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A Technical and Economic Analysis of an Innovative Two-Step Absorption System for Utilizing Low-Temperature Geothermal Resources to Condition Commercial Buildings

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ABSTRACT

Low-temperature geothermal resources (less than 150°C, or 300°F) are abundant in the United States. Although higher temperatures are preferred for power production, low-temperature resources can directly provide buildings with space heating, or drive an absorption chiller for space cooling. One of the barriers to wider utilization of the low-temperature geothermal resources is the typically long distance between geothermal sources and potential end uses. An innovative two-step geothermal absorption (TSGA) system was recently proposed. With this system, the low-temperature geothermal energy is stored and transported at ambient temperature with an energy density significantly higher than transportation of hot water. A conceptual design of the TSGA system has been developed based on the single effect absorption cycle. LiBr/H_2O solution is selected as the working fluid pair. Key design parameters of a 900 ton (3,165 KW) two-step absorption chiller have been determined based on computer simulations. Energy density of the transported solution is 349 kJ of cooling energy per kg of shipped LiBr/H_2O solution, which is up to 5 times higher than that of transporting hot water for typical direct use applications. Technical challenges identified include: (1) minimizing the required volume and the associated transportation cost of the working fluid; (2) maintaining appropriate vacuum levels at various components of the absorption cycle; (3) retaining good quality of the working fluid during transportation and storage; and (4) harvesting heat from geothermal wells sparsely located and with varying production rates. A case study for applying the TSGA system at a large office building at Houston, TX indicates that, for a 10-mile distance from the geothermal site to the building, the simple payback of the TSGA system is 10.7 years compared with a conventional electric-driven vapor compression chiller. It is found that the payback of the TSGA system is highly sensitive to the distance, building size (cooling loads), transportation cost, and the electricity rate. It is also found that, for a 10-mile distance, transporting the working fluid with tanker trucks leads to lower life cycle cost than a pipeline using high-density polyethylene pipes. Transportation cost is the most significant contributor to the life cycle cost of the TSGA system. One approach to reducing transportation cost is to increase the energy density of the transported solution by enlarging the concentration difference between strong and weak solution. It is possible to enlarge the concentration difference by integrating the TSGA system with a desiccant dehumidifier to enable separated sensible and latent cooling, or utilizing crystals of the solution to enable local regeneration.

1. INTRODUCTION

The use of geothermal energy is an emerging area for improving the nation's energy resiliency. Conventionally, geothermal energy applications have focused on power generation using high-temperature hydrothermal resources or enhanced geothermal systems. However, many low-temperature (below 150°C/300°F) geothermal resources are also available but have not been fully utilized. For example, it is estimated that 25 billion barrels of geothermal fluid (mostly water and some dissolved solids) at 176°F to 302°F (80°C to 150°C) is coproduced annually at oil and gas wells in the United States (DOE 2015). The heat contained in coproduced geothermal fluid (also referred as "coproduced water") is typically wasted because the fluid is reinjected back into the ground without extracting the heat.

Hot water from low-temperature geothermal reservoirs can be used to provide heat for industrial processes, agriculture and aquaculture, or to keep buildings warm. Such applications are usually called "direct use." In typical direct-use applications, a well is drilled into a geothermal reservoir, and a pumping system is used to extract a stream of hot water from the well. The hot water then delivers heat through a heat exchanger for its intended use. The cooled water is injected back underground or disposed of on the surface.

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). Kreuter (2012) compared the required temperature of energy sources and common cooling agents for the absorption and adsorption chillers as summarized in Table 1. As shown in Table 1, while higher than 185°F (85°C) energy source is needed to drive an absorption chiller, an adsorption chiller can be driven with lower temperatures (e.g., 55°C or 131°F).

Table 1 Comparison between compression and absorption chillers (Modified based on Kreuter 2012)

Chiller type	Energy source temperature	Common cooling agents
Ab̲sorption	185-302°F (85–150°C)	LiBr/H_2O or H_2O/ammonia
Ad̲sorption	131-392°F (55–200°C)	Water with solid ad̲sorption agent (e.g., silica gel or zeolite)

Lech (2009) studied the technical and economic feasibility of various cooling/heating systems for a commercial building based on computer simulations. This study concludes that the single-stage geothermal hot-water-driven absorption chiller has the least equivalent warming impact for cooling the studied building compared with a wide range of single- and double-stage absorption chillers (driven by geothermal hot water or directly fired) as well as electric-driven chillers. Wang et al. (2013) presented a techno-economical study for a conceptual design of a large-scale geothermal absorption air-conditioning system, which is proposed to provide base-load cooling to the main campus of the University of Western Australia. The study concluded that the payback period for the proposed system is around 11 to 13 years. 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.”

With direct-use and absorption/adsorption technology, low-temperature geothermal resources have the potential to be used to satisfy a significant portion of the cooling demands in buildings. However, due to the high cost for developing pipelines over long distances, utilization of geothermal energy for space conditioning currently is limited to places where the geothermal resources are available at or very near the demand site, usually less than 2 miles away (GHC 2005).

