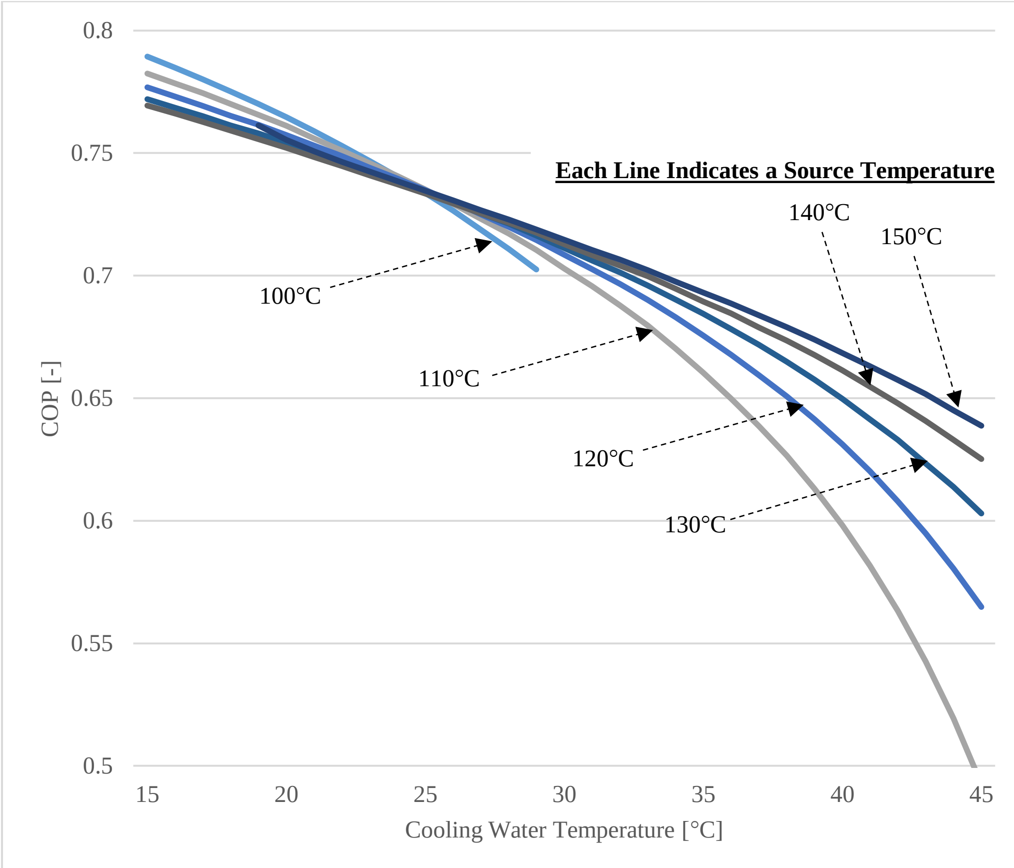

Figure 3 Thermal COP of CTSGA system at various heat source and cooling water temperatures

As shown in Fig. 3, $COP_{a_{absChiller}}$ is affected by both the heat source temperature and the cooling water temperature. It is around 0.7 at the standard rating condition. With lower source temperatures and higher cooling water temperatures, $COP_{a_{absChiller}}$ declines quickly, especially when the cooling water temperature is higher than 30°C.

In the CTSGA system, LiBr-H_2O salt hydrate crystal is used as the energy storage media. The energy density of the crystal is determined by the LiBr mass fraction in the crystal, as well as the LiBr concentration in the weak solution. The concentrations of the solution are calculated using correlations derived from the simulation results with the SorpSim model at various operating conditions. Fig. 4 shows the strong solution concentration (C_{ss}) and weak solution concentration (C_{ws}) at various operating conditions. The strong solution concentration is determined by both the heat source temperature and the wet bulb temperature. It increases when the heat source temperature becomes higher or the wet bulb temperature goes down, and vice versa. Since the chilled water temperature is fixed at 44°F (7.2°C), the weak solution concentration is affected only by the cooling water temperature—it increases with the increase of cooling water temperature. In order to produce crystal in the tank following re-concentration of the strong solution at the geothermal site, the strong solution concentration has to be high enough—typically higher than 65%—for LiBr-H_2O crystal to form when the strong solution is cooled down to the ambient temperature. Therefore, a minimum temperature limit needs to be imposed: only geothermal resources with temperature higher than 120°C can be considered for CTSGA systems using LiBr-H_2O as the working pair.

