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A Preliminary Study on Innovative Absorption Systems that Utilize Low-Temperature Geothermal Energy for Air-Conditioning Buildings

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ABSTRACT

Air conditioning (A/C) systems driven by renewable energy have been studied extensively during the past decade as promising alternatives to conventional electricity-driven vapor compression A/C to alleviate stress on the grid as well as reduce CO_2 emissions. Among the possible renewable energy sources to drive A/C systems, low-temperature geothermal heat (<150°C/300°F) is currently underutilized despite its abundance in the United States and the advantage of steady output. A major barrier to wider utilization is the typically long distances between geothermal sources and potential end uses. In order to overcome this barrier, an innovative two-step geothermal absorption (TSGA) system was studied. With this system, low-temperature geothermal energy is stored and transported at ambient temperature with an energy density of 349 kJ of cooling energy per kg of shipped $LiBr/H_2O$ solution, which is about five times higher than directly transporting geothermal fluid itself for space heating. Key design parameters of a 900 ton TSGA chiller have been determined through computer simulations using SorpSim software. A case study for applying the TSGA system at a large office building in Houston, TX indicates that, for a 10-mile distance from the geothermal site to the building, the simple payback of the TSGA system is 11 years compared with a conventional electric-driven chiller. To further improve the density of the transported energy, thereby reducing transportation cost and improving payback, a new system using three-phase-sorption technology is proposed. In this system, crystallized salt solution is used to boost the transported energy density. A preliminary study of this new system shows that the increased energy density has potential to shorten the payback of the TSGA system by 50%.

1. INTRODUCTION

In the US 24% of primary energy is used for thermal applications, including space heating, space cooling, and water heating, in the form of heat below 120°C (248°F), mostly by consuming electricity and burning natural gas (USDOE 2009). While conventional geothermal energy applications have focused on power generation using high-temperature hydrothermal resources, there are abundant low-temperature (<150°C/300°F) geothermal resources across the country with the potential to satisfy the thermal demand and displace electricity and natural gas consumption. It is estimated that, of the total potential of 42,600 MW_{th} useful thermal energy from low-temperature geothermal resources (Williams 2013), only 624 MW_{th}—less than 2%—has been utilized (GHC 2005). In addition, 25 billion barrels/year of geothermal fluid (mostly water) at 80°C to 150°C (176°F to 302°F) are co-produced at oil and gas wells in the U.S. (USDOE, 2015). The heat contained in coproduced geothermal fluid is typically wasted as the fluid is either disposed of on the surface or reinjected back underground without extracting the heat.

Existing low-temperature geothermal applications directly use hot water from low-temperature geothermal reservoirs to provide heat for industrial processes, agriculture and aquaculture, or to keep buildings warm, thus they are usually called “direct-use”. Low-temperature geothermal energy can also be used to provide space cooling and refrigeration through absorption cooling technologies. In 1980, a 150-ton single-stage absorption chiller was installed at the Oregon Institute of Technology to supply a base cooling load to five campus buildings with a total floor area of 280,000 ft^2. The absorption chiller used $LiBr/H_2O$ as working fluid pair and was powered with geothermal fluid at 88.9°C (192ºF) (Lienau 1996). Another geothermal-powered absorption chiller in Alaska was used to produce -29.4°C (-21ºF) brine to provide refrigeration for an ice museum (Holdmann 2005). Lech (2009) studied the technical and economic feasibility of a new geothermal cooling/heating system for buildings. Based on computer simulations, this study confirms that the geothermal cooling/heating system “can be operated at a generator inlet temperature of 86°C (187°F) and cooling water temperature of 20 to 28°C (68 to 83°F). The coefficient of performance (COP) was 0.73 (for 20°C/68°F cooling water) and 0.68 (for 28°C/83°F cooling water)." The European Geothermal Energy Council (EGEC 2005) projected good future development in the use of geothermal energy for cooling purposes, especially in the warmer regions of Europe. However, the report stated that "like low-temperature geothermal power production, geothermal absorption cooling is restricted to areas with geothermal resources of about 100°C (212°F) and above." Due to the high cost of developing pipelines over long distances, utilization of geothermal energy for space conditioning currently is limited to places where the geothermal resources are available directly at the demand site. If the energy in low-temperature geothermal resources can be stored and transported to demand sites at a cost lower than that of pipelines, utilization can significantly increase.

