GRC Transactions, Vol. 41, 2017

Concept for a Distributed Baseload Binary Power Network

Gosnold, Will[1]; Crowell, Anna[1]; Keller, Kris[1]; Brunson, Daniel[1]; Tyler, Lindsay[1]; Nwachukwu, Francis[1]; Onwumelu, Chioma[1]; Ogochukwu, Ozotta[1], Ruben Havsed[2] and Joachim Karthäuser[2]

[1]Harold Hamm School of Geology and Geological Engineering

University of North Dakota, Grand Forks ND

[2]Climeon AB, Sweden

Keywords

distributed binary power, sedimentary geothermal

ABSTRACT

The geological setting of the Williston Basin with six geothermal aquifers having temperatures ranging from 80 ºC to 145 ºC and access to Missouri River water for cooling is conceptually ideal for distributed, binary power development. The temperatures, depths and hydrologic properties of the geothermal resource are well documented. The efficacy of horizontal drilling for high-volume water production in the basin has been demonstrated at the UND-CLR binary geothermal power plant. A network of high-efficiency, modular power plants installed at intervals along the course of the Missouri River in the Williston Basin could generate as much as 300 MW of electrical power. The key elements in this concept are knowledge of the geothermal resource, horizontal drilling in the geothermal aquifers, a high efficiency, modular, system that cascades the geothermal fluid, and the availability of cold Missouri River water for the condenser phase of the power plant. A special advantage of a distributed power network is its lack of vulnerability to cyber attack.

1. Introduction

Development of geothermal energy in sedimentary basins has several favorable aspects compared to fault-controlled hydrothermal systems. The thermal regime is conduction dominated and sufficient temperatures, although not as high as those in hydrothermal systems, are widespread in contrast to difficult and expensive-to-locate point sources. The fluids necessary to extract heat exist throughout sedimentary aquifers and the risk of drilling dry holes is minimal. Drilling in sedimentary rocks is faster, easier, and less costly than drilling in crystalline rocks and horizontal drilling is a mature technology. And, significantly, the prior research and data needed to identify and characterize a sedimentary geothermal resource are widely available in state and federal geological databases, journal articles, and university theses. With this favorability, one could ask why development has not begun. The answers lie in economics and the constraint of traditional thinking about geothermal power generation. The magnitude of the sedimentary geothermal resource is estimated to exceed 171 EJ (Porro and Augustine, 2006), but due to the low temperatures, 100 °C to 150 °C, which require binary power technology, the volume of fluid required to generate tens of MW of power exceeds the production capacity of sedimentary formations at a single locale. This is the constraint of traditional thinking in that large-scale power plants are the development target. An alternative approach that could make use of the sedimentary geothermal resource would be to install small, i.e. 1 to 2 MW, binary power plants in a distributed network. We propose that the Williston Basin is conceptually ideal for developing a network of binary power plants along the course of the Missouri River. The resource is well known, cooling water for the condenser phase of the power plant is available in deep lakes along the course of the river, and horizontal drilling at multiple sites spaced a few km apart could provide sufficient water to generate several hundred MW of power. In this paper we describe the resource and deployment of an innovative, high efficiency modular power plant along a 400 km energy corridor from eastern Montana to central North Dakota.

2. The Geothermal Resource

Estimates of the geothermal resource in the Williston Basin have been refined over time through continued data collection and analyses (Table 1). Each estimate of the accessible resource was based on the total energy contained specific formations determine as the product of fluid density, fluid heat capacity, aquifer volume, and the temperature difference between the resource and a reference temperature. However, the three early estimates used the mean annual air temperature as a reference temperature while the most recent estimate fixed the temperature difference at 50 ºC. The selection of a lower temperature difference permitted realistic calculations of electrical energy that could be produced by binary power conversion systems. All estimates of the recoverable resource followed the approach of Reed (1983) in assuming that approximately one-thousandth of the accessible resource could be recovered.