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. This can reduce greenhouse gas emissions, extend the economic life of oil and gas fields, and profitably utilize the abandoned oil and gas field infrastructure.

An innovative two-step geothermal absorption (TSGA) system is proposed to provide space cooling to buildings, which stores geothermal energy in liquid desiccant at the ambient temperature and transport the liquid desiccant instead of hot water between a geothermal site and a building. This paper introduces the conceptual design of the TSGA system and assesses the associated technical challenges. In addition, a case study is presented to evaluate the cost-effectiveness of the TSGA system compared with a conventional electric-driven vapor compression chiller, and the impacts of various parameters on the economical viability of the TSGA system. Possible improvements of the TSGA system are also discussed.

2. TWO-STEP GEOTHERMAL ABSORPTION SYSTEM

2.1 Design and modeling of the TSGA system

The proposed TSGA system is a split single-effect absorption cycle. As illustrated in Figure 1, 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 near the geothermal resource. A weak solution of lithium bromide (LiBr) and water, or another working fluid pair, is heated using geothermal heat to drive off moisture from the weak solution. The resulting concentrated strong solution is then allowed to cool down to ambient temperature at the geothermal site and is transported to commercial or industrial buildings by tanker trucks (or other appropriate means, including but not limited to, trains or ships). The second step is to produce chilled water at the building site, where liquid water is evaporated to cool the chilled water and then the water vapor is absorbed by the strong solution. The diluted weak solution is then 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 circulation pump associated with the cooling tower. Equipment at building site includes an assembly of absorber and evaporator, two flow restrictors, a wet cooling tower and an associated circulation pump, holding tanks, and a solution pump. The design conditions of the TSGA system are listed in Table 2.

LiBr/H_2O is selected as the working fluid pair of the TSGA system given its superior performance over other options (e.g., H_2O/NH_3, LiCl/H_2O, and $CaCl_2/H_2O$), especially the larger concentration differential between the weak and strong solutions at the design conditions. The two-step absorption cycle of the TSGA system is modeled with SorpSim, which is a design software for absorption systems and developed based on ABSIM (Grossman 1998). Through a series of simulations using the SorpSim model, a set of state points of the two-step absorption cycle are determined, which results in maximal concentration difference between the strong and weak solutions while avoiding crystallization of the LiBr/H_2O solution during transportation and storage. The thermodynamic process of the determined absorption cycle is shown on the Dühring chart of the LiBr/H_2O solution in Figure 2. The line from state point #11 to #10 indicates the desorbing process, where the water vapor pressure in the desorber is maintained at 7.8 kPa and the LiBr/H_2O solution is concentrated from 53% to 62% by the geothermal heat. 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.

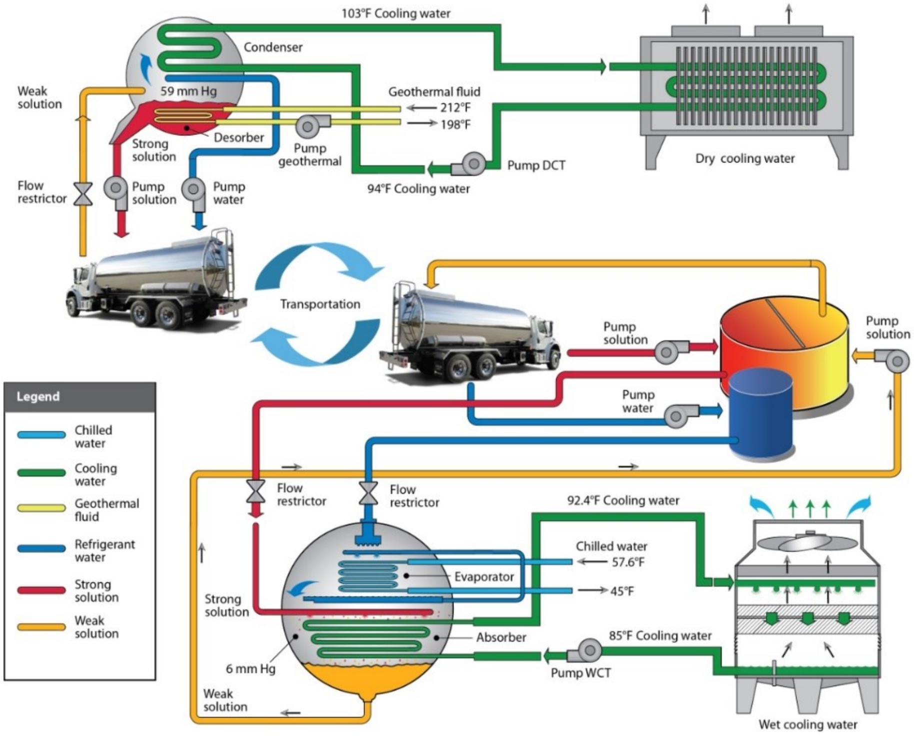

Figure 1 Schematic of the two-step geothermal absorption cooling system

Table 2 Design conditions of the two-step geothermal absorption system

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

Major components of a 900 ton (3,164 kW) two-step absorption chiller are sized using SorpSim and the design specifications of these components are listed in Table 3. The simulation result indicates that the thermal efficiency of the absorption cycle is 0.67 and the energy density of the LiBr/H_2O is 150 Btu/lb (i.e., 349 kJ cooling energy for each kilogram of weak solution), which is about 5 times higher than that of transporting hot water for typical direct use applications (assuming 30ºF or 17 ºC temperature difference between the supply and discharge temperature of the hot water).