In this study, a two-step geothermal absorption (TSGA) system is designed to transport energy from a site of low-temperature geothermal resources to a building. In the TSGA system, components of a conventional single-effect absorption system are separated to be installed at the building and the geothermal site. Instead of transporting hot water as in the conventional direct use systems, the TSGA system stores and transports energy in the form of salt solution used in absorption systems with much higher energy density. It significantly expands the economic distance for low-temperature geothermal energy to be transported and utilized for space conditioning. Furthermore, the concept of using crystallized salt and solution as the energy storage media based on the TSGA system is proposed to enhance the transported energy density and improve the system's economic performance. The following sections introduce the design of the TSGA system and assess its economic viability with a preliminary case study compared with a conventional electric-driven vapor compression chiller. Then the crystal-enhanced TSGA system is introduced with its cost-effectiveness compared with the original TSGA system.

2. TWO-STEP GEOTHERMAL ABSORPTION (TSGA) SYSTEM

The proposed TSGA system is a split single-effect absorption cycle. As illustrated in Figure 1, the TSGA system decouples the chilled water production and desiccant regeneration of the conventional closed-loop absorption cycle into a two-step process. The first step is regeneration and it takes place at the geothermal resource. A weak solution of water/LiBr is heated using geothermal heat to drive off moisture. The resulting concentrated solution is transported to commercial or industrial buildings by tanker truck, train or ship. The second step is to produce chilled water at the building site, where liquid water is evaporated to cool the chilled water and the water vapor is absorbed by the strong solution. Then the diluted weak solution is transported back to the geothermal site for regeneration. As shown in Figure 1, equipment at the geothermal site includes an assembly of desorber and condenser, a dry cooler, and a cooling tower circulation pump. Equipment at building site includes an assembly of absorber and evaporator, a wet cooling tower and an associated circulation pump, holding tanks, and a solution pump.

To evaluate the economic viability of the proposed TSGA cooling system, major components of the system are sized for a targeted building and the available low-temperature geothermal resource. The design parameters for each major component are determined based on simulation results using SorpSim developed by Oak Ridge National Laboratory. LiBr/H_2O was selected as the working fluid pair since it operates with larger solution concentration difference under typical operation temperatures, and therefore yields higher energy density than other working fluid pairs (e.g., LiCl/H_2O and $CaCl_2$/H_2O). The typical operating temperatures of the TSGA system are listed in Table 1:

Table 1: Typical operating temperatures of the TSGA system

Chilled water supply temperature from evaporator	Hot water supply temperature to desorber	Cooling water supply temperature to condenser	Cooling water supply temperature to absorber
7.2°C (45°F)	100°C (212°F)	34.4°C (94°F)	29.4°C (85°F)

The SorpSim simulation predicted thermodynamic process of the TSGA cooling cycle is overlaid on the Dühring chart of the LiBr/H_2O solution in Fig. 2. The line from state point #11 to #10 indicates the desorbing process, where the water vapor pressure in the absorber is maintained at 7.8 kPa and the LiBr/H_2O solution is concentrated from 53% to 62% by the heat from the geothermal resource. The line from state point #20 to #19 indicates the absorbing process, where the water vapor pressure in the absorber is maintained at 0.83 kPa and the LiBr/H_2O solution is diluted from 62% to 53% by absorbing the water vapor.

Based on the simulation results, the thermal coefficient of performance COP_{th} of the TSGA cooling system is 0.67, and each kilogram of the transported solution can deliver 349 kJ cooling energy (i.e., with an energy density of 349 $kJ_{cooling}$/kg or 150 Btu/lb).