Accessible Resource	Method	Number of aquifers	Reference
6,428 EJ	$E = \rho\ c_p\ v\ \Delta T\ (T_f - T_{air})$	2	Sorey et al., 1983
13,500 EJ	$E = \rho\ c_p\ v\ \Delta T\ (T_f - T_{air})$	4	Gosnold, 1984
21,250 EJ	$E = \rho\ c_p\ v\ \Delta T\ (T_f - T_{air})$	12	Gosnold, 1991
28,530 EJ	$E = \rho\ c_p v\ \Delta T\ (50\ ºC)$	11	Crowell et al., 2011
35,000 EJ	$E = \rho\ c_p\ v\ \Delta T\ (T_f - T_{air})$	Total rock volume	Poro & Augustine, 2012

Table 1: Accessible geothermal energy in aquifer systems in the North Dakota portion of the Williston Basin. ρ is density (kg m-3), c_p is heat capacity (J kg^{-1} K^{-1}), v is volume in m^3, ΔT is temperature difference where T_f is formation temperature and T_{air} is mean annual air temperature. The Poro & Augustine (2012) number was inferred by visual summary from a slide.

2.1 Temperatures along the Energy Corridor

We combined the results of Crowell et al., 2011, Gosnold et al., 2012, and Gosnold et al, 2015 to categorize the geothermal resource as consisting of six major aquifer systems having temperatures ranging from 80 °C to 145 °C (Table 2). The uppermost aquifer system, the Dakota Group (Cretaceous), consists of sandstones and shales with a maximum thickness of 371 m and contains low TDS water in the Newcastle and Inyan Kara sandstones. Temperatures on top of the

Inyan Kara are 80 °C to 90 °C along the course of the Missouri River from Eastern Montana to central North Dakota. The Pennsylvanian aquifer system includes 333 m of sandstones and carbonates of the Minnelusa Group. Temperatures on top of the Minneslusa Group are greater than 105 °C. The Madison aquifer system (Mississippian) consists of carbonates having a maximum thickness of 753 m and has a temperature range of 114 °C to 129 °C along the power corridor. The carbonate Devonian aquifer consists of the Birdbear, Duperow, Souris River and

Dawson Bay formations. Temperatures in the Devonian aquifer exceed 130 °C along the power corridor. The Winnipegosis formation is a 67 m thick carbonate aquifer with temperatures of 130 °C to 135 °C. The basal aquifer includes four carbonate formations, Interlake, Stonewall, Stony Mountain, and Red River having a combined maximum thickness of 661 m and the sandstone-carbonate-shale 305 m thick Deadwood formation. Temperatures in the basal aquifer range from 136 °C to 145 °C. Water quality in the five lower aquifer systems is high TDS brine (≈300,000 mg l^{-1}).

2.2 Fluid Production

The critical factor in extracting heat from the resource is fluid volume. An apparently good source for geothermal fluids in a sedimentary basin would be the existing oil field infrastructure (INEL, 2006). North Dakota oil fields contain more than 7000 dry or plugged and abandoned oil and gas wells that potentially could be redeveloped for geothermal use. However, the wells are irregularly scattered by tens of km, a spacing would not facilitate concentration of sufficient water for power production. Another alternative is water co-produced with oil and gas (McKenna, et al., 2005; Blackwell and Richards, 2006). The attractiveness of co-production for power production is due to advances in organic Rankine cycle (ORC) technology (Brasz and Holdman, 2005) that have enabled power production using water temperatures as low as 92 ºC. Although co-production is promising in concept, our analysis of overall fluid production from active wells, units, fields and formations in the Williston Basin indicates that few sites co-produce sufficient fluid for power production. Average co-produced water for 10,480 wells is 3.2 gallons per minute (0.2 l s^{-1}). Excluding the tight shale formations, Bakken and Three Forks, average co-produced water for the remaining 3,337carbonate wells is only 5 gpm (0.315 l s^{-1}). The output of the highest producing well is 184 gpm (11.6 s^{-1}) and the average of the top 100 wells is only 52 gpm (3.3 l s^{-1}). The reason for low co-produced water volume is that the depths of the oil producing formations in the Williston Basin are 3 km or greater and pumps are operated slowly to prevent watering out. Thus, except in a few locations, co-produced fluids are not a potential geothermal resource in the Williston Basin.