Table 3 Design parameters for a 900 ton (3,165 kW cooling) two-step absorption chiller

Component	UA value (kW/°C)	NTU (-)	Effectiveness (-)	Closest approach (°C)	LMTD (°C)	Heat transfer rate (kW)
Evaporator	600	1.2	0.712	2.844	5.644	3388
Desorber	350	1.6	0.73	8.272	14.38	5032
Condenser	1000	1.5	0.776	1.533	3.55	3551
Absorber	700	2.9	0.912	1.522	5.411	3789

UA	overall heat transfer coefficient
NTU	number of heat transfer units
LMTD	logarithmic mean temperature difference

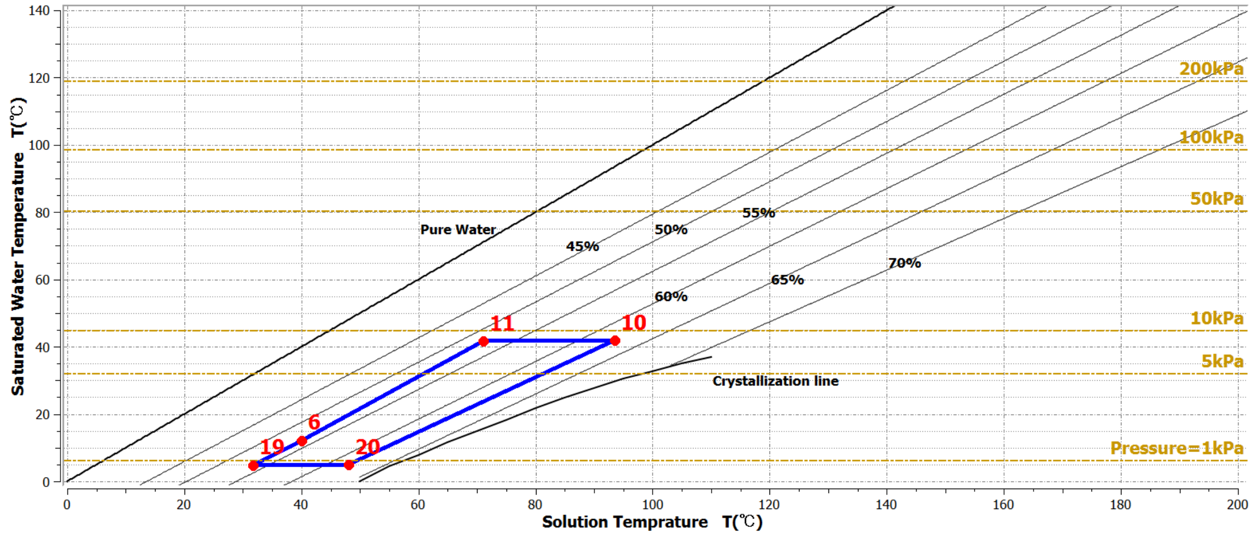

Figure 2 State points of two-step geothermal absorption cooling shown on Dühring chart of LiBr/H2O solution

Other accessory equipment of the TSGA system, including cooling towers and circulation pumps, is sized based on the capacity and the thermal efficiency of the two-step absorption chiller. The tanker trucks used in the TSGA system have the largest allowable weight when they are fully loaded with the LiBr/H_2O solution. The trailer tanks are sized to allow continuous operation of the TSGA system before the regenerated strong solution arrives at the building. Specifications of the accessory equipment are listed in Table 4.

Table 4 Specifications of accessory equipment of the 900 ton (3,165 kW cooling) TSGA system

Item	Specification
Building site cooling tower (serving absorber)	Type: wet cooling tower Design supply temperature: 85°F (29.4°C) Flow rate: 3,487 GPM (220 kg/s) Cooling capacity at design condition: 1,082 tons (3,789 kW)
Geothermal site cooling tower (serving condenser)	Type: dry cooler Design supply temperature: 94°F (34.4°C) Flow rate: 2,536 GPM (160 kg/s) Cooling capacity at design condition: 933 tons (3,551 kW)
Dry cooler pump	2,536 GPM (160 kg/s) flow, 30 ft (9.2 m) head
Wet cooling tower pump	3,487 GPM (220 kg/s) flow, 30 ft (9.2 m) head
Geothermal fluid pump	2,456 GPM (155 kg/s) flow, 30 ft (9.2 m) head
LiBr/H_2O solution pump	158.5 GPM (10 kg/s) flow, 40 ft (12.2 m) head
Refrigerant water pump	23.8 GPM (1.5 kg/s) flow, 40 ft (12.2 m) head
Tanker truck	5,000 gal (18. 75 m^3), insulated, pressurized with inert gas. This tanker truck load is determined based the maximum allowed gross vehicle weight of 80,000 lb and the empty vehicle weight for the Class 8B truck, which is about 20,000 lb according to US National Research Council (2010).
Trailer tanks	Three 5,000 gallon (18.75 m^3) insulated trailer tanks, pressurized with inert gas.