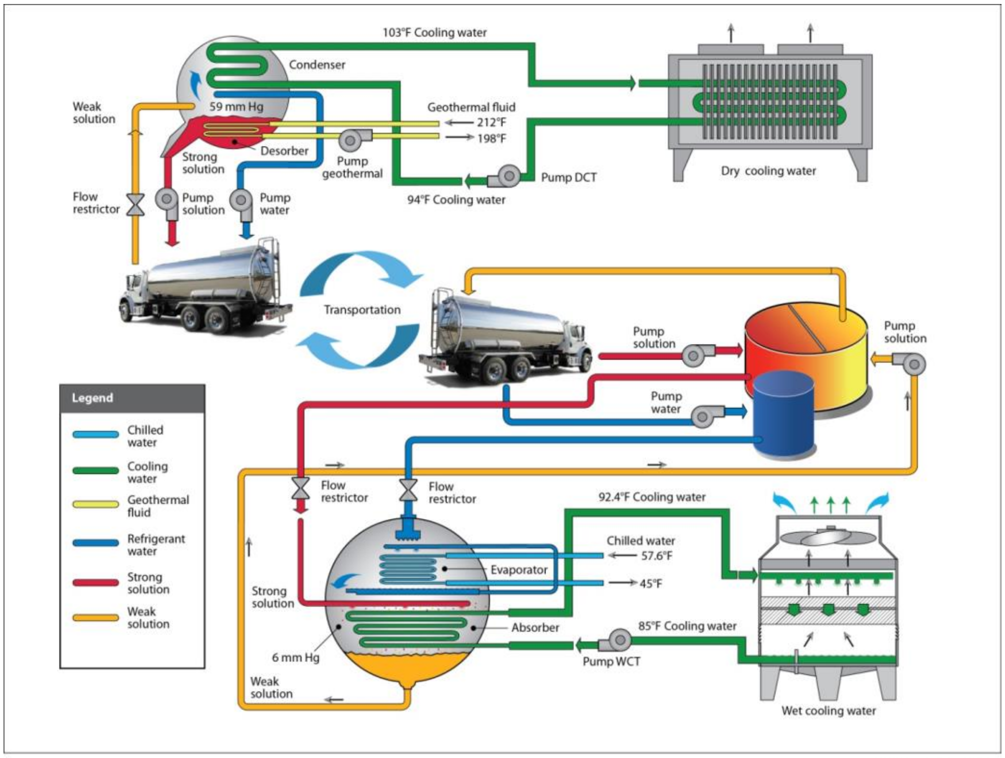

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Figure 1: Schematic of the two-step solution looping geothermal absorption cooling

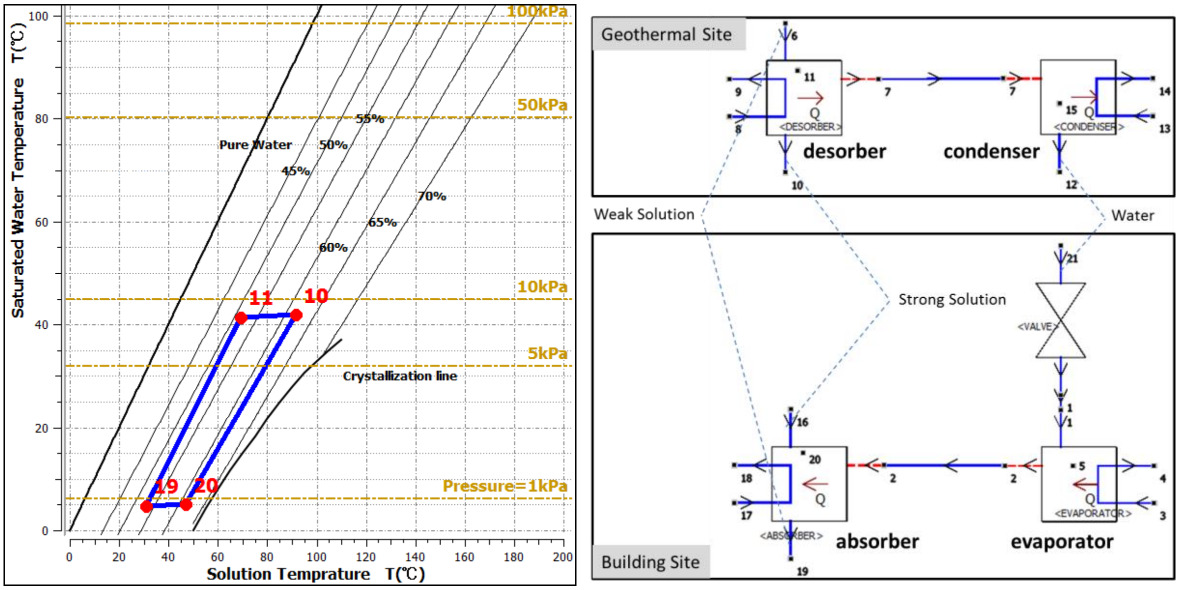

Figure 2: SorpSim model (right) and state points of LiBr/H_2O TSGA cooling cycle shown on Dühring chart (left)

3. CASE STUDY

3.1 Methodology

A case study is conducted to compare the economics of applying the TSGA system to provide space cooling in a large office building in Houston, Texas against a baseline, which is to provide space cooling with a conventional water-cooled electric-driven vapor compression chiller. With the cost difference in the initial and operating costs of the two systems, the cost-effectiveness of the TSGA system is evaluated with two performance metrics – simple payback and levelized cost of saved electricity (LCoSE). The simple payback period is the time period that the capital cost premium is recovered with the cumulative operating cost savings achieved by the TSGA system. The LCoSE indicates the cost for saving each kWh of electric energy by replacing the baseline system with the TSGA system over a given time period.

