ORNL/TM-2015/131

Overview of Available Low-Temperature/ Coproduced Geothermal Resources in the United States and the State of the Art in Utilizing Geothermal Resources for Space Conditioning in Commercial Buildings

Xiaobing Liu
Kyle Gluesenkamp
Ayyoub M. Momen

May 2015

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2015/131

Energy and Transportation Science Division

OVERVIEW OF AVAILABLE LOW-TEMPERATURE/COPRODUCED GEOTHERMAL RESOURCES IN THE UNITED STATES AND THE STATE OF THE ART IN UTILIZING GEOTHERMAL RESOURCES FOR SPACE CONDITIONING IN COMMERCIAL BUILDINGS

Xiaobing Liu
Kyle Gluesenkamp
Ayyoub M. Momen

Date Published: May 2015

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

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 geothermal resources of low temperature (below 150°C/300°F) are also available that have not been fully utilized. It is estimated that 25 billion barrels of fluid (mostly water and some dissolved solids) at 80–150°C are coproduced annually at oil and gas wells in the United States (DOE 2015). The heat contained in this coproduced geothermal fluid (usually also referred as "coproduced/produced water") is typically wasted by reinjecting it back into the ground. In addition to the coproduced geothermal fluid, there are low-temperature hydrothermal resources located throughout the United States.

Low-temperature geothermal energy can provide space conditioning and water heating to the built environment. Using geothermal energy through absorption technology to provide space cooling or refrigeration has significant advantages over conventional electric-driven chilling in reducing electric demand and greenhouse gas emissions. While naturally occurring geothermal reservoirs with high enough heat to produce power occur mostly in the Western U.S., much of it along existing transmission corridors, geothermal base load electricity for the most part of the country depends on proximity to transmission lines. In the Midwest and Eastern U.S. lower-temperature resources and Enhanced Geothermal Systems will also benefit from proximity to transmission infrastructure.

Regarding the direct use of geothermal fluid, the cost of developing transmission pipelines over long distances, as well as significant pressure and heat loss and deposition of dissolved solids in pipelines, makes use of this energy resource uneconomical. If the energy in low-temperature geothermal resources can be stored and transported to demand sites at a cost lower than that of transmission pipelines, use of this otherwise wasted energy will significantly increase and displace the use of electricity or fossil fuel for space conditioning. In addition, it can reduce greenhouse gas emissions, extend the economic life of oil and gas fields, and profitably utilize the abandoned oil and gas field infrastructure.

ORNL proposed the development of a system that uses low-temperature geothermal energy to provide space conditioning for buildings in populated areas located 10-100 miles away from geothermal resources. Figure 1 is a schematic of the proposed technology, which decouples the production and regeneration of the conventional absorption cycle into a two-step process. The first step is regeneration and takes place near the geothermal resource. A weak aqueous solution of lithium bromide (LiBr) or another salt solution is heated using geothermal heat to drive off moisture from the solution. The concentrated solution is then allowed to cool to ambient temperature and transported to commercial or industrial buildings by tanker trucks (or other appropriate means including, but not limited to, trains or ships).[1] The second step is space conditioning at the building site, where liquid water is evaporated to provide cooling and the water vapor is absorbed at low pressure by the concentrated solution, which is kept near ambient temperature. The diluted solution is then transported back to the geothermal site to regenerate (concentrate) it. The proposed technology has the potential to significantly reduce electricity consumption and associated energy costs and carbon emissions for space conditioning in commercial buildings.

This report summarizes the results of a literature review in three areas:

- available low-temperature (Section 2.2)/coproduced geothermal resources in the United States,

[1] LiBr solution is not hazardous as defined by 49 CFR 172.101 by the U.S. Department of Transportation. Shipments of LiBr solution require no hazardous shipping labels. Shipments by post, parcel, air, water, rail, or truck are acceptable within each carrier's weight limits and packaging requirements (http://www.seiberlich.com/files/msds/LIB00006.pdf).

- energy use for space conditioning in commercial buildings, and
- state of the art of geothermal absorption cooling.

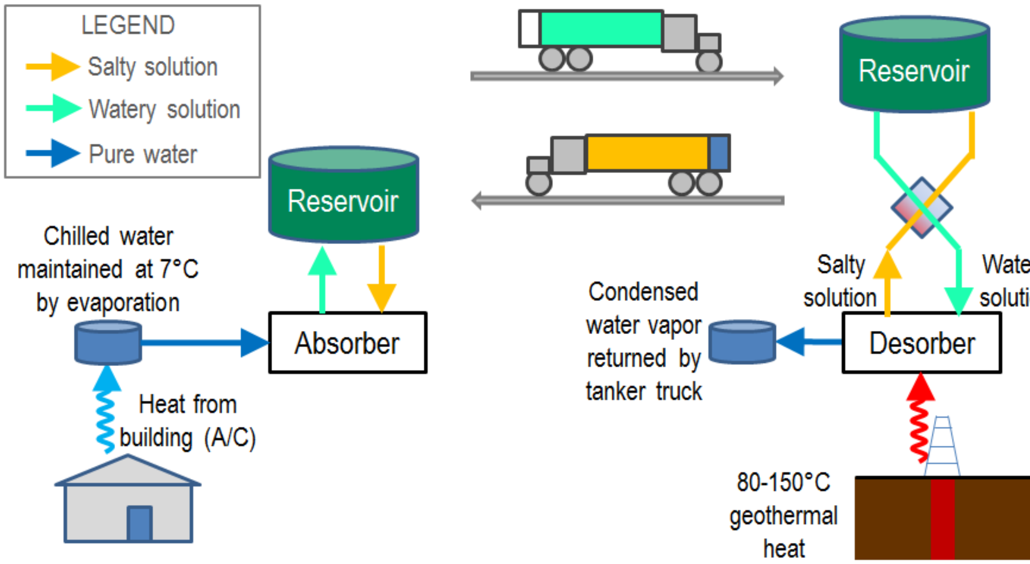

Fig. 1. Proposed two-step looping solution for using remote low-temperature geothermal energy to cool commercial buildings.