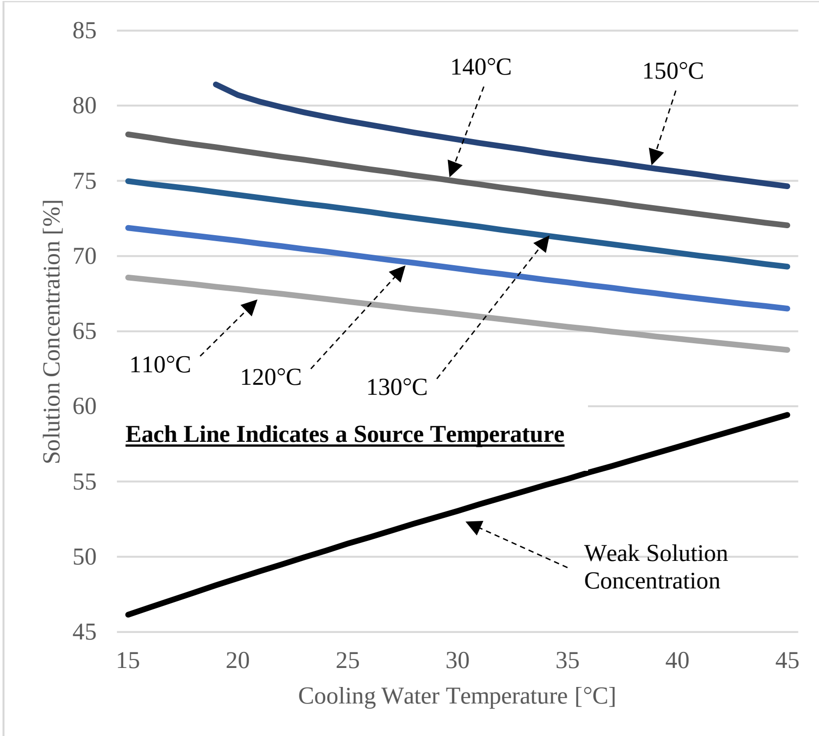

Figure 4 Solution concentration in CTSGA system

At a given operation condition, the concentrations of the strong and weak solutions are determined using correlations shown in Figure 4. Then a parameter indicating the mass ratio of crystals in the storage tank ($crystalRatio$) is introduced to account for the incomplete crystallization in the storage tank. This crystal ratio is set to be 0.9 in following analysis, namely assuming crystals takes up 90% of the crystal-saturated solution mixture. The equivalent concentration of the crystal-solution mixture in the storage tank ($C_{ss_{eq}}$) is calculated as expressed with Eq. (3):

$$C_{ss_{eq}} = C_{crystal} * crystalRatio + C_{ss} * (1 - crystalRatio) \quad (3)$$

where, $C_{crystal}$ is the mass fraction of the salt in the crystal (i.e., 83% for LiBr-H_2O).

The energy density of CTSGA (ED_{CTSGA}), which is the energy transported by a CTSGA system based on the mass of weak solution, is calculated with Eq. (4) where h_{fg} is the evaporation heat of water:

$$ED_{CTSGA} = \left(1 - \frac{C_{ws}}{C_{ss_{eq}}}\right) * h_{fg} \quad (4)$$

With the initial cost (IC_{CTSGA}), operating cost (OPC_{CTSGA}), and the energy density (ED_{CTSGA}) correlations, the economic performance of the CTSGA system can be calculated following the procedure described in Yang et al. (2016). The procedure as well as unique correlations to calculate performance of the TSGA, ADS, CTSGA, and Ice systems have been programmed into a technical and economic analysis tool for convenient evaluation of these technologies under various operating scenarios. In the next section, this analysis tool is used for a case study to investigate the economics of transporting and utilizing a low-temperature geothermal resource in Calistoga, CA.