A computer model of a large office building adopted from the DOE Commercial Reference Building Models is used in this case study. The modeled building has a total floor space of 498,588 ft^2 (46,320 m^2), and it is designed in accordance with the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2004 (ASHRAE 2004). Details of this building are described in a technical report (Deru et al. 2011). The baseline cooling system for the large office building includes two water-cooled electric-driven centrifugal vapor compression (VC) chillers with a total capacity of 3063 kW$_{clg}$ (871 ton), a cooling tower with a circulating pump, and other HVAC components inside the building. The nominal efficiency (electrical coefficient of performance or COP$_{el}$) of the VC chillers is 5.5.

3.2 Economic Analysis

The size and initial cost of major equipment used in the TSGA and the baseline system are estimated using RSMeans Mechanical Cost Data (Reed Construction 2010), which includes costs of material, labor, overhead, equipment purchase, equipment installation, and profit. The operating costs of the systems are estimated based on the building cooling load and empirical correlation of parasitic energy consumption. Detailed information of the cost calculation is provided in a technical report by Liu et al. (2015). Transportation cost is determined by the distance and frequency of deliveries. In the 10-mile distance scenario, the carrier cost is \$52.2/hour, which is calculated based on the national average carrier cost (Fender et al. 2013) and the travel distance in each hour according to a truck operation schedule (Liu et al. 2015). Table 2 compares the energy consumptions and equivalent CO$_2$ emissions between the TSGA system and the baseline system. The primary energy consumptions and equivalent CO$_2$ emissions (the equivalent carbon dioxide based on the GWP) are calculated based on the electricity and diesel fuel consumptions using corresponding conversion factors obtained from Deru and Torcellini (2007).

Table 2: Annual electricity, primary energy savings and CO$_2$e reduction of TSGA system

	Electricity consumption [kWh$_e$]	Diesel fuel consumption [gal]	Primary energy consumption [kWh$_{pr}$]	CO$_{2e}$ [ton]
Baseline system	2,504,567	-	8,427,868	1,897
TSGA system	704,631	10,603	2,870,202	553
Saving percentages	72%	-	66%	71%

Table 3: Cost comparison between the baseline system and the TSGA system

Cost type	Item	Baseline system	TSGA system
Initial cost (\$)	Chiller	420,578	660,131
	Pumps	11,161	37,436
	Cooling tower	103,861	212,737
	Solution	-	289,845
	Trailer tanks	-	105,000
	Sum	*535,601*	*1,305,150*
Operating cost (\$)	Electricity	255,519	71,887
	Transportation	-	111,669
	Sum	*255,519*	*183,556*

[a] assuming electricity price is \$0.102/kWh

Compared to the baseline system, the TSGA system consumes significantly less electricity while consuming some diesel fuel for truck transportation. The average tanker truck fuel economy is reported as 7.9 mpg by Franzese and Oscar (2011), and it is conservatively set as 5 mpg in this study considering the lower average speed of trucks for the TSGA application. As shown in Table 3, the TSGA system is able to reduce 72% electricity and 66% of primary energy consumption, while also reducing the equivalent CO_2 emission by 71%.

Table 3 lists the initial costs and annual operating costs of the baseline and TSGA system. Based on the initial costs and the annual operating costs of the two systems, the simple payback of the TSGA system for the 10-mile distance scenario is 10.7 years.

A breakdown of LCoSE of the TSGA system is given by costs and percentages in Table 4. It appears that the contributions of the initial costs (for purchasing the absorption chiller, circulation pumps, cooling towers, working fluid, and the trailer tanks) to LCoSE are low—about 22%. The operating costs (i.e., the transportation and electricity costs) are more significant contributors to LCoSE. Reducing these costs, especially the transportation cost, is thus crucial to reduce LCoSE.

Table 4: Levelized cost breakdown of the TSGA system

	Item	Cost ($)	LCoSE ($/kWh)	Percentage
Capital cost	Equipment	374,703	0.0140	11%
	Solution	289,845	0.0109	8%
	Trailer tanks	105,000	0.0039	3%
Operating cost	Electricity	71,887	0.0399	30%
	Transportation	111,669	0.0620	48%
Total levelized cost			0.1307	100%

4. CRYSTAL-ENHANCED TSGA SYSTEM

In order to reduce the transportation cost of a TSGA system for a given distance and means of transportation, the energy density of the transported media needs to be increased. Through a comprehensive literature review, a few potential technologies are identified for transporting and utilizing low-temperature geothermal energy for thermal applications. Energy densities of these technologies (i.e., the amount of heating/cooling energy provided by each unit mass of the transported media) are compared in Table 5, which are obtained from or calculated based on information presented in available literature. In addition, advantages and limitations of each of these technologies are also listed in the table. Fig. 3 is a graphical presentation of the energy densities of these technologies.