2. AVAILABLE LOW-TEMPERATURE/COPRODUCED GEOTHERMAL RESOURCES IN THE UNITED STATES

2.1 COPRODUCED WATER

Coproduced hot water is the water extracted from underground formations to the surface during oil or gas production. It is the largest volume by-product or waste stream associated with oil and gas exploration and production (Clark and Veil 2009). The cost of managing such a large volume of water is a key consideration for oil and gas producers.

Figure 2 shows the distribution of oil and natural gas producing regions across the United States. The distinct regions where oil and gas production occur include, but are not limited to, the Mid-Continent, Gulf Coast, the Rocky Mountain Region, Appalachian Mountain Region, California, and Alaska (IOGCCAC 2006). Data on oil and gas wells in various states, especially in Texas, are accessible through the National Geothermal Data System (NGDS), which is a catalog of documents and datasets that provides information about geothermal resources.[2] Data relevant to this project include location of the well, temperature at the bottom of boreholes, and the production rate of geothermal fluid.[3]

The quality of coproduced water varies across the United States. National-level data for the chemistry of coproduced water are available from the DOE-USGS Produced Water Database (USGS 2015), and state-specific data are usually collected by and stored in databases of oil- and gas-producing states. Many water

[2] http://geothermal.smu.edu/static/DownloadFilesButtonPage.htm?

[3] Since there will be some temperature change when the water travels from bottom of the well to the surface, there will be some difference between the available bottom borehole temperature and the actual usable fluid temperature at the well head. However, the well head fluid temperature is not included in the available database. In many cases, either the temperature or the flow rate, or even both, are missing.

chemistry databases only provide values of total dissolved solids (TDS), but others include detailed cation and anion concentrations. Coproduced water with a TDS less than 10,000 mg/L may be used for industrial and agricultural activities, while water with a TDS greater than 50,000 mg/L will likely require injection disposal for proper management (IOGCCAC 2006). Since the proposed two-step absorption technology only uses the heat of the coproduced water (not the water itself), the TDS level is not a concern. However, water chemistry data are needed for the material selection and design of the heat exchanger for exchanging heat with the coproduced water.

According to a survey conducted by Argonne National Laboratory (Clark and Veil 2009), a total of about 21 billion barrels (bbl; 1 bbl = 42 US gallons; about 160 L) of coproduced water was generated from most of the nearly 1 million actively producing oil and gas wells in the United States in 2007. The five states with the greatest coproduced water volumes were Texas, California, Wyoming, Oklahoma, and Kansas. The coproduced water volumes from these states represent nearly 75% of total US production (onshore and offshore) as shown in Fig. 3. With more than 216,000 active oil and gas wells statewide, Texas alone contributed 7,377,000,000 bbl of coproduced water, which accounts for 35% of the total volume of coproduced water generated in the United States. On average, an oil/gas well in Texas produced 93.6 bbl of water each day. More than 75% of oil wells in the United States are classified as “stripper” wells. On average, these stripper wells produce about 2 bbl of oil per day. The water-to-oil ratio of stripper wells can be as high as 40 bbl of water to 1 bbl of oil produced (API 2006).

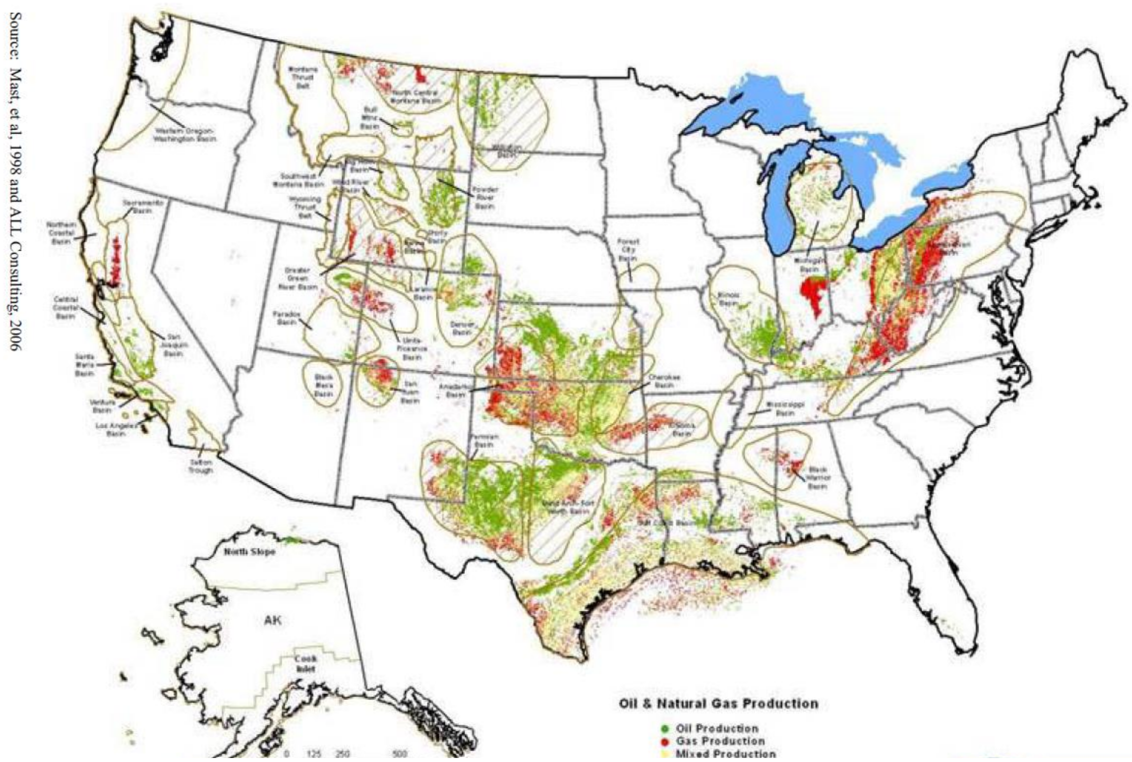

Fig. 2. Oil and natural gas production in the United States. (Source: IOGCCAC 2006)