4. CASE STUDY

To evaluate the economics of applying the alternative cooling technologies including TSGA, ADS, and CTSGA systems to utilize low temperature geothermal energy for thermal end uses, a case study was carried out based on a low temperature hydrothermal resource in Calistoga, CA. Located in north of Napa County, California and close to the Geysers, Calistoga has enjoyed low-temperature geothermal resources for decades. While the 35 geothermal wells located at Calistoga are only 244 m deep, their bottom hole temperature reaches 138°C (Mullane et al. 2016), and the total flow rate of geothermal fluid from these wells is 4,447 L/min. Calistoga is a small town and only has a population of 5,155 during the 2010 census and population density in the surrounding area of Calistoga is very low (less than 1,000 people per square mile). Since the amount of cooling load in commercial buildings is generally proportional to population density, the target building is set in the closest population center: Santa Rosa. Santa Rosa is a city in Sonoma County, California. Its estimated population was 174,170 in 2014. Although these two towns are connected with a 16.7-mile Petrified Forest Road across a mountain, this road is not a designated truck route, and therefore not considered for this study. The shortest truck route is through US highway 101 from Santa Rosa to Geyserville, then through California state road 128 to Calistoga, covering 47 miles (75 km) one-way. The truck route is highlighted in Fig. 5. With an assumed average speed at 40 mph and 10 minutes to disconnect and switch trailers at both the geothermal site and the building, it takes a tractor-trailer 2.7 hour to complete a round trip between the geothermal site and the building. The cost per round trip is calculated as $164.4 based on the traveling time and distance with a generic truck transportation cost model described by Liu et al. (2015).

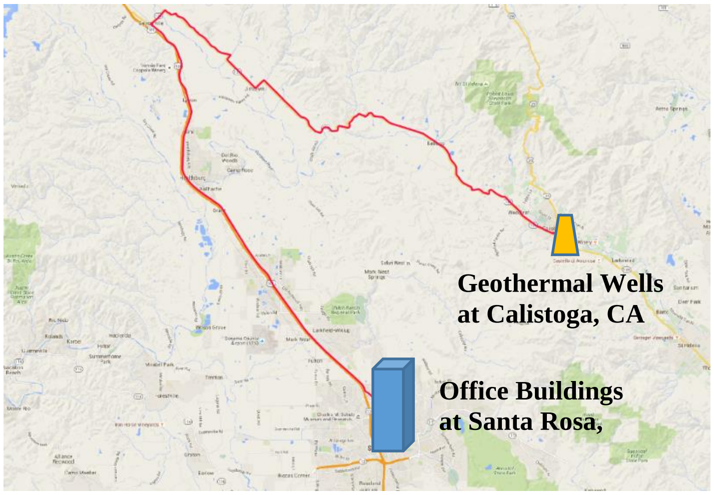

Figure 5 Truck route connecting the geothermal resources at Calistoga, CA and the office building at Santa Rosa, CA

The 138°C geothermal fluid produced from the geothermal wells in Calistoga has sufficiently high temperature to run TSGA, CTSGA, or ADS system. Assuming a 15°C temperature drop in the geothermal fluid when heat is extracted to run the geothermal cooling system, the maximum cooling capacity that the 4,447 L/min geothermal fluid can support is around 2975 kW. In this case study the heat source temperature used for modelling the geothermal cooling system is set at 115°C to account for the temperature difference between at the well head and at the bottom hole. The geothermal fluid can be utilized in a cascaded approach—it can first be used to regenerate the energy storage material, and then the cooler geothermal fluid (but still around 100°C) can be used for hot spring, spa, or providing heating for industrial processes or agricultural productions. In this case, the cost of utilizing the geothermal fluid for space cooling may be shared with the other usages of the same geothermal resource, or probably even be waived. The cost of using the geothermal fluid is included as a variable this case study and will be discussed later.

The target thermal demand is the space cooling load of an office building in Santa Rosa. The DOE commercial reference building model (Deru et al. 2011) is used to estimate the annual cooling load and the peak cooling demand of an office building in Santa Rosa. To make full use of the geothermal resources, the target building has a peak cooling load of 2975 kW, and the corresponding total annual cooling load is calculated using the reference building model as 2,284,800 kWh. The baseline cooling system in the target building to be compared with the geothermal cooling technologies is a packaged electric chiller with integral air-cooled condenser. According to California title 24 (California Energy Commission, 2015), the minimum allowed electrical COP is 2.8 for air-cooled chillers with larger than 63 tons (220 kW) cooling capacity. The air-cooled chiller doesn't need a wet cooling tower and a cooling water circulation pump. Therefore, it is commonly used in California given the mild weather and the lack of water. To have a fair comparison, all the investigated geothermal cooling systems use dry coolers as well. The performance difference between cooling tower and dry coolers are accounted for by taking the average dry-bulb temperature instead of wet-bulb temperature, and using different temperature approaches listed in Table 2. According to EIA data (EIA 2016), the average electricity rate in California is $0.18/kWh for commercial customers.

