December 2022

Geothermal Energy: Direct Use Application From Repurposed Oil And Gas Wells For Williston State College

Nnaemeka C. Ngobidi

Recommended Citation

Ngobidi, Nnaemeka C., "Geothermal Energy: Direct Use Application From Repurposed Oil And Gas Wells For Williston State College" (2022). *Theses and Dissertations*. 4551.
https://commons.und.edu/theses/4551

GEOTHERMAL ENERGY: DIRECT USE APPLICATION FROM REPURPOSED OIL AND GAS WELLS FOR WILLISTON STATE COLLEGE

by

Nnaemeka Ngobidi
Bachelor of Technology, Federal University of Technology, Owerri, Nigeria. 2012

A Thesis

Submitted to the Graduate Faculty

Of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science in Geology

Grand Forks, North Dakota
December
2022

Name: Nnaemeka Ngobidi

Degree: Master of Science

This document, submitted in partial fulfillment of the requirements for the degree from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

DocuSigned by:
William Gosnold
53AACDF0D79A43B...
William Gosnold

DocuSigned by:
Stephan Nordeng
313181BF2DED4CC...
Stephan Nordeng

DocuSigned by:
Taufique Mahmood
3F7DA8280EB4408...
Taufique Magmood

Name of Member 4 - delete if not needed

Name of Member 5 - delete if not needed

Name of Member 6 - delete if not needed

This document is being submitted by the appointed advisory committee as having met all the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

DocuSigned by:
Chris Nelson
2E0AF088C733403...
Chris Nelson
Dean of the School of Graduate Studies

11/22/2022
Date

DEDICATION

This thesis is dedicated to my mother. I may not have seen God, but I have seen my mother.

PERMISSION

Title: Geothermal Energy: Direct Use Application from Repurposed Oil and Gas Wells for Williston State College.

Department: Harold Hamm School of Geology and Geological Engineering

Degree: Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the library of the University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in his absence, by the Chairperson of the department or the Dean of the School of Graduate Studies. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota for any scholarly use which may be made of any material in my thesis.

Nnaemeka Ngobidi
November 18, 2022

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENT

I would like to thank my advisor, Professor William Gosnold, for his support, guidance, and encouragement and for carefully making out time to review my research and offer advice to my research, from the start of my graduate program until date. A sincere appreciation goes to my committee members - Dr Stephan H. Nordeng, and Dr Taufique Mahmood, for their guidance during my research and their helpful insight.

A big thank you to the Niger Delta Development Commission for support/scholarship through the years, The Institute of Energy Studies, Professor Michael Mann, and Nolan Theaker for funding and a Graduate Research Assistant (GRA) position.

To Anna Crowell for providing me with the necessary data and training, I needed for this research.

To Michael K. Nord of UND facilities for heating consumption data I used to reference my work,

To Moones, Shane, Sidike, members of the UND Geothermal team - all of whom I learned a thing or two from in this journey and to my family and friends especially Kene Obi for their support and motivation throughout the years, I say a big thank you. I appreciate every one of you.

ABSTRACT

This analysis of the logistics of repurposing plugged and abandoned oil wells for use in district heating indicates that it is economically feasible and provides a guide to inform the development of geothermal direct use in the Williston Basin. This study focused on Williston State College where data on campus infrastructure, heating and cooling loads, oil well status, and geothermal resource potential are available. I selected a PA well and an SWD well that lie within 2 km of the WSC campus for the production and injection wells for the analysis. The alternative to using PA wells, drilling a new production well, is significantly less economical. The WSC campus buildings occupy an area of >250,000 sqft and energy usage is 36 MMBTU per year. The geothermal resource is 80+ °C (176 °F) water in the 177 m (580 ft) thick Inyan Kara formation (Cretaceous) at a depth of 1.5 km (5230 ft.). The geothermal resource lies in a 110 m thick Inyan Kara sandstone unit with a known porosity of 21%, a productivity index of 31.93 bbl/day/psi, Total Thermal energy of 1.12 x10^{16}J, and Heat produced as 2.81 x 10^9 BTU/day.

I used the GEOPHIRES software to input the resource parameters of the selected well. The GEOPHIRES simulation indicates that the LCOH for this analysis is 12.0 $/MMBTU which exceeds the current price of heat by natural gas. However, switching to geothermal from natural gas would eliminate approximately 215million metric tons/year of CO_2. Extending this analysis throughout the Williston Basin suggests that the replacement of fossil fuels by geothermal district heating could eliminate CO_2 production of hundreds of millions of tons per year.

INTRODUCTION

According to Safronov, 1969; Levin, 1972; Greenberg et al., 1978; Wetherill, 1985; Ahrens, 1990, The Earth was formed by accretion from a hot cloud of gas and dust about 4.56 billion years ago and upon completion of the accumulation process was hot and fully differentiated into a mantle and core with the core superliquidus and the mantle near its solidus (Schubert 1979; Schubert et al., 1979a, b,1980; Stevenson et al., 1983).

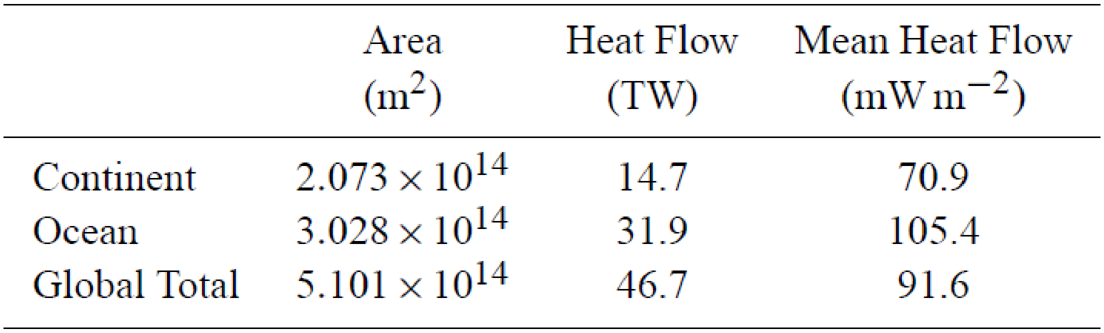
Accretion and separation of the core from the mantle by gravitational settling liberated a vast amount of heat, which has since been dissipating through the Earth's surface. However, only part of the present surface heat flow is due to primordial heat - radiogenic sources within the mantle and crust account for as much as 83% of the present total. The crust itself generates approximately 40% of the observed surface heat flow from the radioactive decay of uranium, thorium, and potassium.

Heat flows through the Earth primarily by convection in the mantle and conduction and advection in the crust; heat flow is not uniform across the surface. More heat is lost through the oceans than through the continental shields.

Measurements of temperature at depth are of limited value if the thermal profile cannot be extrapolated to the surface. The thermal gradient in the top portion of the crust remains unconstrained without an estimate of the average surface temperature. The temperature at the center of the inner core is about 7000 ^{o}C. The average surface temperature is 16 ^{o}C and varies from below zero at the polar latitudes to tens of degrees above zero in tropical latitudes.

The key measurement in geothermal exploration is the geothermal gradient.

According to Davies and Davies (2010), Earth’s total surface heat flow is 47±2TW which suggests a mean heat flow of 0.092 Wm^2 and an average geothermal gradient at the surface of 35 K/km.



	Area (m^2)	Heat Flow (TW)	Mean Heat Flow ($mW\,m^{-2}$)
Continent	2.073×10^{14}	14.7	70.9
Ocean	3.028×10^{14}	31.9	105.4
Global Total	5.101×10^{14}	46.7	91.6

Table 1: Summary of continental and oceanic heat flow from preferred estimates. (Davies and Davies, 2010)

Heat is generated in rocks by the radioactive decay of unstable isotopes of uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K) that releases energy and the absorption of the kinetic energy by the surrounding rocks (Beardsmore, Cull, 2001). The rate of radiogenic heat generation within rocks is related to the quantity of radioactive material, the rate of decay, and the energy of the emitted particles. The energy emission and rate of decay depend only on the species of radioactive isotope so the absolute abundance of individual isotopes in a rock determines the rate of heat production (Beardsmore, Cull, 2001). Heat moves by convection through the Earth, but conduction is the dominant means of its movement through the crust. Heat flow and calculated geothermal gradients vary from place to place. It is higher in areas with either high radioactivity or where the Earth's crust is thinner, such as the mid-oceanic ridges or the Basin and Range Province of the Western United States. This is related to its geologic age and tectonic activity (it is hot and young). High heat flow cannot be entirely explained by heat production in the crust. The mantle beneath this region must also be hotter than normal. In contrast, the eastern U.S. consists of old and cold crust, lithosphere, and asthenosphere. Heat flow in the ocean basins is also highly variable. The highest values correspond to the mid-ocean ridges. Heat flow decreases away from the mid-ocean ridges and is at a minimum over the convergent plate boundaries, deep ocean trenches, or subduction zones (Stein and Stein, 1992). In general, the lithosphere is hot where the underlying asthenosphere is hot, and cold where it is cold. Heat flow at the surface of the continental crust averages 59 mW/m^2 (milliwatts per meter squared) (Tester et al., 2006). Many factors influence regional heat flow, including localized radioactivity, crustal thickness, and water advection (Lachenbruch, 1970, Cermak 1983).