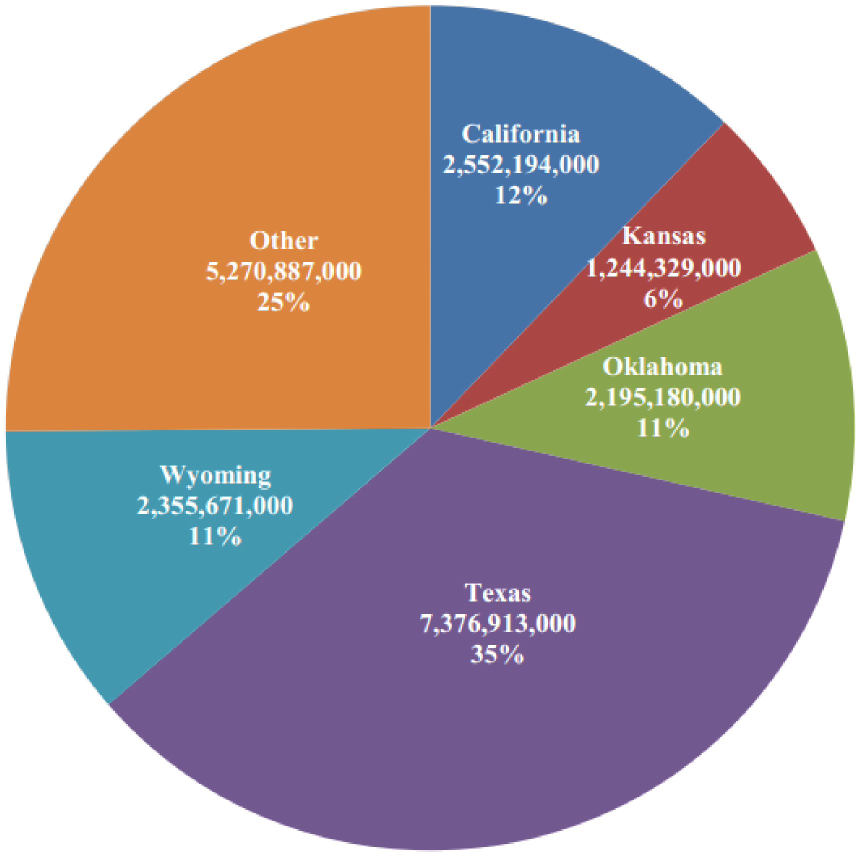

Fig. 3. Volume of coproduced water (barrels) in 2007 by five states with the greatest generation. (Source: Clark and Veil 2009)

Figure 4 is a map of the ground temperature at a 3 km (9,842 ft) depth below the surface for the continental United States. This map was originally developed by the Geothermal Laboratory at Southern Methodist University (SMU).[4] Maps of this type use a combination of actual temperature measured in the earth at as many sites as possible and the calculated deeper temperatures based on the thermal conductance of the rocks, the area heat flow, and the rock density. Of most interest to this project is the 3 km temperature-at-depth maps since typical oil and gas drilling is 4,000 to 10,000 ft (1.2 to 3 km) depending on the depth to the resource. Figure 4 indicates that some areas in East Texas and some spots in the Rocky Mountains have higher than 215°F (102°C) ground temperatures at depths of 3 km.

[4] http://www.smu.edu/Dedman/Academics/Programs/GeothermalLab/DataMaps/TemperatureMaps

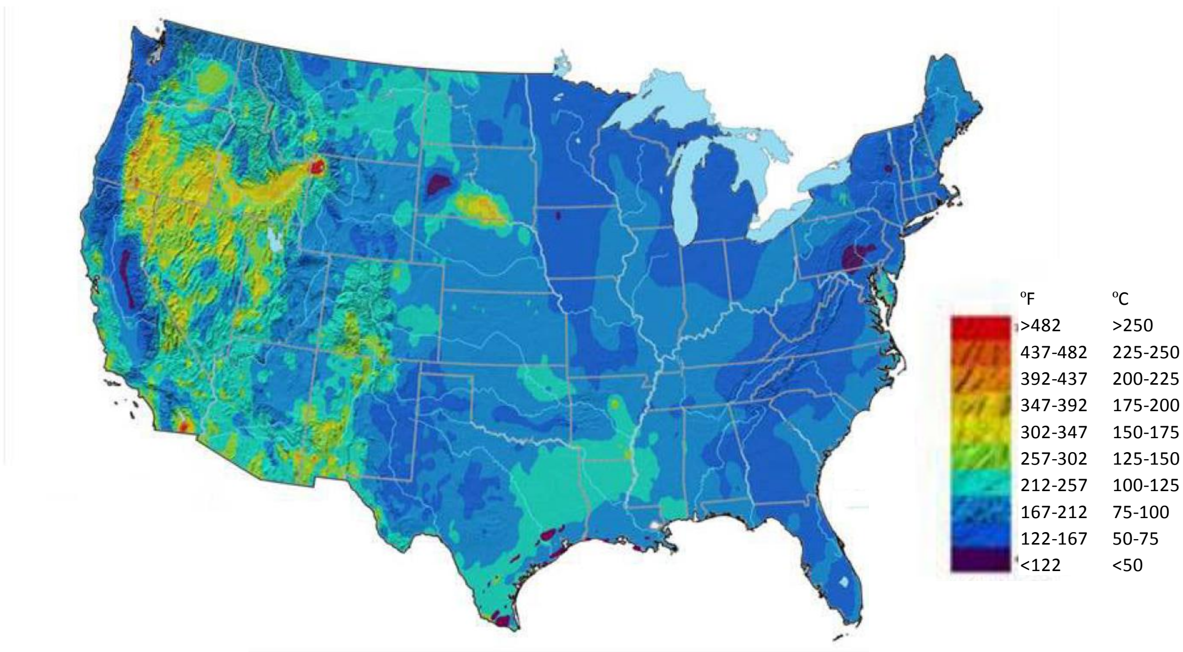

Fig. 4. Ground temperature at 3 km below the surface in the continental United States.
(Source: IOGCCAC 2006)