With the geothermal resource and target building defined, the annual primary energy consumption and carbon emission of the baseline and the geothermal cooling systems are calculated with the abovementioned analysis tool. Figure 6 and Figure 7 illustrate the energy and environmental impacts of replacing the conventional electric chiller with the geothermal cooling systems for the target building: all the three geothermal cooling systems can result in more than 45% primary energy savings and more than 20% carbon emission reductions compared with the baseline cooling system. The calculations of source energy and carbon emission accounts for both the electricity savings and fuel consumption for the transportation. The CTSGA system, with the best performance among the three, saves 61% of primary energy and cut the carbon emission by half compared to the baseline.

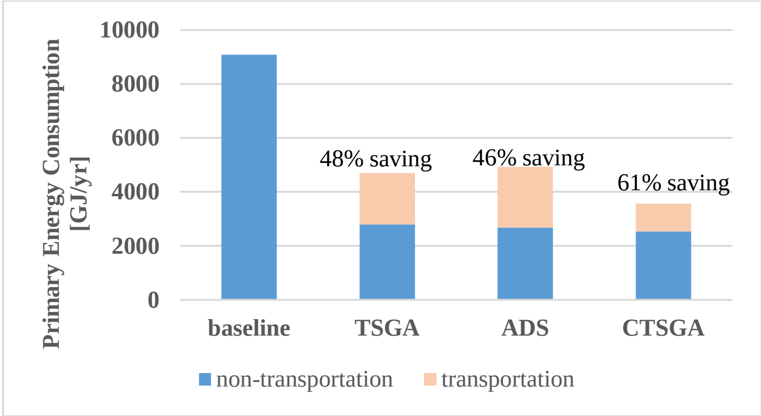

Figure 6 Primary energy consumptions of the geothermal cooling systems and the baseline electric cooling system

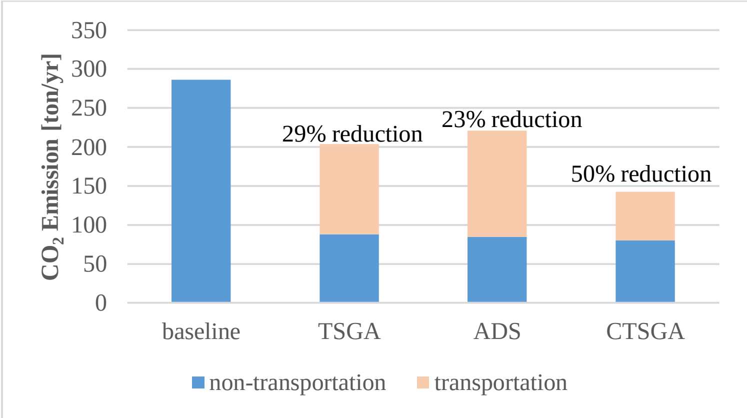

Figure 7 Carbon emissions of the geothermal cooling systems and the baseline electric cooling system

The economics of replacing the electric chiller with the geothermal cooling systems vary due to their different transportation operation cost. Table 3 lists all the initial and operation costs of the baseline as well as alternative cooling systems. Figure 8 illustrates the comparison of annual operation costs between the baseline and alternative cooling systems. As shown in Figure 8 and Table 3, the non-transportation part of annual operation costs (i.e. electricity cost for circulation pumps) of all the geothermal cooling systems are less than 30% of that of the baseline. However, due to the long distance between the geothermal resource and the target building, the transportation operation costs (i.e. to pay driver wages and fuel) are significant. The TSGA system barely break even compared to the baseline, while the ADS system operating under this resource temperature has even lower energy density and thus higher transportation demand. Neither of these two system achieve a payback within the assumed 20-year lifetime. The CTSGA system achieves annual operation cost savings and thus results in a 12.8-year payback.

Table 3 Cost breakdown of the geothermal cooling systems and the baseline electric cooling system

Costs	Baseline Electric Chiller	CTSGA	TSGA	ADS
Initial cost	$566,772	$747,723	$753,079	$769,252
Annual equipment operation cost	$146,880	$41,060	$45,170	$43,352
Transportation initial cost	$0	$491,460	$982,921	$548,225
Annual transportation operation cost	$0	$53,114	$98,335	$115,931
Total initial cost	$566,772	$1,239,183	$1,736,000	$1,317,477
Total annual operation cost	$146,880	$94,174	$143,505	$159,283