The comparison indicates that the "three-phase sorption cycle" described by Yu et al (2014) has the greatest potential to increase the energy density of TSGA. The three-phase sorption cycle utilizes the crystallization process of the aqueous solution of salt, at which the vapor, liquid solution, and solid crystal coexist, to store more energy than the conventional two-phase liquid/vapor absorption cycle. During the charging (desorbing) process, the solution is continuously heated and concentrated to its saturation point. As the water vapor is released from the solution, solid crystal is formed from the solution. If the charging temperature is higher than the dehydration temperature of the crystals, the crystalline hydrate will lose its water molecules and become anhydrous salt (dehydrated salt). A desorbing process including all the liquid/vapor absorption, solid/liquid/vapor crystallization and solid/vapor dehydration reaction has the largest concentration difference between the inlet and outlet of the desorber hence has the greatest energy storage capacity. Several generations of prototypes for the "three-phase sorption cycle" are described by Bales et al. 2005, Boilin 2004, and Olsson & Bolin, 2014.

Instead of being a main challenge in the operation of conventional absorption chillers, the crystallization process can be employed as an enhancement measure in the TSGA system to increase the energy density of the transported media. As shown in Figure 4, instead of the "once-through" approach in the previous TGSA system, the weak solution is re-strengthened locally at the building by dissolving crystals before being regenerated at the remote geothermal site. The “local re-strengthening” process is depicted in the rectangular box (bordered with dashed blue lines) in Figure 4. The “local re-strengthening” is processed in a holding tank, which has four compartments.

Table 5: A comparison of potential technologies for utilizing low-temperature geothermal energy

Medium	**Application technology**	**Energy density**		**Advantages**	**Limitations**
		Heating [kJ_{th}/kg]	**Cooling [kJ_{clg}/kg]**		
Water	Direct use	146	24	Simplest technology	Only feasible for short distance
Solid desiccant	Adsorption	151[1]	-	Improved energy density than direct use	High T_{charge}, slow charge/discharge rate, varying outputs
Salt solution	Absorption with $LiBr/H_2O$ TSGA	-	360 (Liu et al. 2016)	High energy density	Challenges to maintain vacuum at components, need to prevent crystallization
	Dehumidification with evaporative cooling (DEVap)	-	516 (Kozubal et al. 2011)	Low initial cost, high energy density	Performance is dependent on climate
Salt crystal	Three phase absorption	857[2]	1071[3]	High energy density at low T_{charge}	New tech. and need to be customized for geothermal applications
Phase changing material (PCM)	PCM chemicals	265 (Abhat 1983)	165 (Demirbas 2006)	Improved energy density than direct use	Lower energy density, long charge/discharge time
	Ice[4]	-	355[5]	Mature tech. with lower initial cost	Need heavy insulation to transport ice in summer, varying charge/discharge rate

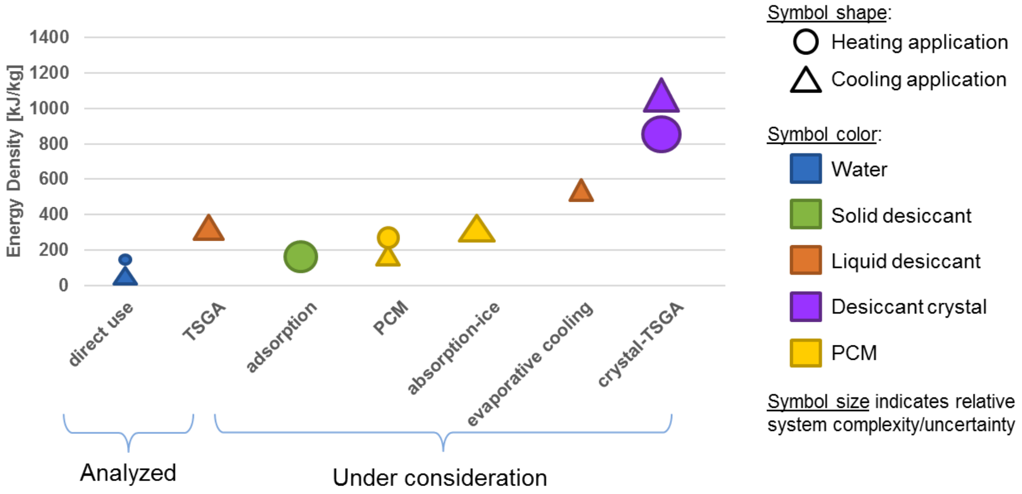

Figure 3: A comparison of energy densities of potential transportable technologies

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[1] Zeolite 13X operates with T_{des} = 100°C, T_{ads}=50°C, T_{evap}=5°C, T_{cond}=10°C. A few literatures (Jänchen et al. 2004, Storch et al. 2006, Krönauer et al. 2015) reported higher energy densities (536kJ/kg – 1188kJ/kg) when high temperature heat source (>180°C) is used to drive the adsorption system.