In addition to the raw data available on the National Geothermal Data System (geothermaldata.org) the "Geothermal Prospector" mapping tool further groups the raw data by temperature and other parameters. Southern Methodist University's Geothermal Laboratory node on Geothermaldata.org also provides a tool for interpreting well data. This National Renewable Energy Laboratory (NREL) web-based geographic information system (GIS) application, Geothermal Prospector,[5] supports resource assessment and data exploration for geothermal energy. The oil and gas well data collected by SMU's Geothermal Laboratory are accessible through Geothermal Prospector. Figure 5 shows the locations of oil and gas wells with ground temperatures higher than 215°F (102°C) at the bottom of the boreholes. However, data for the coproduced water flow rate at each oil/gas well are not accessible from Geothermal Prospector.

[5] http://maps.nrel.gov/gt_prospector

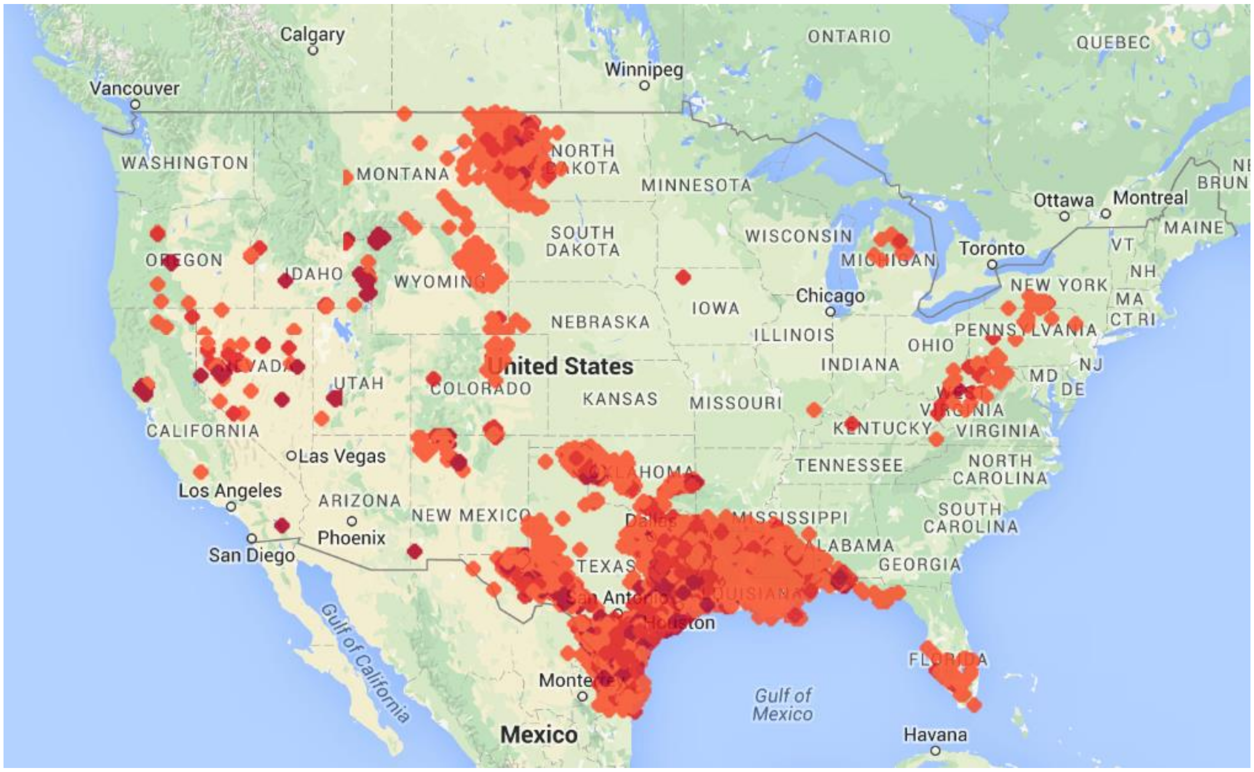

Fig. 5. Locations of oil and gas wells with a ground temperature higher than 215°F (102°C) at the bottom of the boreholes (the view was made with NREL's Geothermal Prospector).

One of the current practices for utilizing coproduced water is to generate electricity through a binary Organic Rankine Cycle (ORC), which transfers heat from the coproduced water to a second fluid that vaporizes at a lower temperature and higher pressure than water. This vapor is then used to drive a turbine to produce electricity. A few demonstration projects have successfully generated electricity using binary geothermal technologies with either stationary equipment integrated into existing oil and gas field infrastructures (Ormat Technologies and Rocky Mountain Oilfield Testing Center project) or a mobile geothermal power plant (Chena Power, LLC). Demonstration projects have been conducted in Wyoming, Utah, western North Dakota, and Texas (DOE 2010). Currently available technologies typically require at least 15,000 bbl of water per day with a minimum temperature of 215°F for efficient and economic power generation. This volume of water usually can be provided by medium and large oil and gas fields in the United States where wells may produce 200 to 500 bbl of water per day on average (IOGCCAC 2006).