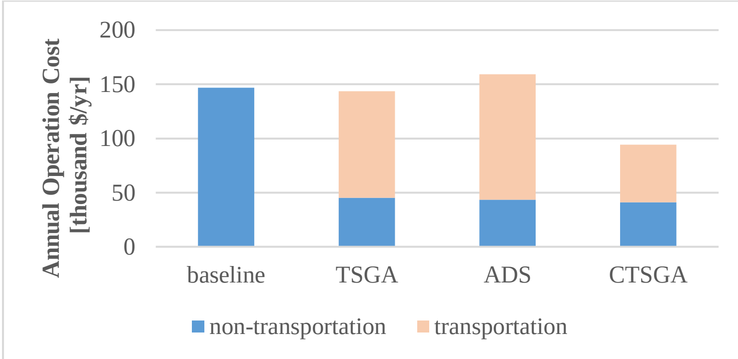

Figure 8 Annual operation cost of the geothermal cooling systems and the baseline electric cooling system

Since the cooling demand of the building determines the amount of needed energy storage media as well as the transportation frequency, a sensitivity study was carried out to investigate the impact of the cooling load as well as distance on the system economics, based on which a more suitable target building could be identified. The cooling load of buildings used in the sensitivity analysis are estimated based on their peak cooling demands assuming the annual total cooling load is proportional to the peak cooling load. For instance, the reference office building in Santa Rosa has a peak cooling load of 2,975 kW and a total annual cooling load of 2,284,800 kWh. Therefore, the annual total cooling load of another office building in the same area can be estimated based on its peak cooling demand compared to the 2975-kW reference. The simple paybacks of applying the CTSGA system in buildings with various peak cooling load and at different distances away from the geothermal resource are calculated with the economic analysis tool and the results are shown in Fig. 9. The X-axis of this figure is the peak cooling load ranging from 350 kW to 2975 kW, which is the maximum cooling capacity that the available geothermal resource can support. The Y-axis is the distance between the geothermal resource and the building, which ranges from 5 to 75 miles (8 – 120 km). The various colors at different area in this figure indicate different simple payback periods. Fig. 9 shows that, for the same distance, the payback declines with the increase of the building peak cooling load. For a distance less than 45 miles (72 km), the shortest payback comes from the largest possible peak cooling load (2975 kW). Once the distance is longer than 45 miles, the shortest payback for each distance is achieved by applying the CTSGA system at buildings with a peak cooling load less than 2975 kW. It is because that an additional tanker-trailer (filled with working fluid) is needed to ensure continuous operation of the CTSGA system at buildings with 2975 kW peak cooling load and more than 45 miles away from the geothermal site, thus adding significantly to investment but with only moderate increase in energy savings.

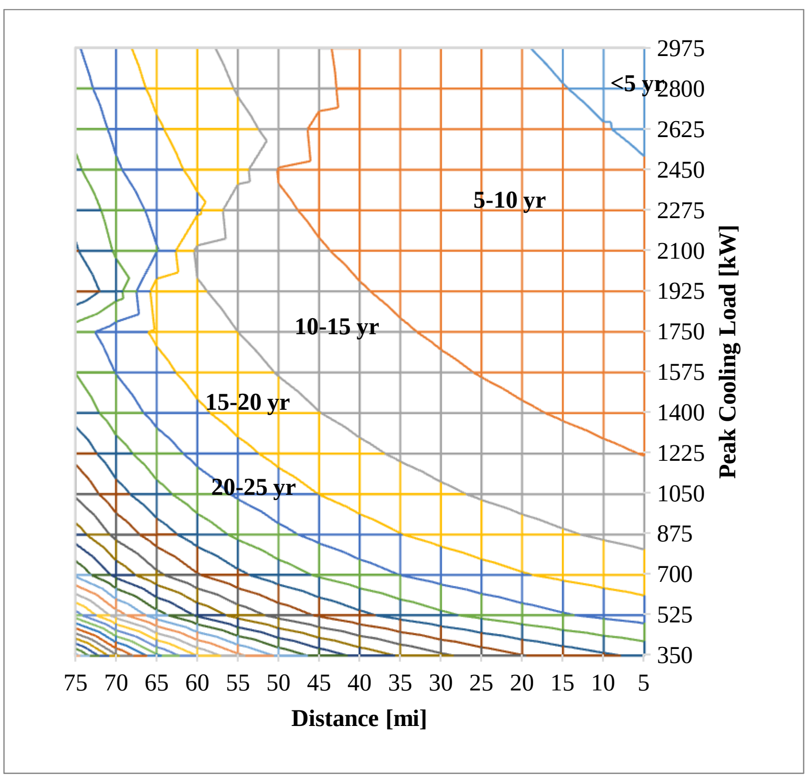

Figure 9 Simple paybacks of CTSGA system serving various peak cooling load and distances from geothermal resource

The shortest paybacks and the corresponding peak cooling load at distances ranging from 5 to 75 miles are listed in Table 4. With the current electricity rate, to make the CTSGA system economically viable, the system should be applied to buildings that are closer to the geothermal resource and have a peak cooling load closer to the distance-specific optimum listed in this table.