A solution to the water volume problem is demonstrated by the Continental Resources (CLR) water flood project in the Cedar Hills field in southwestern North Dakota. CLR operates five eight-inch diameter water supply wells drilled horizontally into a carbonate aquifer (Lodgepole, Miss.) to produce a total flow of 1,960 gpm (124 l s^{-1}). The average flow per well is 360 gpm (22.7 l s^{-1}) and the average temperature is about 100 ºC. The UND-CLR Geothermal Power Plant (Gosnold, Mann, and Salehfar, 2017) uses water from two of the wells to generate 250 kW of power. The hydrostatic head for the carbonate aquifer is at ground surface and down-hole pumps set at 735 m and 967 m depths have produced water continuously since 2008. Geohydrology research on the Mesozoic and Paleozoic carbonate aquifers of the Williston Basin (Downey, 1986) suggests that all potential geothermal aquifers could produce similar fluid volumes.

Age		Generalized Stratigraphy	Hydrostratigraphy
Quaternary		Ft. Union, White River, & Coleharbor Groups	Upper Aquifer
Tertiary			
		Fox Hills Fm. & Hell Creek Fm.	
Cretaceous	U	Pierre Shale	Cretaceous Aquitard System
		Colorado Group (includes Niobrara & Belle Fourche)	
	L	Newcastle Fm.	Dakota Aquifer T 80 to 90 C
		Scull Creek Fm.	
		Inyan Kara Fm.	
Jurassic	U	Swift Fm.	Jurassic, Triassic, Permian Aquitard System
	M	Rierdon Fm.	
		Piper Fm.	
Triassic		Spearfish Fm.	
Permian	U	Minnekahta Fm.	
	L	Opeche Fm.	
Pennsylvanian		Minnelusa Group (Broom Creek Fm., Amsden Fm., Tyler Fm.)	Pennsylvanian Aquifer T 105 to 109 C
Mississippian	U	Big Snowy Group	Mississippian Aquitard
		Madison Group: Charles Fm.	
	L	Madison Group: Mission Canyon Fm.	Madison Aquifer T 114 to 129 C
		Madison Group: Lodgepole Fm.	
Devonian	U	Bakken Fm.	Bakken/Three Forks Aquitard
		Three Forks Fm.	
		Jefferson Group (Duperow Fm. & Birdbear Fm.)	Minor Devonian Aquifer T 131 to 135 C
		Manitoba Group (Dawson Bay Fm. & Souris River Fm.)	
	M	Prairie Fm.	Prairie Aquiclude
		Winnipegosis Fm.	Winnipegosis Aquifer T 135 C
		Ashern Fm.	Basal Aquitard
Silurian		Interlake Fm.	
Ordovician	U	Red River Fm.	Basal Aquifer T 136 to 145 C
	M	Winnipeg Group	
	L		
Cambrian	U	Deadwood Fm.	
	M		
Precambrian		Superior Province & Trans-Hudson Orogenic Belt	Lower Boundary

Table 2: Stratigraphy, hydrostratigraphy, and aquifer temperatures of the Williston Basin the course of the Missouri River. Modified after Ricker and Gosnold, 2014.