2.2 Technical challenges of the TSGA system

In contrast to conventional packaged absorption chillers, which re-circulate a small amount of LiBr/H_2O solution in a closed-loop cycle, the proposed two-step absorption system uses LiBr/H_2O solution in a "once through" approach at the building site—a stream of strong solution goes from a holding tank into the absorber and becomes weak after absorbing water vapor, then it is pumped to another holding tank. When the tank holding the weak solution is full, it is transported to the geothermal site for regeneration. To keep continuous operation of the TSGA system while reducing the frequency and associated costs of transportation, a large amount of LiBr/H_2O solution is required, which brings a couple of technical challenges in the design and operation of the TSGA system, including (1) minimizing the required volume and the associated transportation cost of the working fluid, (2) maintaining appropriate vacuum levels at various components of the absorption cycle, (3) retaining good quality of the working fluid during transportation and storage, and (4) harvesting heat from geothermal wells that are sparsely located and that vary in production rates.

3. CASE STUDY

A case study for applying the TSGA system in a large office building in Houston, Texas is conducted to evaluate the economic viability of the TSGA system. The office building has a total floor space of 498,588 ft^2 (46,320m^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 by 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 871 tons (3063 kW_{clg}), a wet cooling tower, a pump to circulate condensing water between the cooling tower and the chiller, and other HVAC components inside the building, such as the distribution system for the chilled water, air-handling-unit, fan coils, or other heat-transfer terminals. The nominal efficiency (electrical coefficient of performance or COP_{el}) of the VC chillers is 5.5 and the annual operational COP_{el} is 3.05. The annual cooling load of the building is 6,767,238 kWh_{clg} and the annual chiller electricity consumption is 2,219 MWh.

To evaluate the economic viability of the TSGA system, its initial and operating costs are compared with the baseline system. The compared cost components and the evaluation procedure are shown in Figure 3. The operating cost of the baseline system (OPC_{base}) is the electricity cost for operating the chiller and the associated equipment (i.e., cooling tower and circulation pump). The operating cost of the TSGA system (OPC_{new}) includes the electricity cost for operating the cooling tower and circulation pumps, as well as the cost for transporting LiBr/H_2O solution back and forth between the geothermal site and the building. The operating electricity costs of the two systems are calculated based on the building cooling load, equipment efficiency, and electricity price in Houston area ($0.102/kWh). The transportation costs involved with the TSGA system is estimated based on an operation schedule of the tanker trucks (by Liu et al. (2015) and the national average of the operational costs of trucking (Fender et al. 2013). The initial cost of the baseline system (IC_{base}) includes the costs for the VC chiller and associated equipment; the initial cost of the TSGA system (IC_{new}) includes the cost of the LiBr/H_2O solution and holding tanks in addition to the cost of the absorption chiller and the other associated equipment. Initial cost of the major equipment used in the TSGA and the baseline system are calculated with RSMeans Mechanical Cost Data (Reed Construction 2010), which includes costs of material/equipment, labor, and overhead and profit. Algorithms for calculating the initial cost and the operating cost of the two systems are described in a technical report by Liu et al. (2015).