Table 4 Distance-specific Optimal Peak Cooling Loads for Applying the CTSGA Systems in California

Distance	**<45 miles**	**45 miles**	**50 miles**	**55 miles**	**60 miles**	**65 miles**	**70 miles**	**75 miles**
Capacity	2975 kW	2625 kW	2450 kW	2275 kW	2100 kW	1925 kW	1750 kW	1750 kW
Payback	4.3-6.8 years	8.3 years	9.8 years	11.6 years	14.1 years	17.8 years	22.6 years	27.2 years

A series of parametric study has been carried out to investigate the impact of distance and electricity rate on the payback of the CTSGA system. Fig. 10 shows the simple payback of CTSGA system resulting from various combinations of distance and electricity rate. The distance ranges from 5 to 75 miles and the electricity rate ranges from 0.15 to 0.215 $/kWh (about ±20% from $0.18/kWh). The different colors at various areas in Fig. 10 indicate different simple payback periods. Generally, with a shorter distance and a higher electricity rate the payback is lower. The increase of electricity price helps to stretch the economically feasible distance for applying the CTSGA system: the longest distance for a payback less than 10 years is 50 miles (80 km) with $0.18/kWh electric rate, and it is extended to over 60 miles (96 km) when the electricity rate increases by 20% to $0.215/kWh. An increase in the electricity rate could result in shorter payback period for a given distance. For example, while applying a 2,975 kW CTSGA system to a building 30 miles (48 km) away from the geothermal site takes more than 5 years to achieve a payback with current electricity rate, it takes less than 5 years when the rate increases above $0.2/kWh.

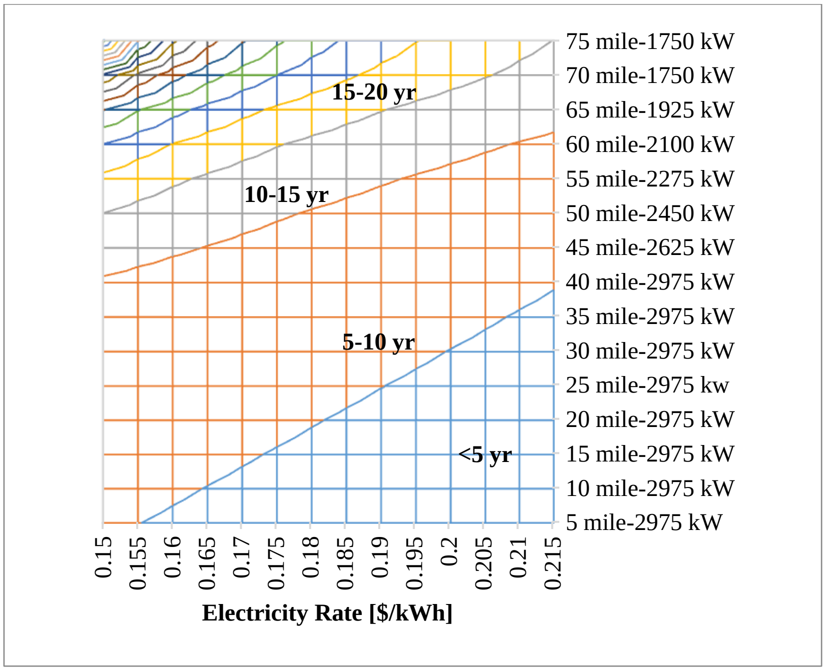

Figure 10 Simple paybacks of CTSGA system with various transportation distances and various electricity rates

For the original 47-mile case between Calistoga and Santa Rosa, 2,450 kW is the optimum capacity and the corresponding payback is 9.4 years. The maximum allowed annual cost for utilizing the existing geothermal fluid is $32,800 to achieve life-time cost saving.