Geothermal Energy's driving force is heat flow and that explains the reason continuous power production is possible. On average, the temperature of the Earth increases with depth at about 30˚C/km. Thus, assuming a conductive gradient and mean surface ambient temperature, the temperature of the earth at 10 km would be over 300˚C (Lund et al., 2008).

Geothermal energy can effectively meet all of humanity's energy requirements for many generations. The stored thermal energy in place in the upper 3 to 10 km of the crust in the United States is approximately 14 x 10^6 EJ (Sanyal and Butler 2005). However, technological innovations to harness it faces numerous technical and commercial challenges. The main difficulty is the high cost and commercial risks associated with deep drilling and failure to extract enough heat.

This energy could be harnessed for a variety of uses, which are power production, direct use, and heat pumps.

Geothermal Power production: Heat energy with temperatures greater than 150^{o}C is required for power production using standard steam power plant technology (Muffler, L.J.P. 1979). The energy can be converted to mechanical energy which can run a dynamo and generate electricity. The categories for power generation are direct steam, flash, binary plant, and Enhanced Geothermal Systems **(**The National Renewable Energy Laboratory (NREL)). Direct steam plants are the rarest and most valuable because they have access to such high ground temperatures. The plants use elevated-temperature steam via production wells that are thousands of feet underground. The steam in these systems is processed so that particulates and non-essential fluids are removed and then it is piped to operate turbines that generate electricity (Hulen, et al 2001). Flash-steam power plants are much more common, and these systems primarily use highly pressurized hot water that is transported to the surface via production wells. The pressure of this water is reduced during transport, a fraction of the water "flashes" or explosively boils into steam, and then this steam is moved to a turbine to generate electricity. Water that does not flash into steam is channeled back to the reservoir to maintain pressure and productivity. Binary-cycle power systems, hot water is circulated through a heat exchanger which heats a secondary working fluid that turns to vapor at a lower temperature than water. Closed-loop systems use vapor to spin turbines to generate electricity. The vapor then condenses back into the liquid and is transported back to the heat exchanger where the process begins again (Hulen, et al 2001). Enhanced Geothermal Systems is to extract heat by creating a subsurface fracture system to which water can be added through injection wells. Creating an enhanced, or engineered geothermal system requires improving the natural permeability of the rock. Rocks are permeable due to minute fractures and pore spaces between mineral grains. Injected water is heated by contact with the rock and returns to the surface through production wells, as in naturally occurring hydrothermal systems. EGS are reservoirs created to improve the economics of resources without adequate water and/or permeability.

Geothermal Heat Pumps (GHP): A GHP is an electric heat pump that transfers natural heating and cooling from the ground to regulate building air temperature. The resource temperature needed here is surface temperatures of 40-80ºF. it can be harnessed everywhere. In the winter, a GHP works by utilizing the ground temperature that is warmer than the air above it to heat buildings; in the summer, the opposite process can be used to cool buildings where the heat from indoor air is transferred out of the house into the cooler ground. The ground can be thought of as a heat source during the cold of winter and a heat sink during the hot summer months.

Geothermal Direct Use: Direct utilization (direct use) of geothermal energy is one of the oldest, most versatile, and most common forms of utilizing geothermal energy (Dickson and Fanelli, 2003). The early history of geothermal direct use has been reviewed for over 25 countries in the *Stories from a Heated Earth – Our Geothermal Heritage* (Cataldi, et al., 1999), which documents geothermal use for over 2,000 years. Geothermal direct-use systems in the United States have historically been limited to utilizing shallow resources, from hot springs at the surface to wells typically not deeper than 1–2 km. These shallow, higher-grade resources tend to occur in the western United States, where all the current ~100 direct-use systems are located (Snyder et al. 2017). Geothermal direct use involves utilizing low to moderate-temperature resources to provide heat directly to a wide variety of residential, industrial, and commercial applications such as homes, offices, commercial greenhouses, fish farms, food processing facilities, and mining operations as well as other direct-heating applications like melting snow on sidewalks. Directly using geothermal energy in homes and commercial operations is much less expensive than using traditional fuels. Savings can be as much as 80% over fossil fuels. It is also clean, producing only a small percentage (and in many cases none) of the air pollutants emitted by burning fossil fuels. (NREL 2022)

Beckers et al. (2021) investigated the feasibility of utilizing deep geothermal resources for direct-use applications in the United States including for heating, cooling, and thermal storage. The feasibility of DDU was assessed by reviewing the results of six recently conducted DOE-funded DDU projects in the United States and running additional techno-economic simulations with the tool GEOPHIRES. Results were compared with prior studies, existing GDH systems in the United States and Europe, and the performance of non-geothermal centralized and non-centralized heating, cooling, and thermal storage systems. Analysis from the study indicates that deep direct-use feasibility varies widely, depending on subsurface characteristics, system design, and financial conditions. John Lund (2015) recommended the guidelines for selecting the necessary equipment for successfully implementing a direct-use project, including downhole pumps, piping, heat exchangers, and heat convectors.

Direct-use systems are typically composed of three components:

- A production facility – usually a well capable of extracting heat from the source/target formation and bringing the hot water to the surface.
- A mechanical system – piping, heat exchanger, controls – to deliver the heat to the space or process; and
- A disposal system – injection well, storage pond, or river – to receive the cooled geothermal fluid.

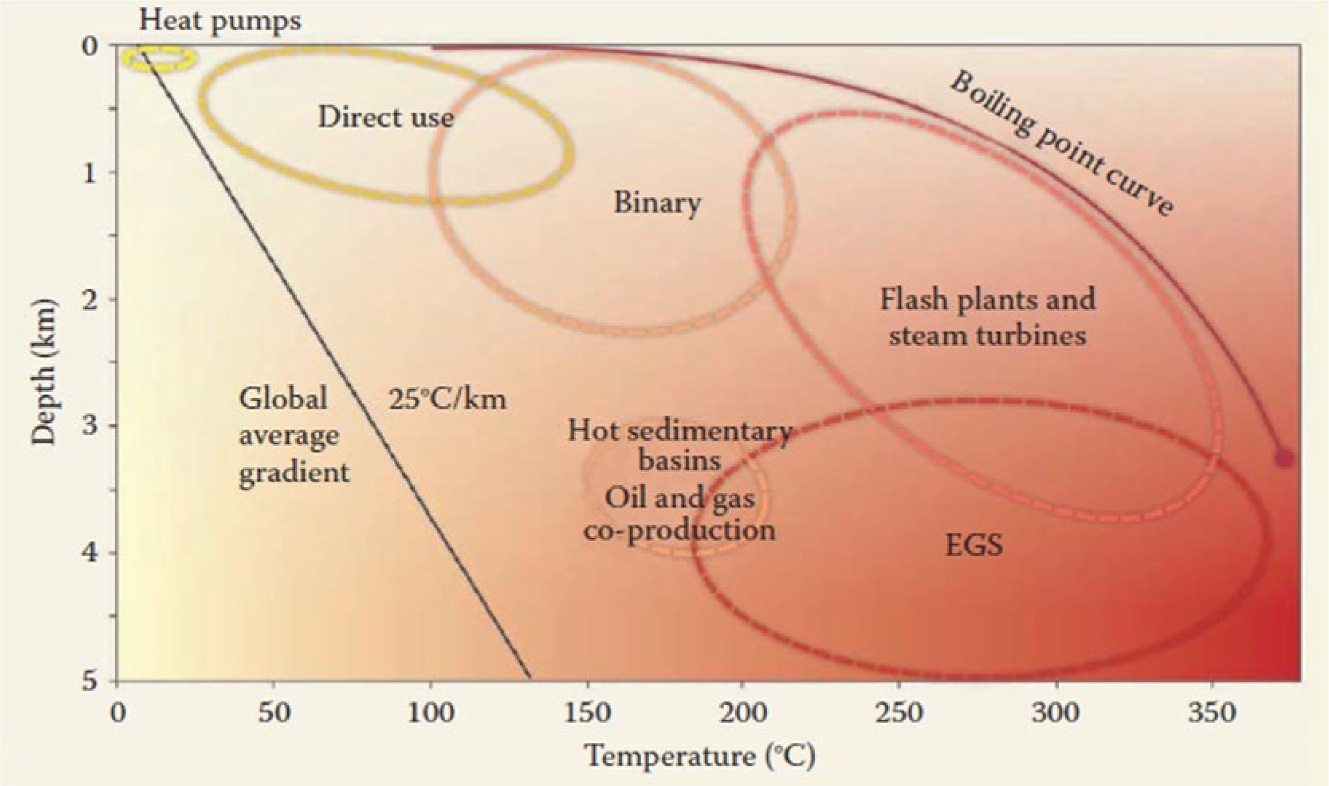


Figure 1: Generic temperature with depth graph showing the temperature-depth regions of different types of geothermal energy adapted from Moore, Simmons, (2013)

According to Fox et al. (2011) and Tester (2011), The estimated energy consumed as a function of utilization temperatures places domestic, commercial and some industrial usage ranges from 20-120ºC while the demand for low-temperature heat is over 30% of total statewide energy end use (McCabe et al. 2016). This heat demand includes space and water heating, cooking, clothes drying, hot tub heating in the residential sector and greenhouse farming, fish farming, vegetable and fruit drying, etc.