The coproduced water at 215°F or below can be used directly to provide space heating and space cooling (e.g., using absorption chillers) to buildings. Unless electricity is generated on-site and fed to the grid, the typically long distances between the wells and population centers limit the direct use of geothermal fluid or co-produced geothermal fluid applications. Figure 6 illustrates the population density within a 50 km radius ring surrounding each of the oil/gas wells in Texas that have a ground temperature higher than 215°F (102°C) at the bottom of the boreholes. The population data are from ORNL's LandScan™ dataset and are the finest resolution (at approximately 1 km resolution) global population distribution data available.[6] The population density (i.e., population within approximately 1 km^2 area) within each 50 km radius ring is color-coded (e.g., red indicates more than 500 people within 1 km^2 area). As shown in

[6] http://web.ornl.gov/sci/landscan/

Fig. 6, except for the wells in or around the Dallas/Fort Worth and Houston areas, most wells are located in areas that have a population density of less than 50 people/km^2 (indicated by yellow color) within the 50 km radius ring surrounding the well. This indicates that there may not be enough demand within a short distance of these wells for use of this energy to be cost-effective.

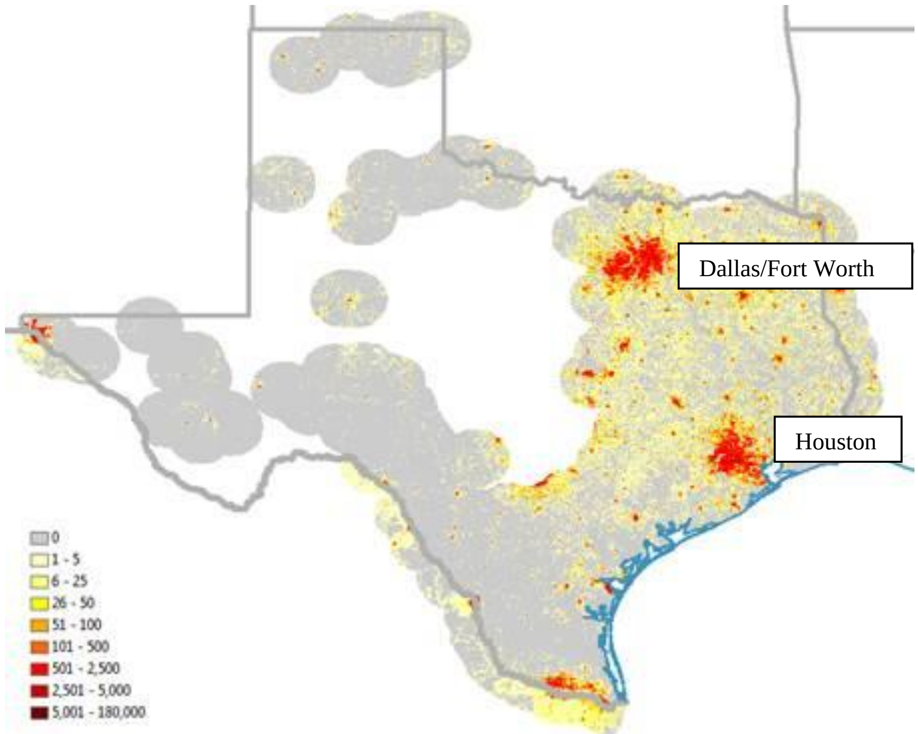

Fig. 6. Population intensity within a 50 km radius ring surrounding each of the oil/gas wells in Texas that has a ground temperature higher than 215°F (102°C) at the bottom of the borehole.

To make full use of a geothermal resource co-produced from an oil and gas well, it is necessary to harvest it from multiple wells and then transport it to population centers far away. Calpine operates the largest complex of geothermal plants in the world at the Geysers, located in Sonoma and Lake Counties in California. The facility pipes in 11 million gallons of municipal wastewater from Santa Rosa each day – water that the city did not want to discharge into the Russian River. This system produces enough electricity to power the entire city of San Francisco, without diminishing California's over-stained water supply (Calpine, July 2010).

In addition to distance, there are two technical challenges associated with using coproduced water: (1) fouling and corrosion of the heat exchanger (depending on the site-specific chemistry of the coproduced water), which will increase the operating and maintenance cost of the system and reduce the economic benefits and (2) the reliability of the coproduced water (Nordquist 2009).The quantities of coproduced water from oil and gas wells are highly variable from field to field. Furthermore, the dynamics of coproduced water quantities can also vary as the field is developed. While conventional fields typically yield more water as production progresses, nonconventional fields, such as coal bed natural gas, shale and diatomites, and dewatering,[7] might yield less water as production progresses (IOCCAC 2006).

2.2 LOW-MEDIUM TEMPERATURE HYDROTHERMAL (FOR DIRECT USE)

The U.S. Geological Survey updated its evaluation of geothermal resources with temperatures less than 90 ºC. This lower end of the low-temperature resources could provide 2,600 MWth, with a total wellhead thermal energy of 87x1018 J. or a modest addition to the 9060 MWe estimated for higher temperature systems but one which may have significance in meeting certain local power needs, particularly in remote areas. The potential for the higher end of the low-temperature resource (90-150C) is 1,640 MWe. The potential of thermal energy recovery was developed for 2008 assessment of resources (>90 ºC) by Reed and Mariner (2008) and Williams et al. (2008).

Hot water from low-medium temperature geothermal reservoirs can be used to provide heat for industrial processes and agricultural/aquaculture productions or to keep buildings warm. Such application is usually called “direct use.” In typical direct-use applications, a well is drilled into a geothermal reservoir to extract a steady stream of hot water from the well using a pumping system. The hot water then delivers heat through a heat exchanger for its intended use. The cooled water can be injected back underground or disposed on the surface. Spent fluids from geothermal electric plants may also be subsequently used for direct-use applications in a cascaded operation (DOE 2015).

The low-medium geothermal fluids used for direct use typically contain lower levels of gas and dissolved solids than the higher temperature fluids used for power generation (DOE 2004). Most direct-use geothermal wells are drilled using conventional water-well technology and equipment, which have less impact than the drilling technologies used for geothermal power plants or oil/gas wells. Direct use of geothermal energy to provide space heating and/or water heating is much less expensive than using traditional fuels, if the geothermal resources are near the buildings. It can also significantly reduce fossil fuels consumption and associated air pollutants (DOE 2015).