[2] $LiCl/H_2O$ operates with T_{des} = 90°C, T_{ads}=45°C, T_{cond} = 10°C, T_{evap} = 10°C.

[3] $LiCl/H_2O$ operates with T_{des} = 90°C, T_{ads}=30°C, T_{cond} = 30°C, T_{evap} = 5°C.

[4] produced with packaged NH_3/H_2O absorption chiller

[5] Melting 0°C ice to 5°C water.

Referring to Figure 4, at the beginning, the two compartments on the top are filled with the mixture of the saturated solution and crystals, and the compartment in the left-bottom is full of strong solution. During cooling operation, the strong solution absorbs water vapor and becomes weak, then returns to the holding tank through the compartment at the right-bottom. The weak solution travels to the top two compartments and is re-strengthened by dissolving the crystals there. The concentration of the strong solution is maintained until all the crystals in the holding tank are dissolved. Then, the weak solution is pumped out of the holding tank to a tanker truck and transported to the geothermal site. The weak solution is regenerated there to form crystals. Given the technical challenges to remove the dehydrated salt from the desorber, the crystals are not further dehydrated to the solid form. A mixture of saturated solution and crystals is then transported back to the holding tank at the building site. A significant technical challenge of the "local re-strengthening" process is to dissolve the crystals in time and prevent them from going into the absorber. A special system to mix the crystals with the weak solution and a solid/liquid separation system need to be used in the holding tank to effectively re-strengthen the weak solution.