Geothermal energy in oil and gas settings has the potential to offset fossil fuel energy use. These low-temperature demands (<150ºC) are currently being supplied for these uses by on-site fossil fuel combustion machinery, analyzing the heat flow map of the conterminous United States, low temperature can be generated from all over the United States and Midwestern states like North Dakota, Minnesota etc. with extreme temperatures can harness these energies and use for residential, commercial, and agricultural purposes while also reducing the emission from fossil fuel.

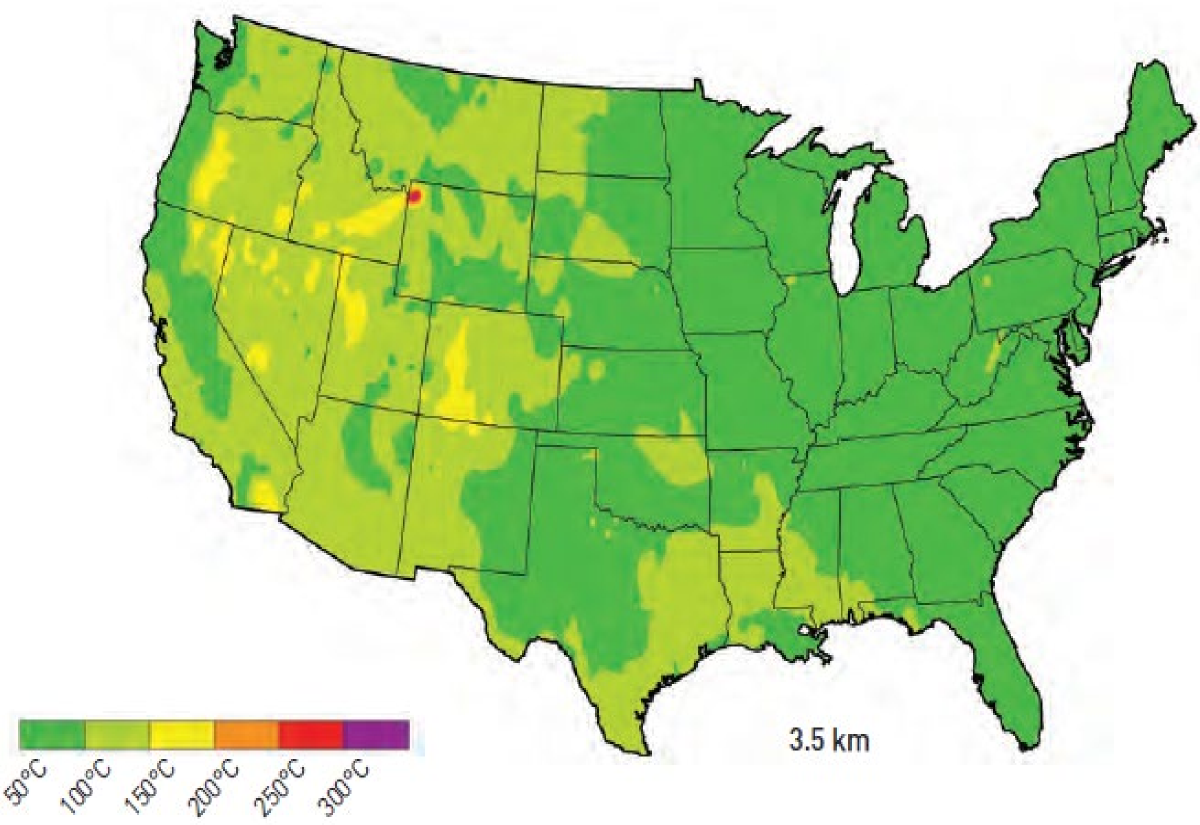


Figure 2: Average temperature at 3.5km depth (Tester et al. 2006)

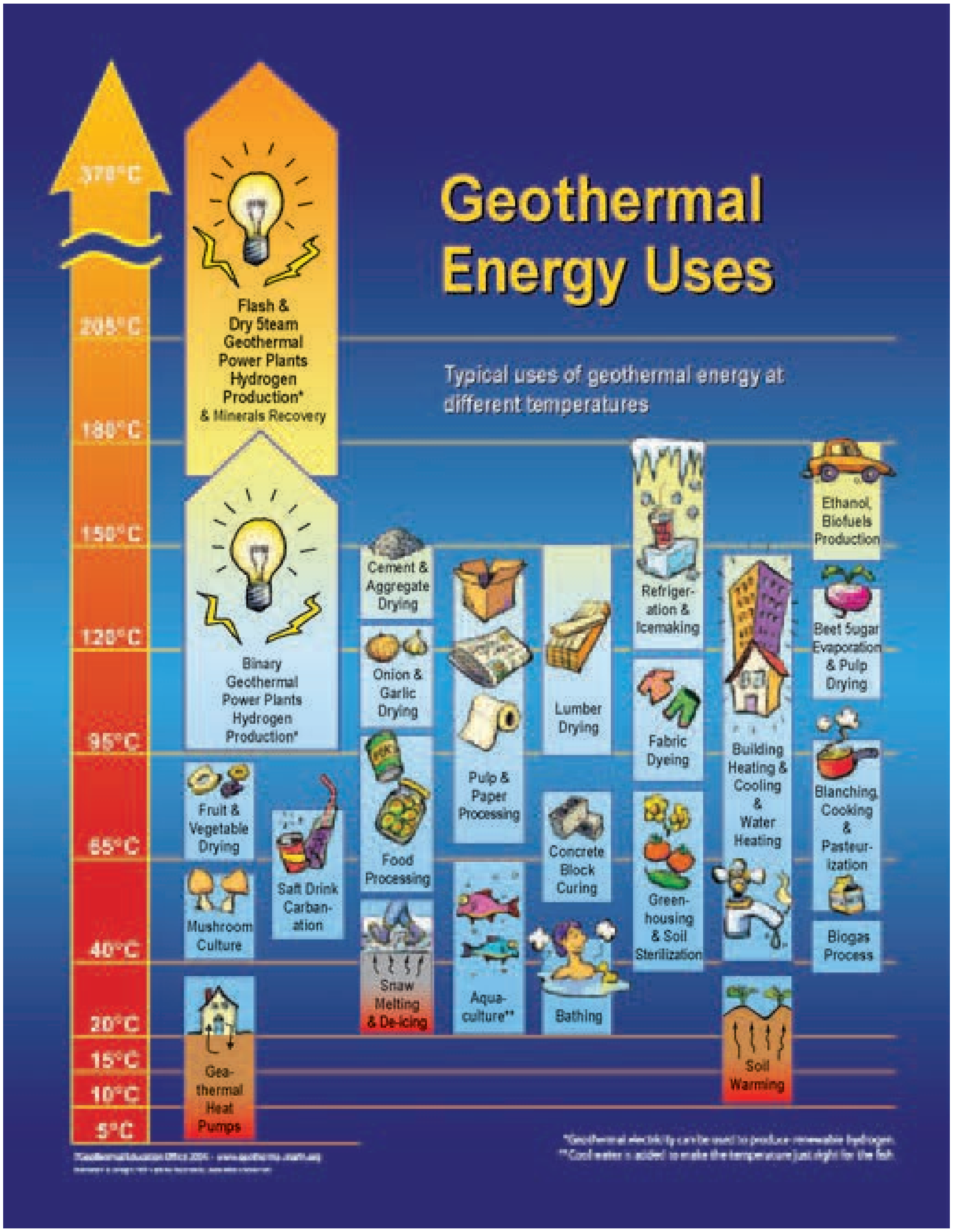
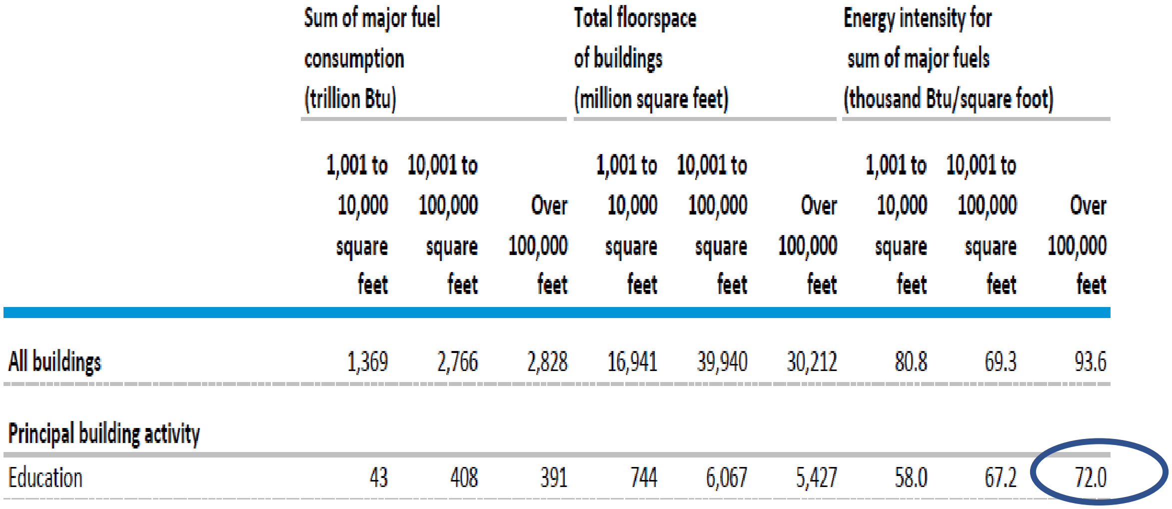