Most of the shallow or near-surface low-medium temperature geothermal resources are located in the western part of the country. A survey of 10 western states identified more than 9,000 thermal wells and springs, more than 900 low- to-moderate-temperature geothermal resource areas, and hundreds of direct-use sites. Figure 7 shows the distribution of geothermal resources in the United States and the locations of direct-use projects (GHC 2012). The original map (available at http://geoheat.oit.edu/dusys.htm) is clickable and can provide available data for direct-use sites in each state, including temperature and flow rate of each available geothermal resource.

[7] These nonconventional fields use large volume of water to facilitate the production of natural gas and oil.

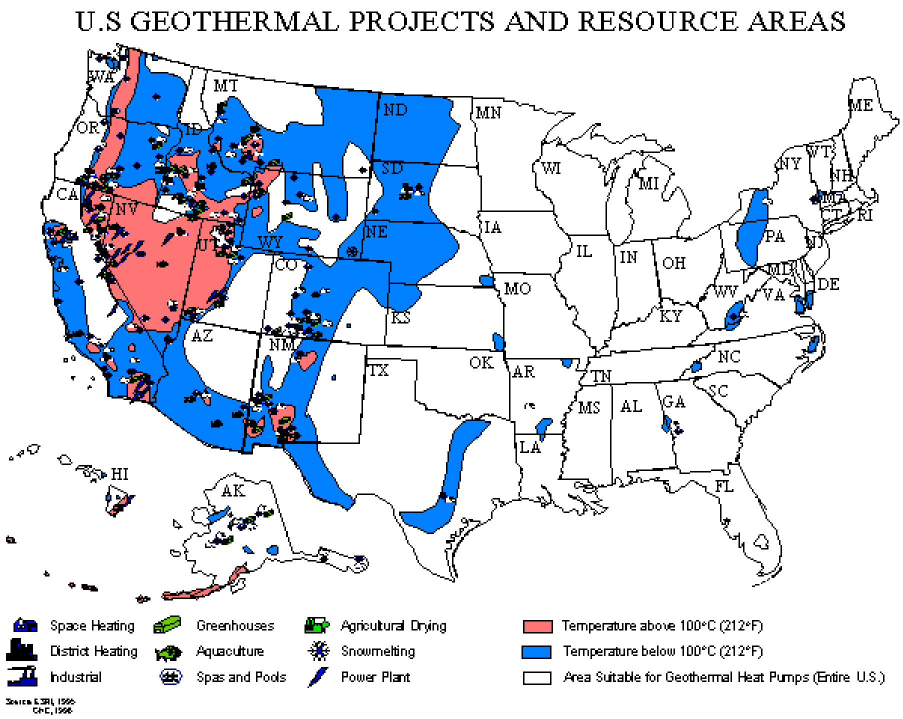

Fig. 7. US geothermal projects and resource areas. (Source: http://geoheat.oit.edu/dusys.htm)

One of the primary uses of low-temperature geothermal in the United States is to heat buildings, either through a district heating system or using one well per building. Currently, more than 120 operations are using geothermal energy for district and space heating, and 1,277 geothermal sites within 5 miles of 373 cities in eight states have been identified. It is reported that geothermal district heating systems can save consumers 30% to 50% in heating costs compared with natural gas heating (DOE 2015). With absorption or adsorption technology (Table 1), some of the low-temperature geothermal resources (with higher than 55°C/131°F temperatures) can also be used to provide space cooling to the building, further reducing the cost of energy for consumers and making geothermal investments more attractive.

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

Chiller type	Compression type	Energy source	Common cooling agents
Electric driven	Mechanical compression	Electric	HCFCs, HFCs, HFOs
A**b**sorption	Thermal absorption loop	Heat at 85–150°C	LiBr/water or water/ammonia
A**d**sorption	Thermal adsorption of water vapor	Heat at 55–200°C	Water with solid adsorption agent (e.g., silica gel or zeolite) or ammonia with carbon adsorbent

3. ENERGY USE FOR SPACE CONDITIONING IN COMMERCIAL BUILDINGS

Energy use for space conditioning in commercial buildings depends on many factors, including the local weather, use of the building, and size of the building. As shown in Fig. 8, the US territory can be divided into five climate zones based on heating and cooling degree days, which are usually used to indicate the demands for space cooling and space heating. The southeastern part of the United States has the highest cooling degree days, which means the greatest demand for space cooling in buildings.

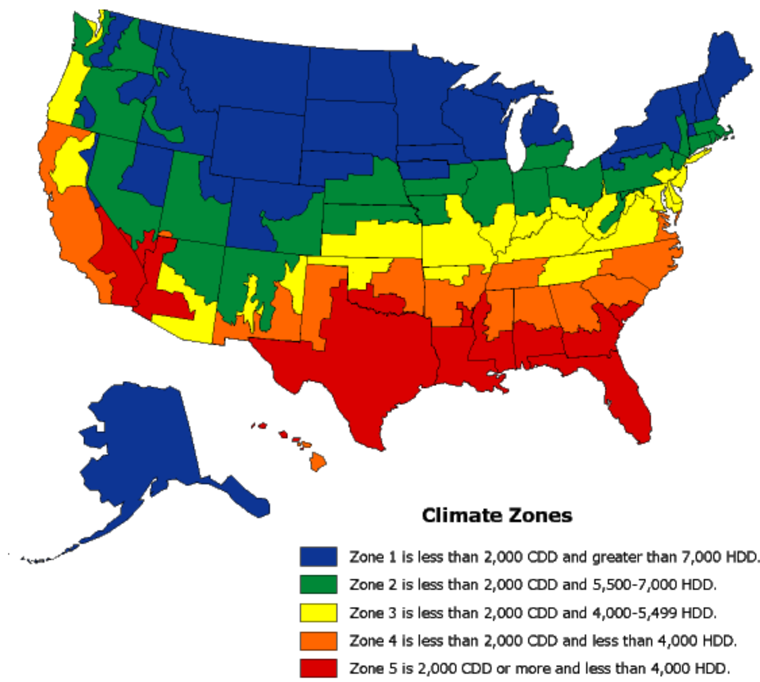

Fig. 8. Climate zones and associated heating and cooling degree days in the United States. (Source: http://buildingsdatabook.eren.doe.gov/CBECS.aspx).