5. TECHNICAL CHALLENGES OF CTSGA SYSTEM IMPLEMENTATION

Similar to the TSGA system, the CTSGA system uses a two-step absorption cycle design. Therefore, to implement the CTSGA system, the inherent technical challenges for the two-step absorption process need to be properly addressed. Unlike in a conventional packaged absorption chiller where a small amount of solution is re-circulated in a stationary closed-loop system, the two-step absorption design requires a large amount of solution to store and transport energy, while also uses the solution to generate cooling through the absorption process. Such design brings several technical challenges including (1) retaining good quality of the storage material (fluid/crystal) during transportation and storage; (2) insulating the storage material at all times from infiltration of moisture and other contamination such as oxygen; and (3) maintaining sufficient vacuum levels in components at both sites during operation to ensure proper operation. Moreover, while crystallization is introduced in the CTSGA system to boost the energy density of transported material, it is only designed to occur inside the storage tank: any crystallization outside the tank—inside components or pipes—would force the operation to shut down. Therefore, special component design and proper control of crystallization is required in addition to the abovementioned challenges. Although recently there have been preliminary designs and experimental researches on prototypes of using salt crystals for energy storage (N'Tsoukpoe et al. 2012, 2014), further study is need to ensure reliable and efficient operation of the CTSGA system.

6. CONCLUSION

Low-temperature geothermal resources are abundant in the United States, including hydrothermal resources from underground aquafers and coproduced water from oil and gas production wells. However, the temperatures of these resources are too low to effectively generate electricity, while on the other hand, it is not economically feasible to transport this low-temperature thermal energy across the typically long distance between geothermal sources and potential end uses via the current "direct use" system (i.e. using hot water with energy density of about 145 kJ/kg). As the result of this distance barrier, the potential low-temperature geothermal resources across U.S. remain largely undeveloped. In previous studies, the two-step geothermal absorption (TSGA) system was developed to break the distance barrier. With TSGA system, strong solution of the liquid desiccant was used to provide space cooling in buildings, and the resulted weak solution was regenerated at the geothermal site. It can provide more than double of the energy density (405 kJ/kg) and provide more valuable cooling instead of heating to the end use.

In this study, an enhanced design of the TSGA system referred to as crystal-enhanced TSGA (CTSGA) system, was developed and analyzed. By using salt hydrate crystals (e.g. LiBr-H_2O) as the energy storage material, CTSGA achieved the highest energy density (915 kJ/kg) among all investigated potential technologies. Thermodynamic models of CTSGA system was developed and implemented into an analysis tool that can calculate the energy consumption and efficiency of the system under user-specified operating conditions. Based on the predicted performance, the investment and operation costs of the CTSGA system can then be estimated. With all the costs calculated, the economics of the entire system can be evaluated and compared with the conventional electric cooling system. The thermodynamic performance correlations of several other technologies including TSGA and ADS (solid desiccant adsorption) were also programmed into the analysis tool.

A case study is carried out with the analysis tool to compare the performance of the CTSGA, TSGA, and ADS systems for providing seasonal space cooling using an existing hydrothermal resource near Calistoga, CA, which has 4,447 L/min flow rate and bottom hole temperature (BHT) of 138°C. A sensitivity analysis was conducted based on the capacity of the available geothermal resource over a range of varying operation conditions including distances, electricity rates, and cooling load profile (i.e., peak and total cooling load) of target buildings. The results demonstrated the influences of these parameters on the economic payback: generally, the paybacks of the systems would be shorter with closer distance, higher electricity rate, lower peak load, and larger total cooling demand. Of all three systems, CTSGA system managed to achieve economic payback on buildings with larger cooling loads. For an office building with 2,450 kW peak cooling load 47 miles (75 km) away from the geothermal source, the CTSGA system yielded a less than 10-year payback.

To make the CTSGA system economically competitive and reliable over a long term, further development is needed to address several technical challenges, which include (1) retaining the quality of solution and crystals; (2) insulating the storage material from contamination; (3) maintaining sufficient vacuum in components during operation; and (4) confining the crystallization in the storage tank only to avoid damaging other components.

NOMENCLATURE

ADS	adsorption system
baseline	electric chiller system
C	concentration
CF	capacity correction factor
COP	coefficient of performance
crystalRatio	the mass fraction of crystals in the crystal-solution mixture
CTSGA	crystal enhanced two-step geothermal absorption
DU	direct-use
ED	energy density [kJ/kg]
ElePrice	local electricity price [$/kWh]
h_{fg}	enthalpy of evaporation of water [kJ/kg]
IC	initial cost
OPC	annual operating cost
peakLoad	the maximum design cooling load [kW]
PowerRatio	the approximated power consumption ratio based on the power consumption of the baseline electric chiller
totalLoad	the overall cooling load of the entire cooling season [kWh_{clg}]
TSGA	two-step geothermal absorption

Subscripts

a	average
ABS	absorption system
CT	cooling tower/dry cooler
d	design condition
eq	equivalent
ss	strong solution

ws weak solution

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REFERENCES

AHRI "560–Absorption Water Chilling and Water Heating Packages–Air-Conditioning and Refrigeration Institute. 2000. Standard" Arlington, Va.