3. A Modular High-Efficiency Geothermal Power Plant

Conversion of air conditioning technology to power generation (Brasz and Holdman, 2005) stimulated interest in sedimentary basin geothermal development (McKenna et al., 2005; INEL 2006) more than a decade ago. Subsequently, a series of conferences held at Southern Methodist University beginning in 2006 advanced the concept by bringing together academia, industry, and state and federal government personnel to address geothermal development in oil and gas settings (http://www.smu.edu/Dedman/Academics/Programs/GeothermalLab/Conference). Further interest has grown through the Sedheat Initiative (Holbrook et al., 2012) and the concept was successfully demonstrated in 2016 (Gosnold, Mann and Salehfar, 2017). Although conceptually feasible, development has not occurred for a number reasons largely related to economics and scale (Williams, Snyder, and Gosnold, 2016), and in particular to limitations on the amount of power that can be generated from the resource. However, advances in power conversion during the past decade have resulted in greater efficiency and better matching of power conversion systems with the resource. Yet, a hindrance in all power conversion systems has been a fixed power output by machine so that utilization of the resource is not optimized. A single power conversion system may not use all the resource available or the resource may exceed the capacity of the system. The recently developed Climeon Heat Power System overcomes this hinderance.

3.1 Climeon Heat Power System

The Climeon Heat Power is a modular power plant solution, built on the basis of 150 kWel base modules that bundled together can produce multiple MW of power per plant. The technology differs from traditional ORC units in some key areas. The system is based on the Rankine cycle but the condensation side is under vacuum, and no heat recuperation downstream of the turbine is required. A controlled amount of a benign working fluid is evaporated significantly below 4 bar (a) in a heat exchanger, avoiding droplet formation which could be damaging for the turbine by overheating. A highly efficient and specially designed radial turbine which extracts energy from the expanding medium is coupled to an electrical generator capable of producing 400 or 690 V three-phase electricity at 50 or 60 Hz. The expanded working fluid is easily condensed clearly below 0.6 bar(a) using a modified direct contact technology. Condensed working fluid is cooled via a second heat exchanger and partly recycled to the condenser, partly fed to the evaporation section. The whole design enables a large pressure ratio of >6 with minimal wear of components and a cost-efficient solution. The system has been approved by Lloyds Register LLC for use in environments which are extremely demanding regarding safety, such as the maritime industry and cruise vessels in particular.

The technology achieves > 50% Carnot efficiency, or >10% net efficiency for 90 ^{o}C / 20 ^{o}C heating / cooling due to the high turbine efficiency, minimum losses in heat exchanging operations, and minimum internal power requirements. The parasitic load of the module is only 4 kW and the net electrical output is 150 kW¬¬el. The high efficiency entails benefits such as low space requirement – the 150 kW module has a 2 m*2 m footprint. The high energy density and possibility to stack modules together makes it possible to deploy 2,1 MW with a footprint of 28 m^2.

The modular approach is highly advantageous for cost reasons, both relating to mass production, transport, installation, commissioning and spare part ware-housing, and because modules can be operated independently at optimum conditions, e.g. under partial load or during routine service.

One of the most prominent benefits of a modular well-head power plant is the possibility to shorten the lead time of the project development and mitigate the financial risk. An incremental model for the deployment of geothermal projects makes it possible to finance the expansion with the cash flow from the previous power plant.

Achieving a high utilization factor of a geothermal power plant can be challenging since it is difficult to fully estimate the performance of a well before it has been flow tested. This can delay the project and result in the need to drill additional wells or installing an oversized power plant that cannot be fully utilized. Climeon Heat Power System consists of 150kW building blocks and the power plant can therefore be designed to fit the exact characteristics of each individual well. This saves cost and gives a higher utilization factor of the power plant since only the capacity needed is installed. It is also possible to move individual modules between sites if the well performance changes over time.

Each Climeon Heat Power module operates independently and if one module is taken out of production for maintenance the other modules will keep producing electricity, and if there is capacity available, the modules can even take over the load from that idle module. This create a redundant system that can follow an optimized maintenance schedule that minimize loss of production and guarantees stable baseload electricity to the grid.