Figure 3: examples of direct-use applications courtesy of the geothermal education office

Geothermal energy is the thermal energy from the Earth's interior that is available for exploitation and is a baseload resource. It has a variety of applications, including space heating and cooling, district heating, industrial heat processes, and electrical power generation. Colleges and universities in the US use an average of 18.9 kilowatt-hours (kWh) of electricity and 17 cubic feet of natural gas per square foot (ft^2) of floor space each year. (esource.com). Personal communications with Michael K. Nord (2022) – The Assistant Director, Energy, and Continuous Improvement Services, Facilities Management Department, the University of North Dakota from private data gave heat consumed by academic buildings at the University of North Dakota to be an average of 72 kBtu/sf (Thousand Btu/square foot) and that of housing averaging at 76 kBtu/sf for the year 2019 before COVID-19 outbreak where students were mostly in-person compared to 53kBtu/sf academic building and 60kBtu/sf housing buildings for the year 2021 post-COVID-19 era where students were learning online. This 72kBtu/sf pre-COVID-19 era is in line with the United States Energy Information Administration, Commercial Buildings Energy Consumption Survey (CBECS) data (US EIA, 2016) for buildings over 100,000square feet.



	Sum of major fuel consumption (trillion Btu)			Total floorspace of buildings (million square feet)			Energy intensity for sum of major fuels (thousand Btu/square foot)		
	1,001 to 10,000 square feet	10,001 to 100,000 square feet	Over 100,000 feet	1,001 to 10,000 square feet	10,001 to 100,000 square feet	Over 100,000 feet	1,001 to 10,000 square feet	10,001 to 100,000 square feet	Over 100,000 feet
All buildings	1,369	2,766	2,828	16,941	39,940	30,212	80.8	69.3	93.6
Principal building activity									
Education	43	408	391	744	6,067	5,427	58.0	67.2	72.0

Table 2: Consumption and gross energy intensity by building size for a sum of major fuels, 2012 (EIA, 2016)

The objective of this study is to determine the efficacy of using oil-field infrastructure to produce geothermal energy focusing on Direct Use to reduce Carbon emissions in North Dakota using the Williston State College as the target location for utilization. Its success will provide a road map to the deployment/use of these infrastructures to benefit North Dakota by expanding to other cities in the State.

This study hypothesizes that the 3.68×10^9 BTU/year heating demand by the Williston state college and the Williston Area Recreation Centre (WARC) can be met by reopening well 7290 on the NDIC website - a plugged and abandoned oil and gas well, and perforating intervals within the Inyan Kara Formation.

STUDY AREA

The Williston Basin is an ellipsoidal-shaped depression centered in western North Dakota and extending into parts of Montana, South Dakota, Manitoba, and Saskatchewan. It is flanked on the east by the Sioux Uplift, to the north by the Punnichy Arch and exposed Canadian Shield, and to the west by the Sweetgrass Arch. It is a structurally simple intracratonic sedimentary basin that contains an almost continuous stratigraphic record since the Middle Cambrian. The sedimentary secession has a maximum thickness of over 4km near the basin center in North Dakota, and its history is reflected in a suite of transgressive and regressive sequences indicative of a shallow marine environment (Porter, Price, and McCrossan, 1982). The Williston Basin spans an international border, three domestic political boundaries in the United States, and two in Canada (Figure 4). The Williston Basin started subsiding during the Cambrian, but the significant subsidence was in the Ordovician Period (~495 million years ago), and it underwent episodic subsidence throughout the rest of the Phanerozoic. It is deepest near Watford city in McKenzie County having a maximum thickness of 4000 meters and becomes both shallower and thinner towards the margins. The major structural features present in the basin include the Nesson anticline, the Cedar Creek anticlines and less prominent structural features such as the Billings anticline, Little Knife, and the Poplar Dome

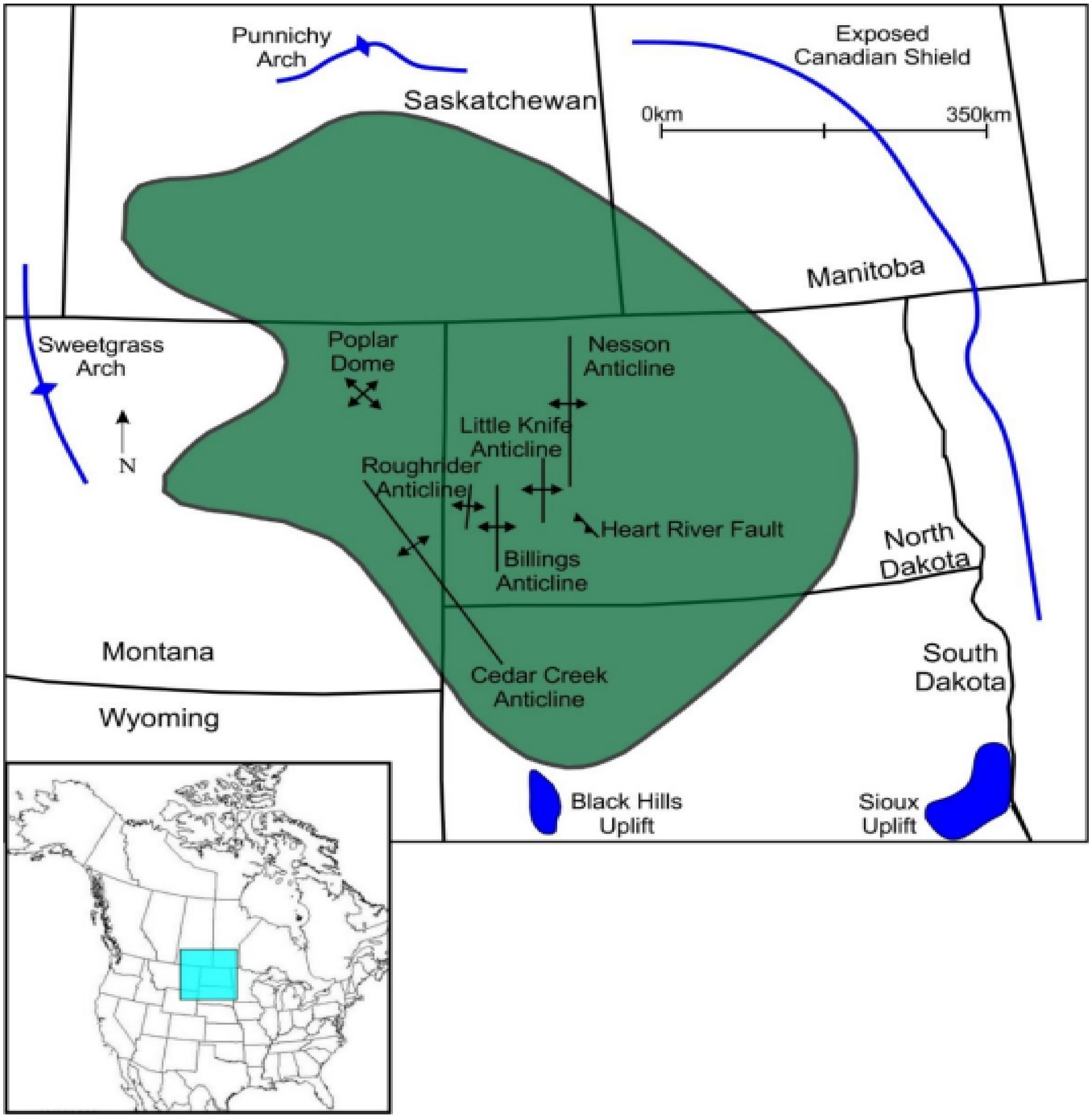


Figure 4: Location and outline of the Williston Basin showing major basement structures. (Modified from Gerhard et al., 1982)

The Inyan Kara in North Dakota consists of fluvial, estuarine, and marginal marine units that were deposited in a paralic (coastal) setting along the Cretaceous Western Interior Seaway circa 100 Ma (Bader, 2016). The formation does not crop out in North Dakota, with the nearest surface exposure of equivalent units being present on the flanks of the Black Hills in South Dakota and eastern Wyoming (Willis, 1997). The paralic depositional environment of the Inyan Kara is complex, with sandstone bodies that may have significant thickness changes laterally, making it difficult to place disposal wells in optimum locations. Sequence stratigraphy allows for a better understanding and prediction of sandstone geometries in these nearshore settings.