The 2009 Buildings Energy Data Book (BEDB) produced by Department of Energy (DOE) provides extensive information on the characteristics and energy uses of commercial buildings in the United States. According to the 2009 DOE BEDB, space heating and space cooling were responsible for 12.6% and 12.1%, respectively, of the 17.9 quadrillion Btu total primary energy consumption in the commercial building sector in 2006. With regard to energy expenditure, $22.3 billion and $19.3 billion were spent in 2006 on providing space heating and space cooling for the US commercial buildings, respectively. Natural gas is the predominant energy source (68% of site energy) for space heating, while electricity is the predominant energy source (97% of site energy) for space cooling. Space cooling and space heating in US commercial buildings resulted in 130.3 and 127.4 million metric tons of carbon emissions in 2006. It is predicted that the emission level resulting from space cooling will be reduced to 113.4 million metric tons in 2030 mainly as a result of efficiency improvements being made to electric-driven chillers.

Although the building heating and cooling market is enormous, not all of it is suitable to the two-step geothermal absorption technology. The ideal candidate buildings for two-step geothermal absorption cooling would have large peak and cumulative cooling loads that (1) take advantage of equipment economies of scale and (2) result in substantial energy cost savings that offset cost premiums compared to baseline conventional space heating and space cooling systems. The cost premium would include the cost of the absorption chiller, infrastructure for extracting heat from the low-temperature geothermal energy (spread among multiple geothermal sites), transportation between the geothermal site and the building site, and facilities to store the working fluid.

Schools, hospitals, and large office buildings are identified as the targeted buildings based on the 2009 DOE BEDB data on average cooling (and heating) energy use intensity, average building floor space, and total stock floor area of various types of commercial buildings.

4. STATE OF THE ART OF GEOTHERMAL ABSORPTION COOLING

Geothermal resources have been used to provide space cooling or refrigeration to buildings through absorption chillers in the United States and other counties. However, these applications are limited to building sites where the geothermal resources can be readily accessed. Figure 9 illustrates a schematic of an absorption chiller using locally accessible geothermal fluids.

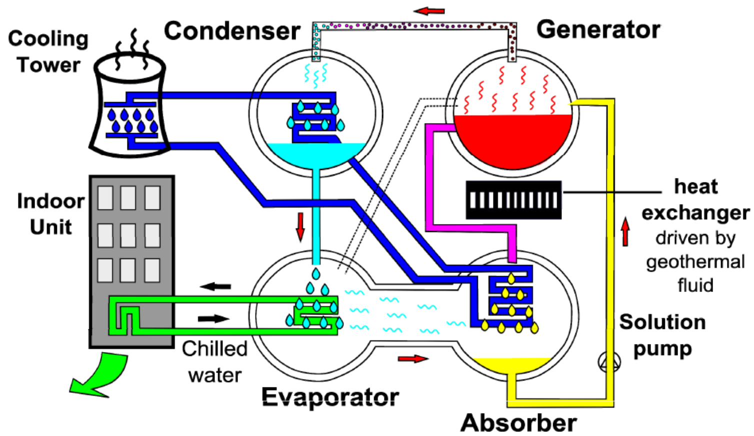

Fig. 9. Schematic for an absorption chiller using locally accessible geothermal fluids (Kreuter 2012).

In 1980, a geothermal-driven absorption chiller was installed at Oregon Institute of Technology to supply a base cooling load to five campus buildings, which have a collected total floor area of 277,000 ft^2. The absorption chiller was a single-stage unit that used LiBr and had a 150 ton operational capacity. It used 685 gal/min. of geothermal fluid at 192ºF (89ºC). The total installed cost of the system was $171,300 ($1,142/ton in 1980 dollars). It is not clear from the available information whether this figure included the cost of the geothermal well. This system was decommissioned in 1999 because of its low efficiency and high water use and was replaced with a centrifugal water chiller (Holdmann 2005). Holdmann (2005) introduced another application of a geothermal absorption chiller at the Chena Hot Springs Resort in Fairbanks, Alaska. It uses 165ºF (74ºC) hot springs as the heat source and the nearly 40ºF (4ºC) water in a nearby creek as the heat sink for condenser. The 15 ton chiller produces -21ºF (-29ºC) brine to provide refrigeration for an ice museum. The geothermal absorption chiller uses 33 kW of power, but a backup conventional chiller (with same capacity) uses 110 kW power to run. The operating cost of the absorption chiller is only one-third the cost of the backup chiller.

Kreuter (2012) compared a conventional electric-driven vapor compression chiller with geothermal-driven absorption and adsorption chillers (a similar technology using a solid instead of a liquid in the absorption process). The required temperature ranges of the geothermal sources and working fluids for geothermal-driven absorption and adsorption chillers are summarized in Table 1.

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 (condenser and absorber) cooling water temperature of 20 to 28°C (68 to 83°F). The COP was 0.73 (for 20°C/68°F cooling water) and 0.68 (for 28°C/83°F cooling water)." It is important to note that, if the same 86°C were used by a 10% efficient organic Rankine cycle driving a vapor compression chiller with COP=3, the total system COP (geothermal heat to cooling water energy) would be only about 0.3, much lower than the absorption COP of 0.7. Furthermore, a COP of 0.68 at 7°C chilled water, 28°C heat rejection, and 86°C heat source represents 32% of the Carnot efficiency limit.