The system can be configured both in parallel and series. This flexibility makes it possible to optimize the utilization of the available flow and temperature. The module has a nominal water flow of 30 kg/s and normally utilizes a dT of ~10°C. Modules connected in series can utilize a broader dT.

Figure 2: Showing a Climeon Heat Power System of 2.7 MW_{el}

4. Concept for the Energy Corridor

The combination of favorable resource temperatures, the potential for significant fluid production, the accessibility of significant fluid for condenser cooling, and the modularity of the Climeon power conversion system offer the opportunity to develop a large scale sedimentary geothermal network. The geothermal network would consist of 200 to 400 modular power conversion systems installed at 1 km to 5 km intervals within a 400 km corridor along the Missouri River from eastern Montana to the Garrison dam in North Dakota (Figure 3). Each site would be modeled after the CLR geothermal power plant. Each installation would use two to four geothermal wells drilled horizontally into a carbonate aquifer having a temperature greater than 125 ºC of up to ten Climeon power conversion modules would generate 1 to 2 MW of power at each site.

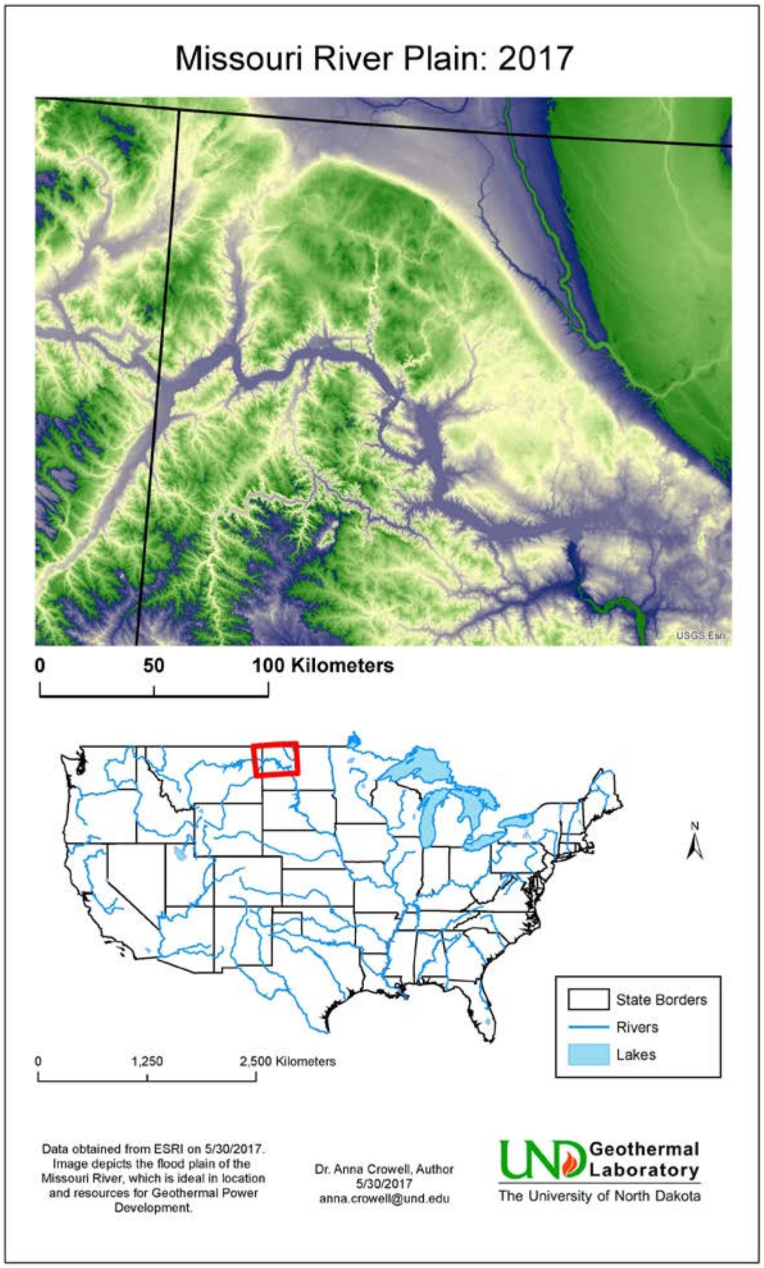

Figure 3: Regional relief map of the Missouri River in eastern Montana and western North Dakota alon the proposed energy corridor.