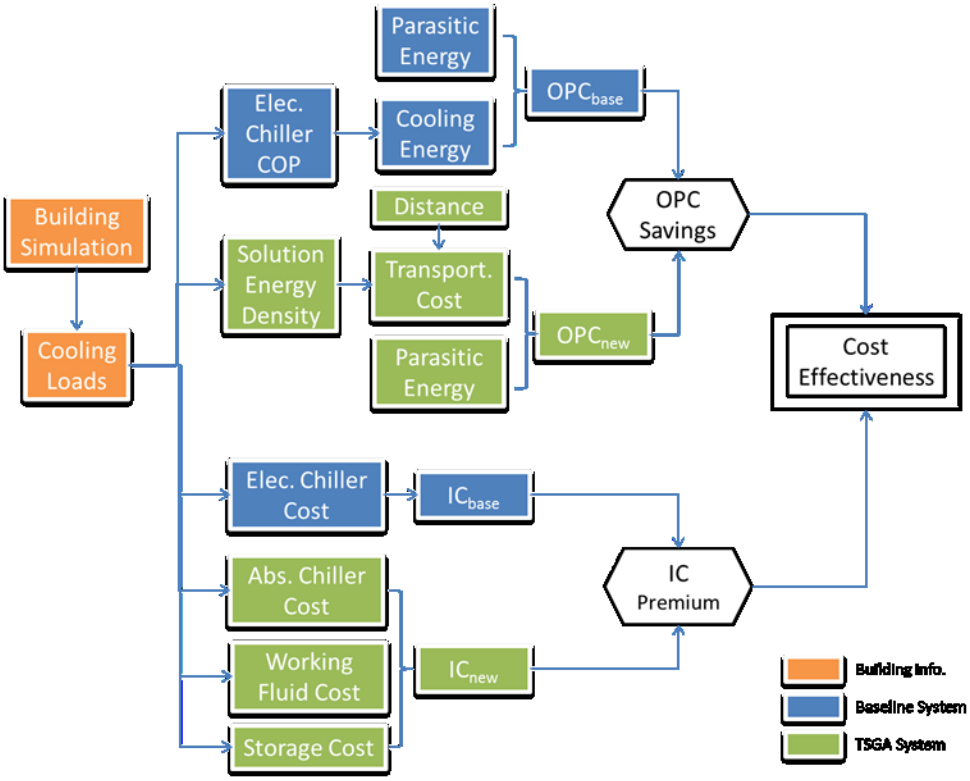

Figure 3 Flow chart for the economic viability study

3.1 Cost analysis

The cost-effectiveness of the TSGA system is evaluated with two metrics: simple payback (SP) and levelized cost of saved electricity (LCOSE). As expressed in Equation (1), SP is the time period that the capital cost premium is recovered with the cumulative operating cost savings achieved by the TSGA system. LCOSE is the ratio of all the investment needed to save electricity, which includes the initial cost premium and the cumulative operating cost over a given time period (e.g., the lifespan of the system), to the cumulative electricity savings over the same time period. In this study, a 20-year lifespan [the value of *n* in Equation (2)] and a 3% discount rate (*DR*) are assumed when calculating LCOSE.

$$SP = \frac{IC_{abs} - IC_{vc}}{OPC_{vc} - OPC_{abs}} \tag{1}$$

$$LCOSE = \frac{Investment}{Electricity\ Saved} = \frac{(IC_{abs} - IC_{vc}) + \sum_{k=1}^{n}[OPC_{abs}\ /(1+DR)^k]}{\sum_{k=1}^{n}[(Ele_{vc} - Ele_{abs})/(1+DR)^k]} \quad (2)$$

where Ele_{vc} *and* Ele_{abs} are the electricity consumption of the conventional cooling system using VC chiller and the TSGA system, respectively.

The initial and operating costs of the baseline and the TSGA system are calculated assuming a 10-mile distance between the geothermal site and the office building. The results are listed in Table 5. As can be seen in this table, TSGA system has higher initial cost than the baseline system. It is due to: (1) the cost premium of the two-step absorption chiller; (2) larger size of pumps and cooling towers due to the lower thermal efficiency of the two-step absorption chiller; and (3) the additional cost for the LiBr/H_2O solution and the holding tanks to enable continuous operation of the TSGA system. The two-step absorption chiller, LiBr/H_2O solution, and the cooling tower contribute 89% of the total initial cost of the TSGA system. However, The TSGA system has less operating cost than the baseline system. It reduces electricity consumption by 72% with the expense of additional transportation cost. Given the initial costs and the annual operating costs of the two systems, the simple payback of the TSGA system is 10.7 years.

Table 5 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*

Assuming a 20-year life span, the LCOSE of the TSGA system for a 10-mile distance is \$0.1307/kWh. It is higher than the retail electricity price in Houston area (\$0.102/kWh), which is used in the economic analysis of this case study. A breakdown of LCOSE of the TSGA system is given by percentage in Figure 4 and by costs in Table 6. As shown in Figure 4, the initial costs only contribute about 22% to LCOSE but the operating costs, especially the transportation cost, are more significant contributors to LCOSE. Reducing these costs is thus crucial to reduce LCOSE of TSGA system.

Table 6 Levelized cost breakdown of the TSGA system with a 10-mile distance

Cost type	Item	Cost ($)	Levelized cost ($/kWh)
Capital cost	Equipment	374,703	0.0140
	Solution	289,845	0.0109
	Trailer tanks	105,000	0.0039
Operating cost	Electricity	71,887	0.0399
	Transportation	111,669	0.0620
Total levelized cost			0.1307