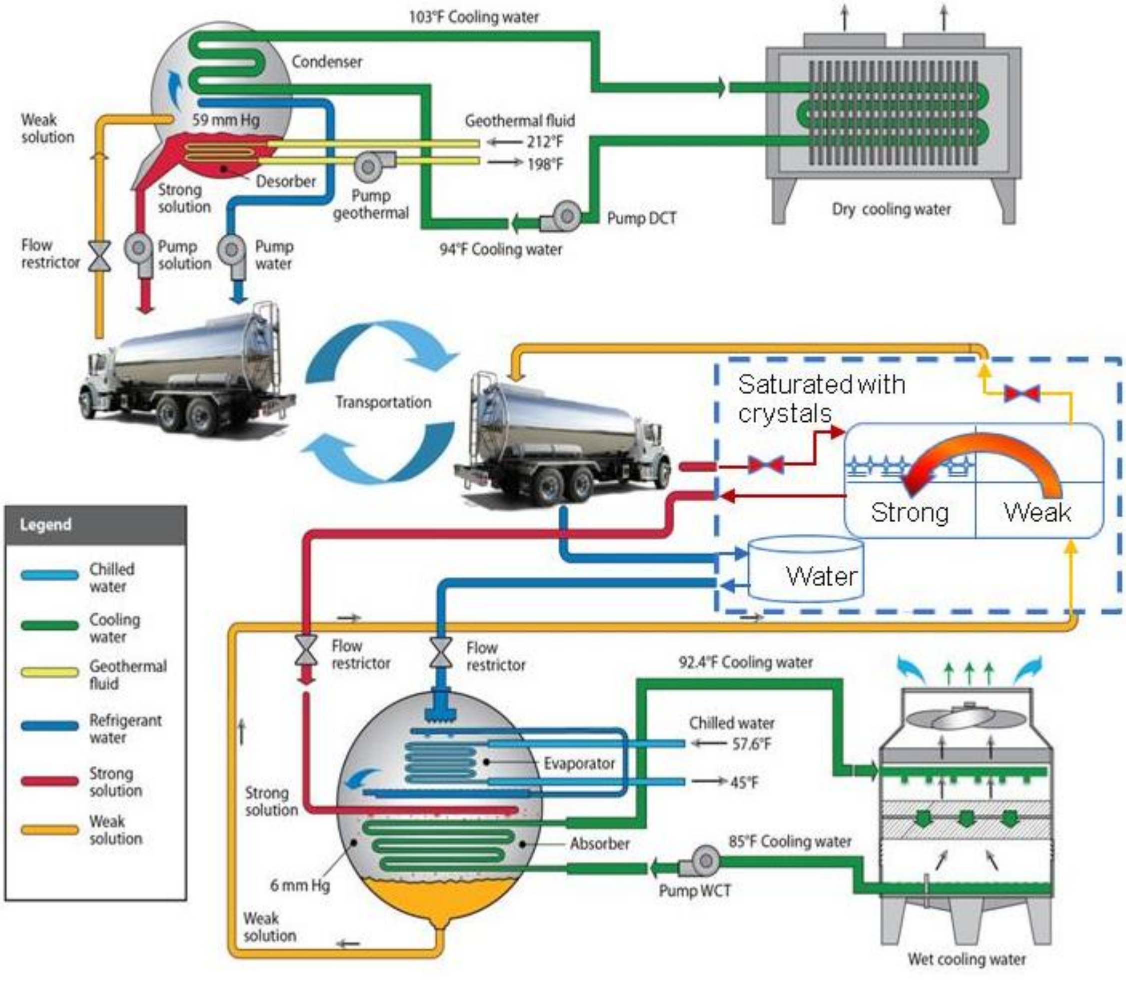

Figure 4: A schematic chart showing a crystal-enhanced TSGA system

Since LiCl/H_2O is easier to be crystallized than LiBr/H_2O, it is proposed for the crystal-enhanced TSGA system. Fig. 5 illustrates the cooling cycle of the crystal-enhanced TSGA on the Dühring chart of the LiCl/H_2O solution. The line from state point #2 to #1 indicates the desorbing process, where the water vapor pressure in the absorber is maintained at 6.3 kPa and the LiCl/H_2O solution is concentrated from 40% to 54% before it crystallizes into monohydrate by heat from a 90°C geothermal resource. The line from state point #4 to #3 indicates the absorbing process, where the water vapor pressure in the absorber is maintained at 0.87 kPa. The LiCl•H_2O crystal dissolves into 45% solution (by mixing with weak solution discharged from the absorber), then the 45% solution absorbs water vapor and is diluted to 40%. This system is able to provide chilled water at 7°C, and the energy density of the transported LiCl•H_2O crystal is 1071 kJ_{clg} per kg of the weak solution (at 40% concentration).

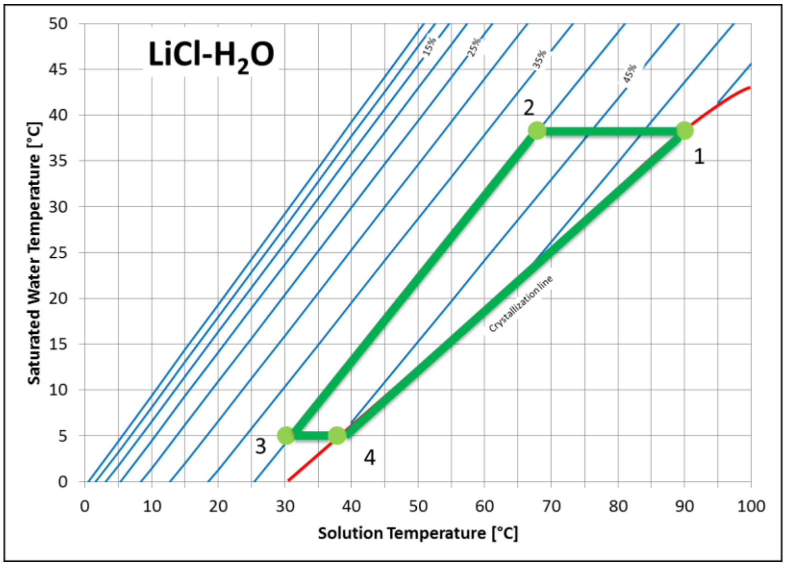

Figure 5: State points of LiCl/H_2O crystal-enhanced TSGA cooling cycle shown on Dühring chart (LiCl aqueous solution property data from Conde 2004)

The energy density of the LiCl•H_2O crystal-enhanced TSGA system is about three times as that of the previously described TSGA system, and therefore requires significantly less transportation cost. Applying the crystal-enhanced TSGA system to the case study described before and assuming the same chiller, pump, cooling tower can operate with LiCl/H_2O solution, the initial cost and electricity cost of the crystal-enhanced TSGA system is the same as the original TSGA system. However, since less transportation is demanded to keep continual operation of the system, the transportation cost is reduced from $111,650/yr down to $41,151/yr. With this 63% cut in operation cost, the crystal-enhanced TSGA system is able to achieve a payback period of 5.2 years.