The Climeon Heat Power System is optimized for low-enthalpy resources and can handle temperatures between 50-120°C. The diagram below shows the net electrical output from a resource with a flow of 30 liter per second. From a well producing 30 liters per second at 120°C and with a 5°C heat sink the system can output up to 950 kW of net electrical output (not including auxiliary power consumption e.g. pumping and cooling). The brine output temperature varies between 56-58°C depending on the input temperature. This example gives an understanding of the systems potential and shows it is possible to utilize low-temperature resources for distributed power production.

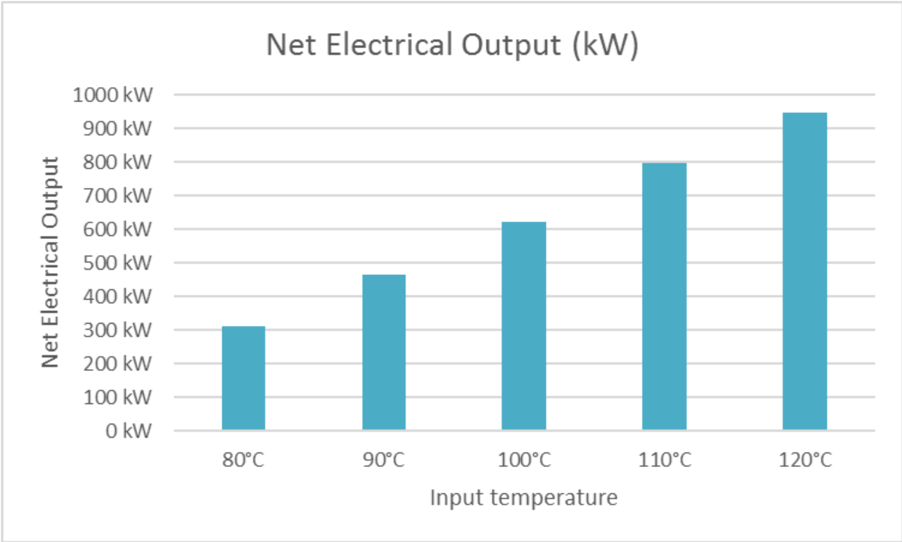

Figure 4: Climeon Heat Power System performance from a resource with a flow of 30 liters per second at varying input temperature.

5. Impact of the Energy Corridor

The proposed geothermal energy corridor could generate about 300 MW of electrical power. The Bakken and Three Forks oil boom, which has raised North Dakota to the second highest oil producing state behind Texas, is estimated to require 2,600 MW power in addition to current capacity. However, the need for this power and the grid to deliver it will exist only for the life of the Bakken and Three Forks plays which are projected to be 20 to 30 years. When the drilling phase for Bakken and Three Forks development is completed in 15 to 20 years, the oil-field service population of western North Dakota will decline to near pre-boom levels and the post boom power demand will decline even more. Thus the new power grid and the fossil-fuel based plants will become unnecessary. We propose that development of a distributed geothermal network could preclude construction of new fossil fuel burning power plants and in the long run be a sound economic investment for the electric power industry. A particular strength of the distributed network is its security from cyber attack.