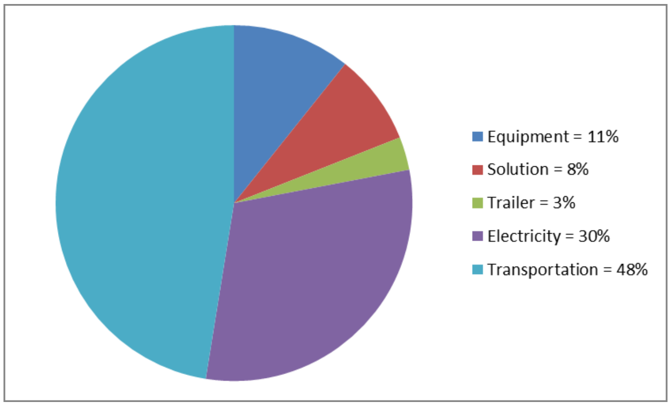

Figure 4 Levelized cost breakdown of the TSGA system with a 10-mile distance

3.2 Energy and emission analysis

Primary energy consumptions and the associated equivalent CO_2 emissions of the TSGA and the baseline systems are converted from the calculated electricity consumptions and the diesel fuel consumptions of the two systems. The conversion factors are from a report by Deru and Torcellini (2007). Primary energy conversion factor for electricity is 3.365, and 1.158 for diesel (distillate) fuel; emission factor for electricity is 1.67 lb CO2e/kWh, and 4.1 lb CO2e/gal for distillate fuel. The average tanker truck fuel economy is reported as 7.9 miles per gallon for a 80,000 pound truck (Franzese and Oscar 2011). In this study, the fuel economy is conservatively set as 5 miles per gallon considering the lower average speed of trucks operated for the TSGA system. As shown in Table 7, compared with the baseline system, the TSGA system consumes significantly less electricity at the expense of diesel fuel consumption by tanker trucks. Overall, the TSGA system reduces primary energy consumption by 66%, and the equivalent CO_2 emission is reduced by 71% as well. If the reduction of CO_2 emission and/or the electricity demand can be monetized (e.g., through carbon trade or electricity demand charge), the cost effectiveness of the TSGA system will become better.

Table 7 Electricity, primary energy savings and CO2e reduction of TSGA system

	Electricity consumption [kWh_e]	**Diesel fuel consumption [gal]**	**Primary energy consumption [kWh_{pr}]**	**CO_{2e} emmision [ton]**
Baseline system	2,504,567	-	8,427,868	1,897
TSGA system	704,631	10,603	2,870,202	553
TSGA system saving	1,799,936	-	5,557,666	1,344
Savings Percentages	72%	-	66%	71%

3.3 Sensitivity analysis

A series of sensitivity analyses were carried out to investigate the impact of various variables on the economics of the TSGA system. These variables include building size, the distance between the geothermal site and the building, and carrier cost for transporting the solution.

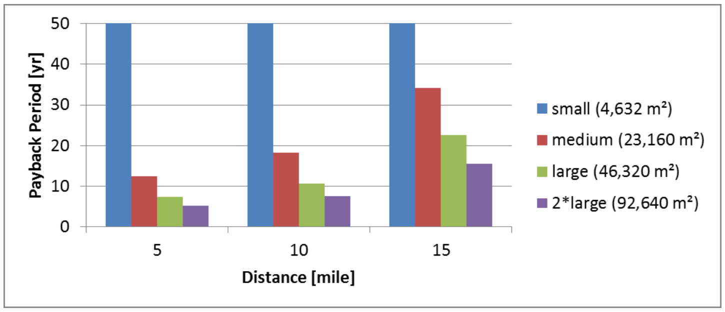

Figure 5 Simple payback periods resulting from different building sizes and distances

Figure 5 shows the simple payback period for buildings with different sizes (and thus different annual cooling loads) versus distance from the geothermal site. Applying the TSGA system in larger buildings would result in shorter payback periods because savings in the operating cost increase more than the capital cost with the increase of the building size. Figure 5 also shows that the payback period increases with longer distance. Applying the TSGA system in buildings with large or double-large (e.g., district system) sizes yields payback periods shorter than 11 years if the building is within 10 miles of the geothermal site. However, the payback for applications in large buildings will be more than 20 years if the distance increases to 15 miles because the transportation cost increases proportionally with the increase in distance.

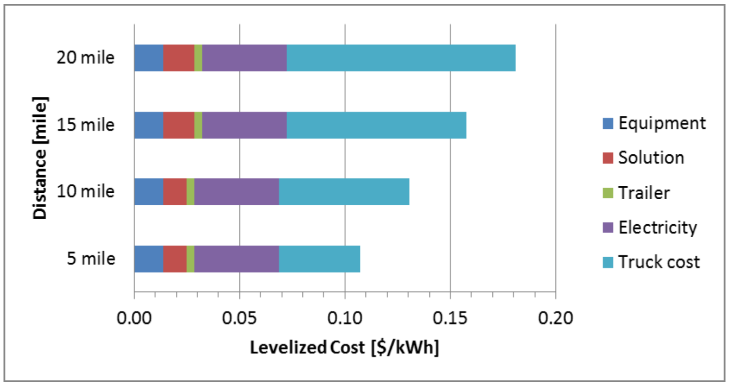

Figure 6 Levelized cost breakdown for different distances

Figure 6 shows breakdown of LCOSEs with different distances ranged from 5 to 20 miles. The total LCOSE increases with the distance due to the linearly increased transportation cost. However, the other components of LCOSE are unaffected, except that the levelized cost of the LiBr/H_2O solution increases by a small amount when the distance increases from 10 to 15 miles due to increased demand of the solution to keep TSGA system operating continuously.