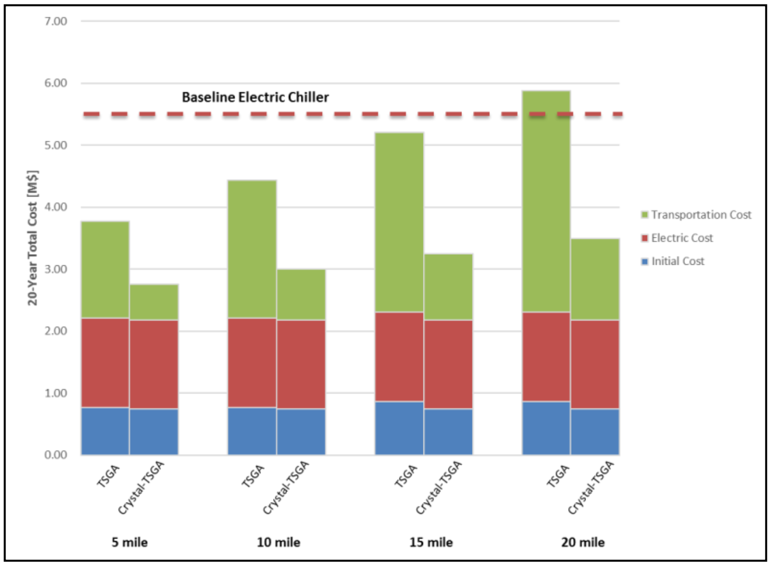

Figure 6: Overall lifetime (20 years) cost of TSGA and crystal-enhanced TSGA systems for distance of 5-20 miles

The total cost of the crystal-enhanced TSGA system (including investment and operation) is compared with the original TSGA system over a 20-year lifespan in Fig. 6. The original TSGA system operating with 5-mile and 10-mile distance yields 32% and 20% of lifetime cost savings compared with the baseline electric chiller, but the increase of its transportation cost offsets the savings with distance longer than 15 miles. In contrast, the crystal-enhanced TSGA system operates with around 1/3 of the original transportation cost. Therefore, it is able to achieve 37% lifetime cost saving even at a 20-mile distance.

5. CONCLUSION

Low-temperature geothermal resources [lower than 150°C (300°F)] are abundant in much of the US at shallow depths and in most of the country at depths of 3 km. In addition, oil and gas production in the South and the Midwest also coproduce water at temperatures higher than 80°C (176°F). However, this abundant energy resource remains underutilized. The typically long distances between geothermal sources and potential end uses and the low density of the transported thermal energy are key barriers preventing its wider use. Most existing operational geothermal end use installations is either at the geothermal resource site or within a 2-mile distance.

To overcome the distance limitation on the utilization of the low-temperature geothermal energy, an innovative two-step geothermal absorption (TSGA) system is proposed in this study. With TSGA, the low-temperature geothermal energy is stored in an aqueous salt and transported at ambient temperature, which with has a significantly higher energy density than the conventional way of transporting hot water. A conceptual design of the TSGA system was developed by splitting the production and regeneration parts of a conventional LiBr/H_2O single-effect absorption chiller system. At the geothermal heat source the TSGA system produces strong solution, which is transported to the building site to generate cooling by absorbing water vapor. Then the diluted solution is transported back to the geothermal site to get regenerated and close the loop.

A case study for applying the TSGA system to a large office building in Houston, Texas was conducted with available data in several related disciplines (e.g., the characteristics of the low-temperature geothermal resources, the demands for space cooling, and available methods for transporting the stored geothermal energy to the demand site). This case study indicates that for a distance of 10 miles from the geothermal site to the building, the simple payback of the investment on the TSGA system is 10.7 years when compared with the conventional minimum code-compliant electric-driven vapor compression chiller.

A crystal-enhanced TSGA system is proposed to reduce the transportation cost and the system payback. Instead of LiBr/H_2O solution, LiCl•H_2O crystal is used to transport geothermal energy with an energy density 3 times higher than the liquid solution. Such increase of energy density reduces the transportation cost by 67%, and significantly improves the economic performance of the TSGA system. The crystal-enhanced TSGA system is able to reduce the payback of the 10-mile case study to 5.2 years.

Despite several technical challenges in implementation of the TSGA and crystal-enhanced TSGA systems, the preliminary design and analysis in this study indicates that these systems can provide space cooling to buildings more than 10 miles away from the geothermal resources, and such applications would be economically competitive with electric-driven vapor compression chilling technologies.

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