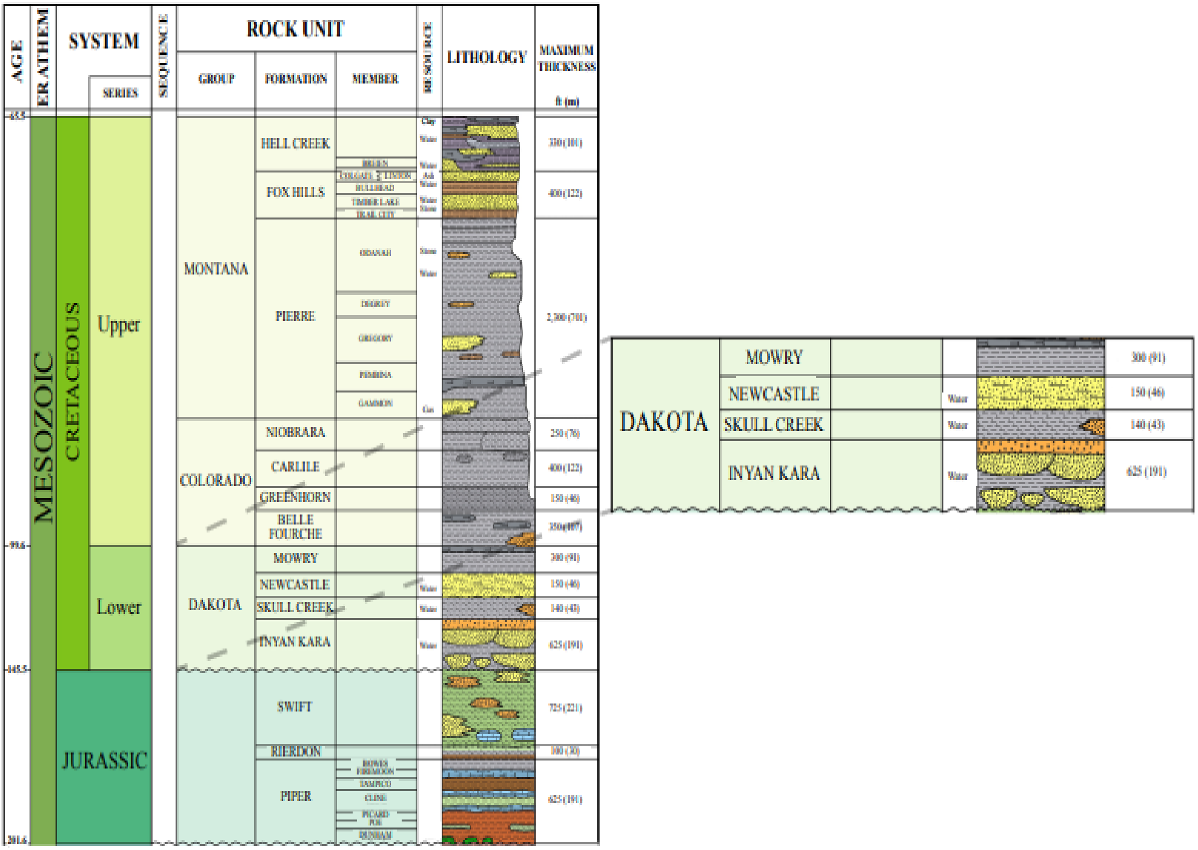


Figure 5. Stratigraphic column for Jurassic and Cretaceous rocks of North Dakota (Murphy et al., 2009, Bader 2019.)

METHODS OF STUDY

The methodology that will be employed here includes a literature review of past research and the collection of data from well-files from the North Dakota Industrial Commission (NDIC) website. Further processes include:

- Wellsite Identification: This includes Identifying potential wells for repurposing and formation of interest. Distance will play a key role in the choice of well as it will reduce transmission pipe from the production well to the location of use which is the Williston State College.
- Resource Characterization: Characterizing the resource involves knowing the temperature of the formation of interest using the Thermostratigraphy 'Tstrat' plot for temperature vs depth, the thermal energy potential of the formation, flow rates, porosity, permeability will be calculated from well log data accessed from the NDIC website.
- Economic feasibility using the GEOPHIRES: Using the tool to stimulate the financial feasibility of the resource based on the parameters derived from the characterization.

PURPOSE AND SCOPE

This study aims to determine the efficacy of using oil-field infrastructure to produce geothermal energy focusing on direct use. Coal is the main source of electricity for North Dakota and as such poses a considerable emission problem. According to USEIA (2021) data sheet, North Dakota's emission for 2018 stands at about 58.9 million metric tons of energy-related carbon dioxide. This information is a reason to seek ways to reduce carbon emissions and save our environment. temperatures in North Dakota can fall as low as -40ºC and to keep warm, heating is needed. This heat demand includes space and water heating, cooking, and clothes drying in the residential sector and the source of this heat is fossil fuels. If we can service the heating demand of the residential sector and some/all of the commercial sector using the direct use of geothermal energy, we would have reduced the consumption need by above 25% in figure 7 invariably decreasing a significant amount of CO_2 in the environment.

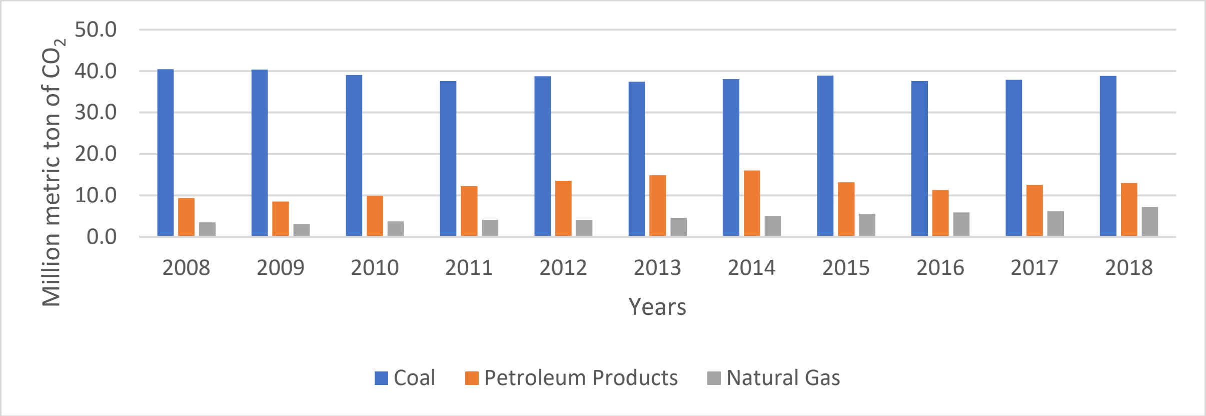


Figure 6: Carbon dioxide emission from fossil fuel consumption from 2008-2018 (Energy Information Administration, State Energy Data System, 2021)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Coal	40.5	40.3	39.0	37.6	38.7	37.5	38.0	38.9	37.6	37.9	38.8
Petroleum Products	9.4	8.5	9.8	12.2	13.6	14.9	16.1	13.2	11.3	12.6	13.0
Natural Gas	3.5	3.1	3.7	4.1	4.1	4.6	5.0	5.6	5.9	6.3	7.2

Table 3: Carbon dioxide emission from fossil fuel consumption from 2008-2018 for North Dakota (Energy Information Administration, State Energy Data System, 2021)