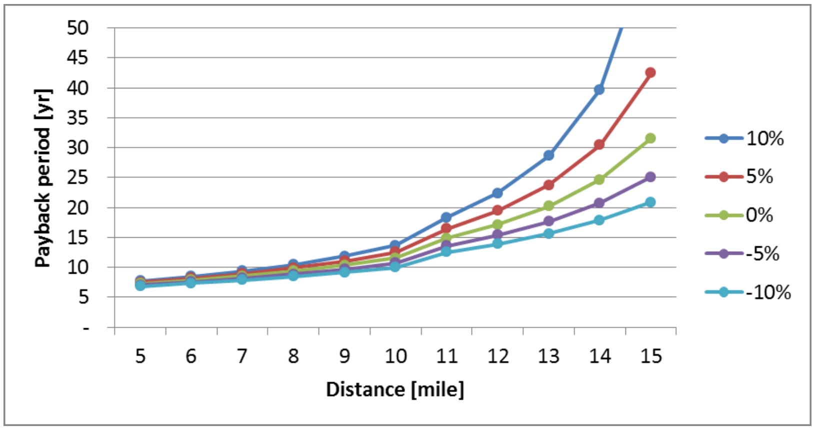

Figure 7 Simple payback against fluctuation of carrier cost

Transportation cost is determined by the distance and the carrier cost. 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 during one hour according to a truck operation schedule for enabling continuous operation of the TSGA system. Figure 7 shows the change of payback period resulting from a ±10% fluctuation in the carrier cost. For the same distance, a higher carrier cost leads to a longer payback period. Furthermore, the influence of carrier cost becomes more significant when the building is further away from the geothermal site. With a 10-mile distance, the ±10% variation in the carrier cost leads to only about a 3.5 year difference in the payback period. However, the same variation leads to a 21 year difference (from 18 to 39 years) for a 14-mile distance.

3.4 Comparison between pipeline and tanker truck transportation

Pipeline is a mainstream transportation method for many applications where a large quantity of fluid needs to be transported. It comes with the advantage of continuous operation and a relatively low operating cost. However, a pipeline application is limited by the large capital investment it requires and possibly by the complicated process to acquire the rights of way (ROWs) to dig trenches and install pipes. The transportation cost associated with a pipeline using high-density polyethylene pipes is calculated and is compared with the cost of using tanker trucks to transport LiBr/H_2O solution. The calculated costs of these two transportation options for a 10-mile distance are listed in Table 8.

Table 8 Costs of using pipeline and tanker trucks for transporting LiBr/H_2O solution over a 10-mile distance

Cost component	Pipeline		Tanker truck
	Without ROW	With ROW	
LiBr/H_2O Solution ($)	833,310	833,310	289,845
Pipeline material and installation cost ($)	357,500	357,500	-
Right-of-way (ROW) cost ($)	0	1,056,000	-
Equipment cost ($)	108,000	108,000	105,000
Total capital cost ($)	1,298,810	2,354,810	394,845
Annual operating cost ($/year)	40,500	40,500	111,669
Life time cost for 20 years ($)	2,108,810	3,164,810	2,628,225

As shown in Table 8, the cost of LiBr/H_2O solution of the pipeline option is higher than that of the tanker truck option. It is because a larger amount of solution is needed to fill the entire pipeline. Equipment used for the pipeline option includes only pumps to circulate the solution between the geothermal site and the building. The equipment for the tanker trucker option only includes three trailer tanks. It is assumed that the tanker trucks are rented and the rental cost is included in the annual operating cost. When ROW is not considered, the total capital cost (including solution, pipeline, and equipment) of the pipeline option is more than three times of the tanker truck option. ROW cost varies widely, depending on the types of land that the pipeline will pass through. Based on ROW costs found in various resources, it is estimated that the ROW cost is about $1/ft/year for the size of the pipelines used in this case study. With the ROW cost, the total capital cost of the pipeline option is six times of the tanker truck option. However, the annual operating cost of a pipeline (for running the circulation pumps to deliver the needed amount of solution to the building and return for regeneration) is less than half of the operating cost of the tanker trucks. When the ROW cost is accounted for, the 20-year lifetime cost (including the total capital cost and the cumulative operating cost) of the pipeline option is 20% higher than that of the tanker truck option.

Figure 8 shows the simple payback periods of the TSGA system resulting from the two transportation options for various distances. The payback period with the pipeline option increases almost linearly with the increase of distance. In contrast, the payback period with the tanker truck option is relatively flat for a short distance but increases drastically for distances more than 15 miles because more tanker trucks are needed then to keep the TSGA system running continuously. Without accounting for the ROW cost, the two options result in similar payback periods for a distance less than 13 miles. However, when the ROW cost is accounted for, the pipeline option results in longer payback periods than the tanker truck option when the distance is more than 3 miles but less than 17 miles. To get a payback period of less than 20 years, the distance for pipeline cannot be more than 10 miles. On the other hand, for very short distances (< 3 miles), pipeline is a more cost effective option than the tanker trucks.