There also are intangible benefits to development of the proposed geothermal energy corridor. Geothermal energy has inherent advantages in the power grid because it is baseload energy. The majority of renewable electrical energy is produced from wind and solar sources. These sources are intermittent and therefore not dispatchable for consumer needs. The electrical system takes the available energy and must increase or decrease the power output from dispatchable sources to meet electrical demand and grid stability. Typically, these sources are coal, gas and hydroelectric (Nuclear sources are generally not cycled). Renewable electrical energy from this geothermal resource is dispatchable and provides baseload capability and capacity. The distributed nature of the energy corridor ensures a high availability for the system due to planned maintenance shutdowns. If there is an unplanned shutdown, only a small fraction of the entire system would be out of service.

Another benefit is the fact that developing geothermal power rather than fossil fuel base power precludes adding CO2 the atmosphere. The amount of CO2 displaced by geothermal resources depends on the carbon-based fuel that is not consumed. For North Dakota lignite, 218.8-lb of CO2 are emitted for every million BTU's (mmBTU) consumed. Natural Gas is 117.0-lb of CO2 per mmBTU. An estimated heat rate for a lignite fired generator is 10,500-BTU/kW and 11,500-BTU/kW for simple cycle combustion turbine (SCCT). Given these values, 1-kW of geothermal generation will displace 2.30-lb of CO2 from lignite or 1.35-lb CO2 from natural gas SCCT.

REFERENCES

Blackwell, D., "Geothermal Resources in Sedimentary Basins." SMU Geothermal Conference, Dallas, Texas. Abstract. SMU Department of Geological Sciences. 2006.

Brasz, J., and Holdmann, G., "Power Production from a Moderate-Temperature Geothermal Resource." Transactions of the Geothermal Resources Council, 29 (2005), 729-734.

Crowell, A. M.; Klenner, R.; and W. Gosnold, "GIS Analysis for the Volume and Available Energy of Selected Reservoirs: Williston Basin, North Dakota," Transactions of the Geothermal Resources Council, 35, (2011), 1557-1561.

Downey, J., "Geohydrology of Bedrock Aquifers in the Northern Great Plains in Parts of Montana, North Dakota, South Dakota, and Wyoming," US Geol. Survey Prof. Paper 1402-E, (1981).

Gosnold, W., Mann, M., and Salehfar, H., "The UND-CLR Binary Geothermal Power Plant," Geothermal Resources Council Transactions, 41 (2017)

Gosnold, W.D., McDonald, M. R., Klenner, R., and Merriam, D. F., "Thermostratigraphy of the Williston Basin," Geothermal Resources Council Transactions, 36, (2012), 663-698.

Gosnold, W., Crowell, A., Nordeng, S., and Mann, M., "Co-Produced and Low-Temperature Geothermal Resources in the Williston Basin," Transactions of the Geothermal Resources Council, 39, (2015), 653-660.

Holbrook, J., Snyder, W., Moore, J., Fairhurst, C., Einstein, H., and Block, K., "Sedheat-Research Community Initiative on Geothermal Energy of Sedimentary Basins." AAPG-Datapages, Search and Discovery Article #80222 (2012).

INL, “The Future of Geothermal Energy. Impact of Enhanced Geothermal Systems [EGS] on the United States in the 21st Century.” INL/EXT-06-11746, (2006).

McKenna, J., Blackwell, D., and Moyes, C., “Geothermal Power Supply Possible from Gulf Coast, Midcontinent Oil Field Waters,” Oil & Gas Journal, (2005), 34-40.

Porro, C., and Augustine, C, “Estimate of Geothermal Energy Resource in Major U.S. Sedimentary Basins.” NREL/PR-6A20-55017, (2012).

Ricker, F, and Gosnold, W., “Characterization of Radiogenic Heat Production from Basement Rocks and Its Relationship to Heat Flow in the Williston Basin and North Dakota.” Stanford Geothermal Workshop, (2014).

Öström, T., Ahlbom, E. and Karthäuser, J., patents /patent applications US 942 9046 and others

Williams, T., Snyder, N., and Gosnold, W, “DOE-GTO Low Temperature Projects Evaluation and Lesson Learned,” Geothermal Resources Council Transactions, 40 (2016)