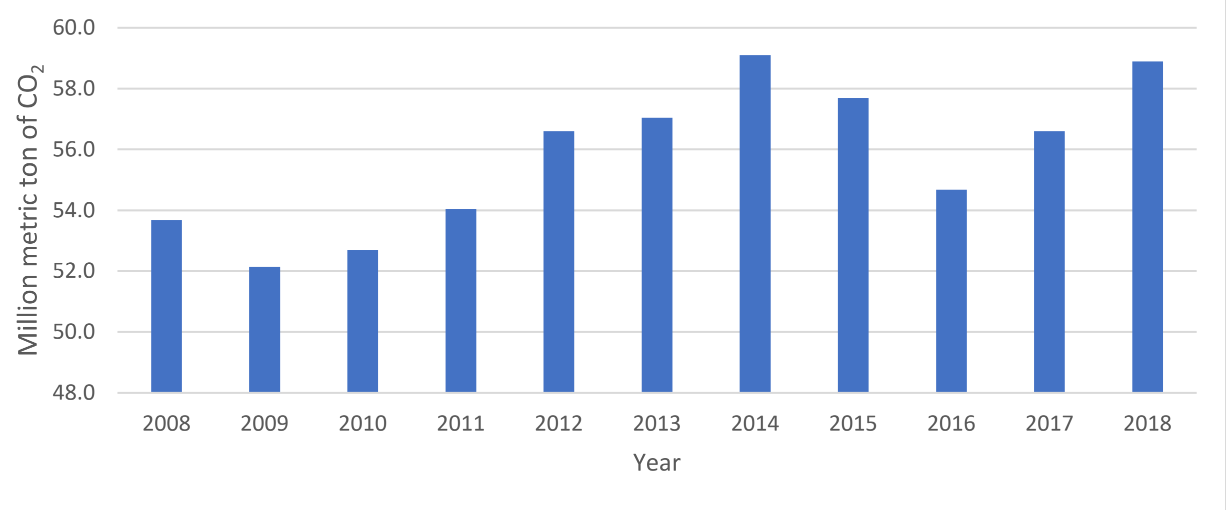


Figure 7: Energy-related Carbon dioxide emissions from 2008-2018 for North Dakota (Energy Information Administration, State Energy Data System, 2021)

In this research work, information on these wells was obtained from the North Dakota Industrial Commission (NDIC) Database.

Repurposing these wells for geothermal use is the reason for considering them and using the information from these wells for new drilling nearby. With the cost of drilling new wells, a major problem for geothermal projects, a cost-effective way to proceed is to repurpose the wells designated for abandonment/plugging. Data from the NDIC database on existing well provides a piece of detailed information on the various formations in the well which in turn helps in evaluating the factors necessary for determining geothermal resource location and provides some certainty in forecasting thermal energy production.

ENERGY RESOURCES OF NORTH DAKOTA

North Dakota has an abundance of energy resources from nonrenewable to renewables alike that includes Petroleum(crude oil), Coal, Natural gas, wind energy, Hydroelectric, Biomass etc. According to the United States Energy Information Administration (USEIA) (2020), North Dakota is ranked second after Texas in both crude oil production and proved crude oil reserves and produces about 3% of the United States fuel ethanol making it one of the top 10 ethanol-producing states in the country. It has almost 3% of U.S. natural gas reserves, in 2020 the state accounted for 2.5% of U.S. natural gas gross withdrawals. North Dakota is a top-10 coal-producing state, accounting for 4% of U.S. total coal production making the United States the fourth largest lignite coal reserves worldwide after Russia, Australia, and Germany. In 2020, coal-fired power plants provided 57% of North Dakota's electricity generation, and wind energy accounted for 31%, which was the fifth-highest share of wind power for any state.

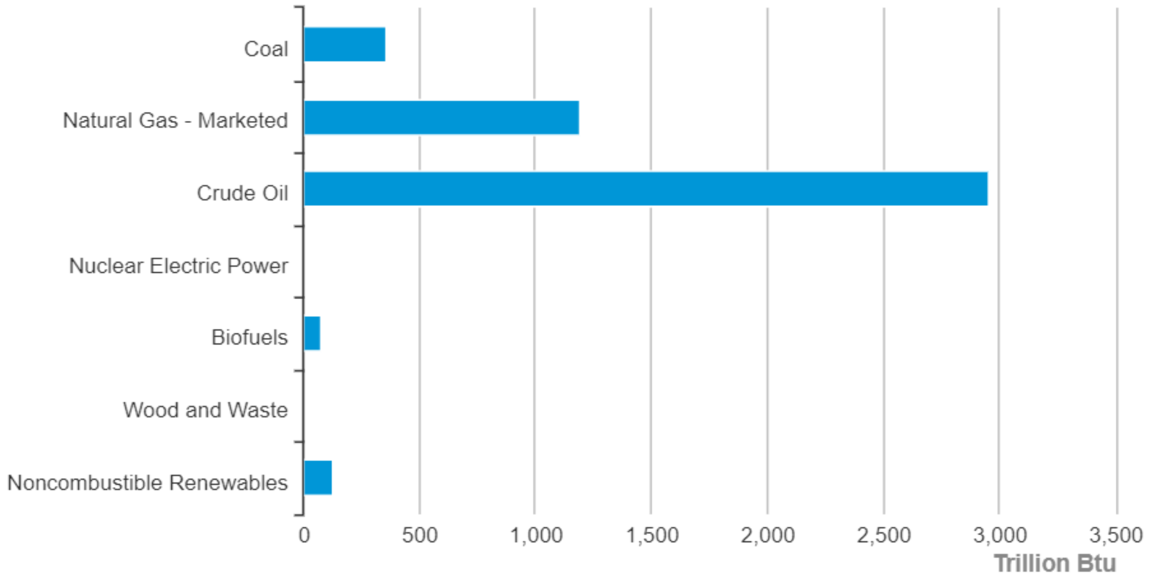


Figure 8: Bar Chart of North Dakota Energy Production Estimates, 2019. (Energy Information Administration, State Energy Data System, 2021)

Category	North Dakota Energy Production Estimates (Trillion Btu)
Coal	361.9
Natural Gas - Marketed	1188.3
Crude Oil	2956.5
Nuclear Electric Power	0
Biofuels	79.2
Wood and Waste	1.9
Noncombustible Renewables	129.2

Table 4: North Dakota Energy Production Estimates, 2019. (Energy Information Administration, State Energy Data System, 2021)

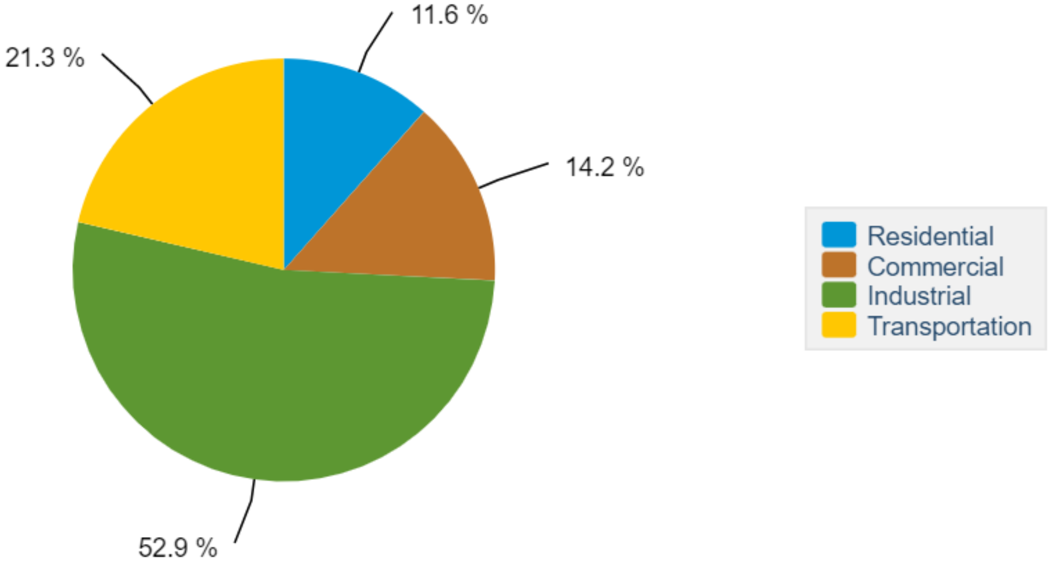


Figure 9: Pie Chart of North Dakota Energy Consumption by End-Use Sector, 2019. (Energy Information Administration, State Energy Data System, 2021)

Category	Energy Consumption by End-Use Sector
Residential	78.9
Commercial	97.2
Industrial	360.9
Transportation	145.7

Table 5: North Dakota Energy Consumption by End-Use Sector, 2019. (Energy Information Administration, State Energy Data System 2021)