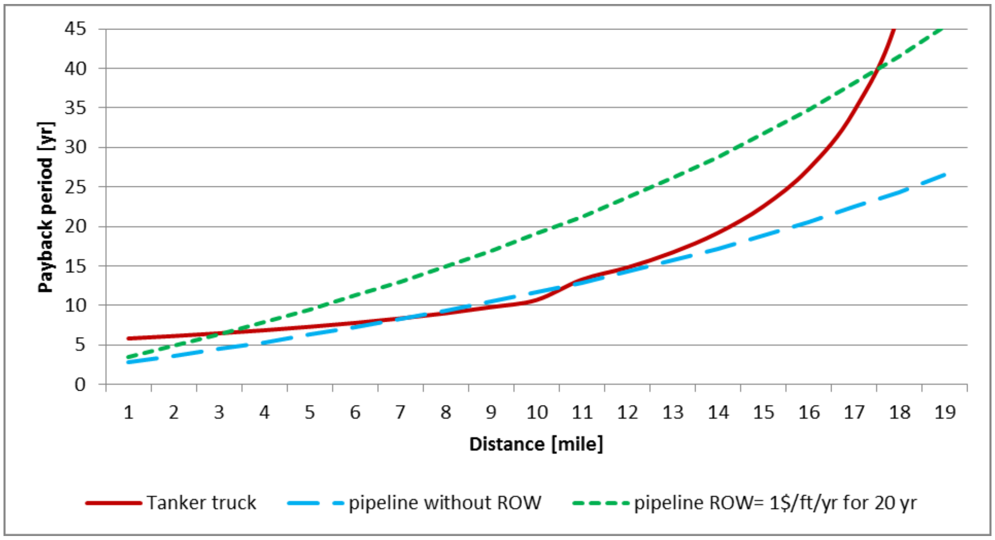

Figure 8 Simple paybacks resulting from different transportation options for various distances

4. POSSIBLE IMPROVEMENTS

As discussed in above case study, transportation cost is the most significant contributor to the life cycle cost of the TSGA system. To shorten the payback, the transportation cost shall be reduced. One approach to reducing transportation cost is to increase the energy density of the transported solution by enlarging the concentration difference between strong and weak solution.

There are two possible ways to enlarge the concentration difference. One is to integrate a desiccant dehumidification process into the TSGA system and deal with the sensible and latent cooling loads of the building separately. In this case, the strong solution first goes through a dehumidifier to dehumidify the outdoor air supplied to the building for ventilation purpose, then enters the absorber to produce chilled water. Since most of the latent cooling load of the building is from the outdoor air ventilation, which has been dehumidified with the strong solution, the chilled water is only needed to deal with the sensible cooling load, and the evaporating temperature can thus be elevated up to 54°F (12.2°C). With this elevated chilled water temperature, the absorption cycle operates with a enlarged solution concentration difference—from 51.7% and 61.8%, which yields an energy density of 173 Btu/lb (400 kJ/kg) and results in a 12.8% decrease in the required amount of the LiBr/H_2O solution.

The other promising way to further enlarge the concentration difference is to regenerate the solution beyond its crystallization line. The highly concentrated crystals of LiBr/H_2O or LiCl/H_2O are then transported to the building to regenerate the weak solution locally. This process can double the energy density, and thus halve the transportation cost. However, some technical challenges need to be resolved to utilize crystals in the TSGA system, including dissolving crystals in time to regenerate strong solution and preventing crystals from blocking passages of the solution in the absorption process.

5. CONCLUSIONS

Low-temperature geothermal resources [lower than 150°C (300°F)] are abundant in the United States, including the coproduced water from oil and gas production wells. However, the typically long distance between the available geothermal sources and potential end uses limits the conventional direct use applications. To overcome this limitation, a two-step geothermal absorption (TSGA) system is proposed. With TSGA, the low-temperature geothermal energy is stored in the LiBr/H_2O solution and transported at ambient temperature, which has a significantly higher energy density than the conventional way of transporting hot water. A conceptual design of a 900 ton TSGA system is developed and its performance is evaluated with computer simulations. The simulation results indicate that the two-step absorption chiller has a thermal COP_{th} of 0.67 at design condition, and the energy density of the transported solution is 150 Btu_{clg}/lb (349 kJ/kg) (i.e., providing 150 Btu of cooling per pound of shipped LiBr/H_2O weak solution), which is about 5 times higher than that of transporting hot water for typical direct use applications.

To make the TSGA system economically competitive and reliable over a long term, several technical challenges need to be addressed, including (1) minimizing the required volume and the associated transportation cost of the working fluid, (2) maintaining appropriate vacuum levels at various components of the absorption cycle, (3) retaining good quality of the working fluid during transportation and storage, and (4) harvesting heat from geothermal wells that are sparsely located and that vary in production rates.

A case study for applying the TSGA system to a large office building at Houston, Texas is 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 10-mile distance from the geothermal site to the building, the simple payback of the TSGA system is 10.7 years when compared with the conventional minimum code-compliant electric-driven vapor compression chiller. The payback of the TSGA system is highly sensitive to the distance, building size (cooling loads), transportation cost, and the electricity rate. Also, for a 10-mile distance, transporting the working fluid with tanker trucks leads to a lower life cycle cost than a pipeline using high-density polyethylene pipes.

Transportation cost is the most significant contributor to the life cycle cost of the TSGA system. One approach to reducing transportation cost is to increase the energy density of the transported solution by enlarging the concentration difference between strong and weak solution. It is possible to enlarge the concentration difference by integrating the TSGA system with a desiccant dehumidifier to enable separated sensible and latent cooling, or utilizing crystals of the solution to enable local regeneration.

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