Lech (2009) also concludes that the cooling water temperature can affect the component size, the installed cost, and the operating cost of the single-stage absorption chiller and compares the total equivalent warming impact (TEWI) on a wide range of single- and double-stage absorption chillers (driven by geothermal hot water or direct fired), as well as electric-driven chillers. The conclusion is that the single-stage geothermal hot-water-driven absorption chiller has the least TEWI compared with other options for the studied building.

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. This study concluded that the payback period for the proposed system is around 11–13 years and that the economic viability of the system is "heavily reliant on the quality of the geothermal resource, drilling costs and the effects of various proposed emission trading schemes."

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, this report stated that "like low-temperature geothermal power production, geothermal absorption cooling is restricted to areas with geothermal resources of about 100°C and above." Again, the two-step absorption approach may solve the distance problem and widely increase the application of low-temperature geothermal resources for space cooling.

Luo et al. (2010) reported a case study of a geothermal absorption cooling system in China. This system consists of a double-effect LiBr/H_2O absorption chiller driven by 70°C (158°F) hot water from a locally accessible geothermal well, a deep well pump, a heat exchanger, a cooling tower, several water pumps, a control box, and an air-conditioning terminal unit. It produces chilled water at 9°C to a coffee house and a lobby. The capacity of this system is 100 kW (28.5 cooling tons). The estimated payback of this geothermal absorption cooling system is less than 4 years compared with conventional air-conditioning system.

5. CONCLUSIONS AND PLANNED STUDY

The abundant low-temperature geothermal energy resources (including coproduced water and low-temperature hydrothermal) can be used not only to provide heating but also cooling to buildings. With absorption or adsorption technologies, low-temperature geothermal energy near buildings has been successfully used to provide space cooling and refrigeration in the United States and other countries. This geothermal absorption cooling system can reduce fossil fuel consumption, peak electric demand, and avoid using refrigerants with high potentials for global warming and ozone depletion.

However, most of the low-temperature geothermal energy is underutilized. One of the barriers preventing wider utilization is the typically long distances between geothermal sources and potential end uses. ORNL proposed an innovative two-step looping absorption/adsorption technology that has potential to utilize low-temperature geothermal energy to provide space cooling to buildings at distances up to tens of miles from the geothermal resources.

Currently, researchers at ORNL are assessing the technical challenges and the economical viability of the two-step looping absorption/adsorption technology. Some technical challenges have been identified, including (1) maintaining appropriate vacuum levels at various components of the two-step absorption cycle; (2) reducing required volume and cost of the absorption working fluid; (3) maintaining the quality of the absorption working fluid during transportation and storage; and (4) harvesting heat from geothermal wells sparsely located and with varying production rate. The economical viability depends on many factors, including the cost to harvest and store the geothermal energy, geothermal water temperature, the cost of the large amount of working fluid needed by the two-step absorption cycle, the distance between the geothermal resources and the buildings, existing infrastructures of transportation and associated costs, the cost of the absorption chiller and other supporting equipment, and the cooling loads of the buildings, as well as the utility rates for the electricity and natural gas.

To evaluate the economical viability, a series of case studies will be conducted with available data in several related disciplines (e.g., the characteristics of geothermal resources, the location and demands for space conditioning, and the distance as well as available methods for transporting the stored energy to the demand site). The performance metrics to be evaluated will include

- simple payback period,
- energy efficiency—cooling provided per unit of primary energy consumed from
  - transportation fuel and
  - parasitic electric loads (e.g., electricity used to drive fans for heat rejection heat exchanger), and
- national/regional technical potential of energy savings compared with baseline systems.

6. REFERENCES

American Petroleum Institute (API). 2006. “Where does the U.S. produce oil and natural gas?” Accessed online at http://www.api.org.

Clark, C. and J. Veil. 2009. *Produced Water Volumes and Management Practices in the United States*. Environmental Science Division, Argonne National Laboratory. Available at http://www.ipd.anl.gov/anlpubs/2009/07/64622.pdf.

DOE. 2015. “Direct Use of Geothermal Energy.” Available at http://energy.gov/eere/geothermal/direct-use-geothermal-energy.

DOE. 2010. “Geothermal Energy Production with Co-produced and Geopressured Resources.” Geothermal Technologies Program. Available at https://www1.eere.energy.gov/geothermal/pdfs/low_temp_copro_fs.pdf.

DOE. 2004. *Buried Treasure: The Environmental, Economic, and Employment Benefits of Geothermal Energy*. Geothermal Technologies Program. DOE/GO-102004-1985. Revised in November 2004.

European Geothermal Energy Council (EGEC). 2005. *Key Issue 5: Innovative Applications Geothermal Utilisation for Cooling*. Available at http://www.erec.org/fileadmin/erec_docs/Projcet_Documents/K4_RES-H/K4RES-H_Geothermal_cooling.pdf.

Interstate Oil and Gas Compact Commission and ALL Consulting (IOGCCAC). 2006. *A Guide to Practical Management of Produced Water from Onshore Oil and Gas Operations in the United States.* Available at https://fracfocus.org/sites/default/files/publications/a_guide_to_practical_management_of_produced_water_from_onshore_oil_and_gas_operations_in_the_united_states.pdf.

GHC. 2012. "US Geothermal Projects and Resource Areas." Available at http://geoheat.oit.edu/dusys.htm

Holdmann G. 2005. "Geothermal Powered Absorption Chiller." Presented at the 2005 Rural Energy Conference, Valdez, Alaska, September 20, 2005.

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

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

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

Nordquist, J. 2009. "Geothermal Power Plant Technologies." Ormat Technologies, Inc.

USGS (United States Geological Survey). 2015. Produced waters database (accessible via http://energy.cr.usgs.gov/prov/prodwat/)

Wang et al. 2013. "Application of geothermal absorption air-conditioning system: a case study*." Applied Thermal Engineering* 50, 71–80.