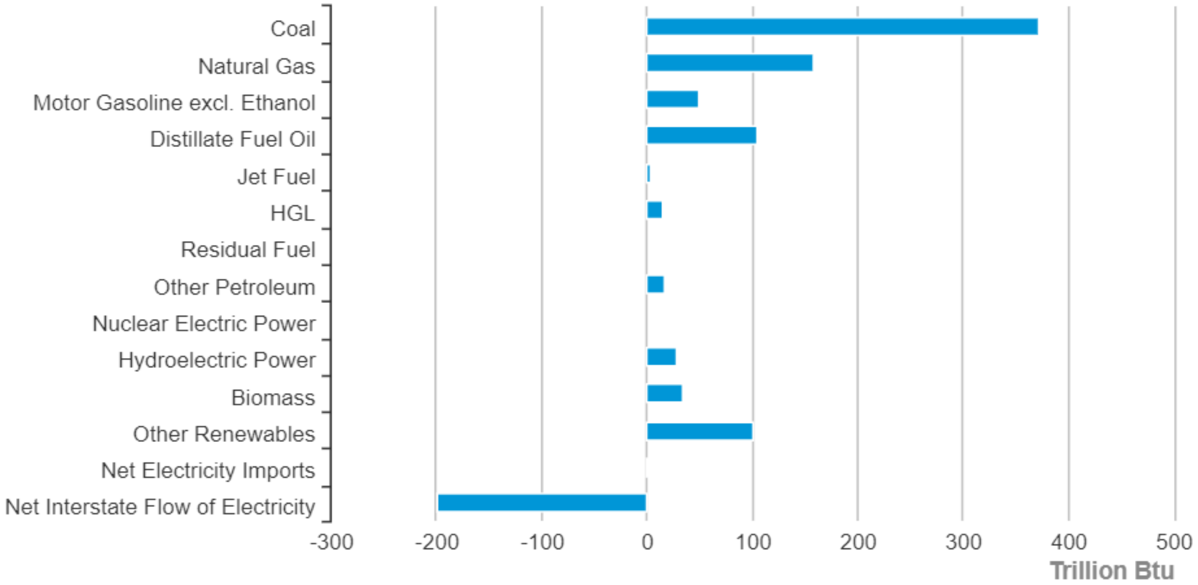


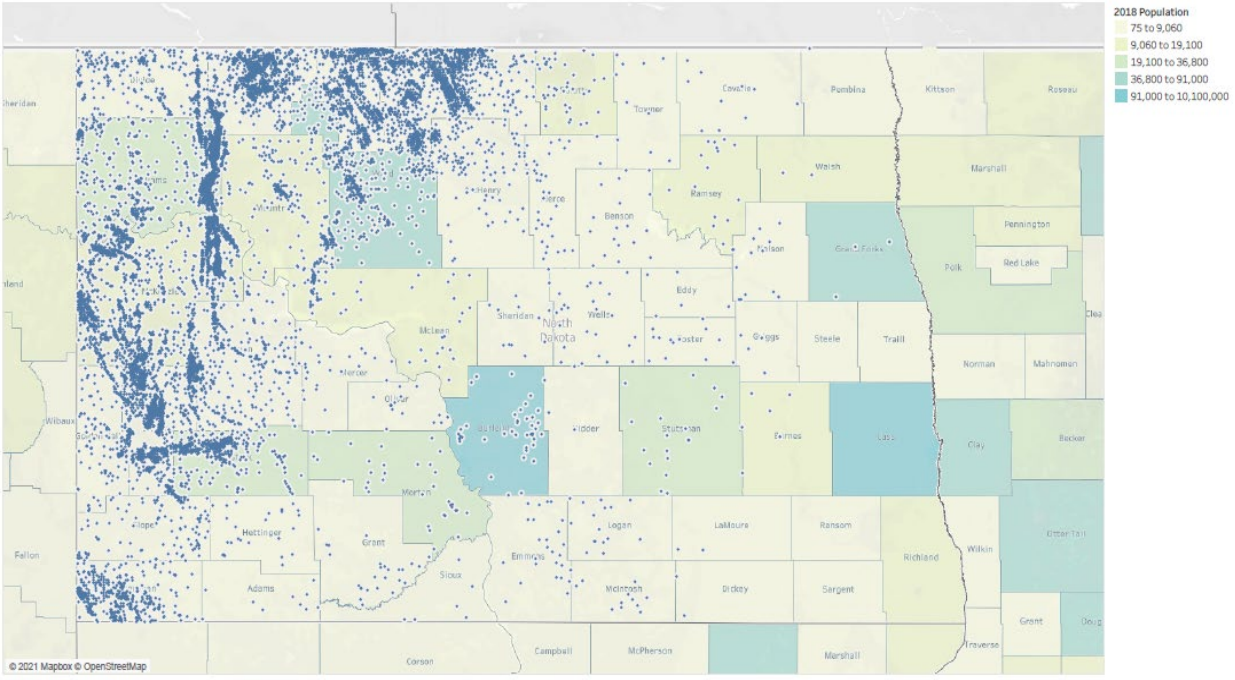
Figure 10: Bar Chart of North Dakota Energy Consumption Estimates, 2019. (Energy Information Administration, State Energy Data System, 2021)

Category	North Dakota Energy Consumption Estimates (Trillion Btu)
Coal	372
Natural Gas	157.4
Motor Gasoline excl. Ethanol	49.1
Distillate Fuel Oil	104.3
Jet Fuel	4.4
HGL	15
Residual Fuel	0
Other Petroleum	17.6
Nuclear Electric Power	0
Hydroelectric Power	28.3
Biomass	34.2
Other Renewables	100.8
Net Electricity Imports	1.2
Net Interstate Flow of Electricity	-199.7

Table 6: North Dakota Energy Consumption Estimates, 2019. (Energy Information Administration, State Energy Data System, 2021)

Emission is a problem in North Dakota - standing at about 58.9 million metric tons of energy-related carbon dioxide (USEIA 2021) which is a reason for doing this research to reduce this we sort to direct use from geothermal energy. Heat is not the only factor to consider when deciding on a geothermal site. Several factors influence whether a geothermal resource can be economically extracted. These factors include an appropriate temperature, adequate production capacity, favorable water chemistry, fluid pressure, permeability, and the thickness of the aquifer. (Gosnold 1991).

Williston State College in Williams County provides a good location to carry out the direct use as it is in a city whose population is the fifth largest in North Dakota and the availability of numerous potential wells whose data exist from oil drilling activities in the county makes it an exciting place for direct use. Success would open doors for the adaptation of direct use throughout Williston city thereby reducing carbon emissions.



Map based on Longitude and Latitude. Map coloring shows 2018 Population by County.

Figure 11: Map of North Dakota based on population and location of wells.

LITERATURE REVIEW

Temperature Estimation

As discussed earlier, Geothermal energy ranges from Low to moderate to high temperatures. In North Dakota, strata-bound geothermal resource temperature ranges from less than 90ºC to a moderate temperature between 90ºC and 150ºC (Gosnold, 1991). Inyan kara at >1500ft is a great choice as it holds geothermal waters of >80ºC which is enough for the direct use we want to do on our site.

Heat is not the only factor to consider when deciding on a geothermal site. Several factors influence whether a geothermal resource can be economically extracted. These factors include an appropriate temperature, adequate production capacity, favorable water chemistry, fluid pressure, permeability, and the thickness of the aquifer. (Gosnold 1991).

One-half of North Dakota is underlain by deep sedimentary basins, with significant potential for geothermal resources. The deep sedimentary basins are capped by a thick layer of low thermal conductivity shale and are underlain by four major aquifers (Gosnold, 1991).

The quantity of geothermal energy found in the Inyan Kara (Cretaceous), Mission Canyon (Mississippian), Duperow (Devonian), and Red River formations (Ordovician) in the Williston Basin constitute a low-temperature geothermal resource that is estimated to exceed 20 x 10^{18}J of energy (Gosnold, 1984).

Thermostratigraphy

Thermostratigraphy has been applied in regional and detailed assessments of geothermal resources in the Williston basin (Lachenbruch; 1970; Gosnold, 1984, 1991, 1999; Gosnold et al., 2010, 2012, 2013, 2014, 2015, 2016, 2017, 2019, 2020; Crowell and Gosnold, 2011; Crowell et al., 2011) and in the Geothermal Map of North America (Blackwell and Richards, 2004). Assuming heat flow, q is conductive and constant, the temperature gradient, dT/dz, varies inversely with thermal conductivity (λ) according to Fourier's law in Eqn. 1 from which the temperature at depth can be calculated from Eq. 2.

$$q = \frac{dT}{dz}\lambda \qquad Eq\ 1$$

$$T(z) = T_0 + \sum_{i=1}^{n} \frac{qz_i}{\lambda_i} \qquad Eq\ 2$$

where: $T(z)$(°C) is the temperature at depth z(m), T_0 is mean surface temperature (°C), q is heat flow (mW m^{-2}), z_i is formation thickness (m), λ_i is the formation thermal conductivity (W m^{-1} K^{-1}) and dT/dz (K km^{-1}) is the temperature gradient (Gosnold et al. 2012). The subsurface temperature is determined by the local heat flow, known from the borehole's direct temperature measurements, the mean average surface temperature, the thermal conductivities, and the thickness of the strata (Gosnold, 1991).