California Energy Commission.: Building energy efficiency standards for residential and nonresidential buildings. *California Code of Regulations*, Title, 24. (2015). Available at http://www.energy.ca.gov/2015publications/CEC-400-2015-037/CEC-400-2015-037-CMF.pdf. (Assessed on 1/14/2017)

Deru, Michael, et al. "US Department of Energy commercial reference building models of the national building stock." (2011): 1.

EIA. (2016). State Average of commercial electricity price (Accessible from http://www.eia.gov/electricity/data.cfm#sales)

GHC (Geo-Heat Center). 2005. Geothermal Direct-Use Case Studies. Website: http://geoheat.oit.edu/casestudies.htm . Accessed: June, 23, 2008.

Herold, Keith E., Reinhard Radermacher, and Sanford A. Klein. Absorption chillers and heat pumps. CRC press, 2016.

Hettiarachchi, H. M., Golubovic, M., Worek, W. M., & Ikegami, Y. Optimum design criteria for an organic Rankine cycle using low-temperature geothermal heat sources. *Energy*, 32(9), (2007), 1698-1706.

Holdmann G.: Geothermal Powered Absorption Chiller. *Proceedings*, 2005 Rural Energy Conference, Valdez, Alaska, September 20, 2005.

Kreuter H.: Geothermal Applications: Geothermal Cooling. *Proceedings*, Renewable Energy Training Program, 10 July 2012, ESMAP – IFC, Washington, DC.

Lech, P.: A New Geothermal Cooling – Heating System for Buildings. Master's Thesis. University of Iceland and the University of Akureyri, (2009).

Liu, X. et al.: A Technical and Economic Analysis of an Innovative Two-step Absorption System for Utilizing Low-temperature Geothermal Resources to Condition Commercial Buildings, Oak Ridge National Laboratory, ORNL/TM-2015/655, (2015)

Liu, X., Yang, Z., Gluesenkamp, K. R., & Momen, A. M. A Technical and Economic Analysis of an Innovative Two-Step Absorption System for Utilizing Low-Temperature Geothermal Resources to Condition Commercial Buildings. *Proceedings*, 41th Workshop on Geothermal Reservoir Engineering, Stanford University. 2016.

Luo et al.: An Absorption Refrigeration System Used for Exploiting Mid-Low Temperature Geothermal Resource. Proceedings, World Geothermal Congress 2010, Bali, Indonesia, 25–29 April 2010.

Mossman, Melville. 2010. RSMeans Mechanical Cost Data 2011, R.S. Means Company, Kingston, MA.

Mullane, Michelle, M. Gleason, K. McCabe, M. Mooney, T. Reber, K. R. Young. 2016. Database of Low-Temperature Hydrothermal Resource. Available at: https://gdr.openei.org/submissions/842 (Assessed on 11/11/2016)

N'Tsoukpoe, Kokouvi Edem, Nolwenn Le Pierrès, and Lingai Luo. "Experimentation of a LiBr-H2O absorption process for long term solar thermal storage." *Energy Procedia* 30 (2012): 331-341.

N'Tsoukpoe, Kokouvi Edem, et al. "Thermodynamic study of a LiBr–H 2 O absorption process for solar heat storage with crystallisation of the solution." *Solar Energy* 104 (2014): 2-15.

Saleh, B., Koglbauer, G., Wendland, M., & Fischer, J. Working fluids for low-temperature organic Rankine cycles. *Energy*, 32(7), (2007), 1210-1221.

U.S. Department of Energy (USDOE). "Direct Use of Geothermal Energy." (2015). Available at: https://energy.gov/eere/geothermal/direct-use-geothermal-workshop-summary. (Assessed on 1/30/2017)

Wang et al.: Application of Geothermal Absorption Air-conditioning System: a Case Study. Applied Thermal Engineering, 50, 71–80, (2013)

Williams C. 2013. National Geothermal Resources Assessment and Classification. Presentation for Geothermal Technologies Program 2013 Peer Review. April 24, 2013. Available at http://energy.gov/sites/prod/files/2014/02/f7/gs_resource_assessment_peer2013.pdf. (Assessed on 1/30/2017)

Yang, Zhiyao, et al. Transported Low Temperature Geothermal Energy for Thermal End Uses—Final Report. No. ORNL/TM-2016/658. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States). Building Technologies Research and Integration Center (BTRIC), 2016.