Porosity and Permeability

The porosity and permeability are routinely obtained from many formations. According to the journal Smith et al (2017), they researched potential CO_2 storage reservoirs within the Williston Basin. One of the wells was well 165 - a well in Williams County which is the same county as Williston state college.

In their work, the porosity was tested using a Helium Porosimeter and Boyles Law calculation was applied to determine the grain volume of each sample. then this value is subtracted from the predetermined bulk volume to determine the amount of void space (porosity) in the rock (Smith et al., 2017). The porosity for the Inyan Kara formation was 21.5% and the permeability of 95.2mD for well 165. In that analysis, it was found that the Inyan Kara formation was heterogeneous compared to other samples from other wells and formations checked showing a distinct difference in grain size and available pore space. X-ray powder diffraction/X-ray fluorescence spectroscopy (XRD/XRF) analysis showed that the Inyan kara had 15% clay, 11% feldspar minerals and 73% quartz.

Bader (2019) modeled a sequence stratigraphy of the Inyan Kara formation traversing over 24 wells through various counties in the Williston Basin, the porosity range of all the wells in his paper are 20-30% and permeabilities from 10-100mD.

Aquifers

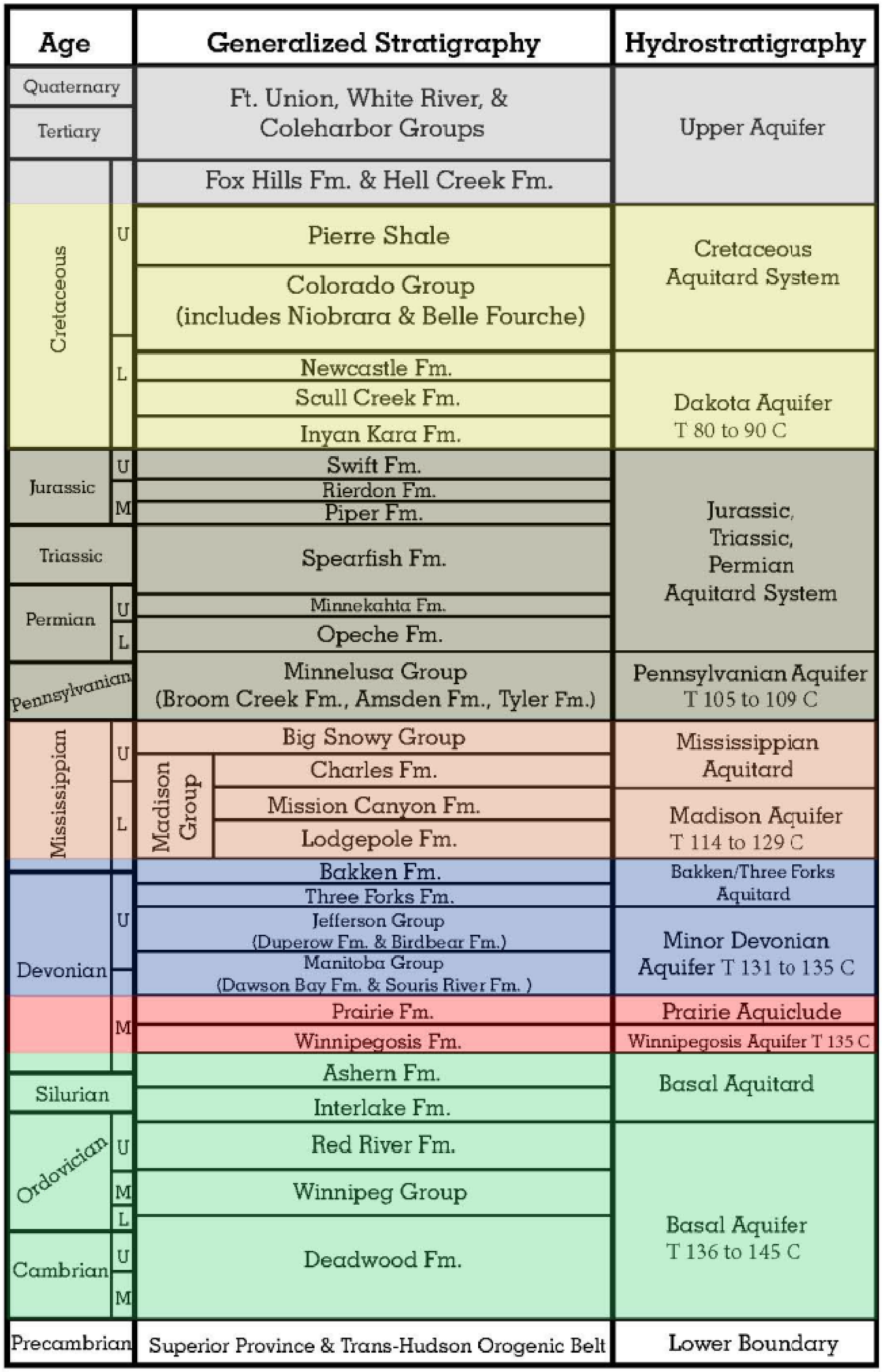
A geothermal aquifer well is an underground water source that supplies two natural resources: water and latent heat energy. Fluid flow and groundwater are necessary factors for consideration for geothermal purposes. Four aquifers Inyan Kara, Madison, Duperow, and Red River underlie North Dakota, which are part of the twelve regional aquifers in the Williston Basin (Gosnold, 1991).

According to Gosnold et al 2017, There are six regional aquifer systems containing eleven different formations. Six of the aquifer systems have temperatures above 80ºC (Gosnold et al 2017). These aquifers include the following:

- Dakota aquifer

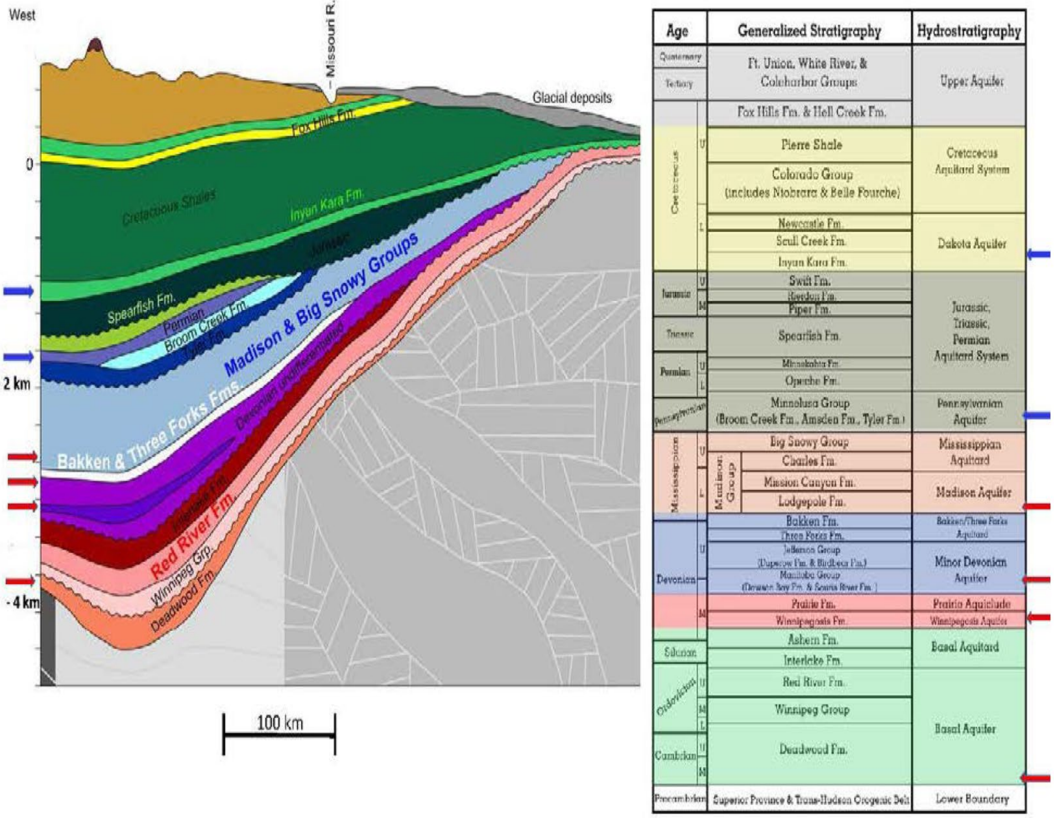
- Pennsylvanian aquifer
- Madison aquifer
- Basal aquifer
- Winnipegosis aquifer
- Minor Devonian aquifer

The uppermost aquifer system, the Dakota Group (Cretaceous), consists of sandstones and shales with a maximum thickness of 371m 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 Minnelusa Group are greater than 105°C. The Madison aquifer system (Mississippian) consists of carbonates having a maximum thickness of 753m and 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 67m 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 661m and the sandstone-carbonate-shale 305m thick Deadwood formation. Temperatures in the basal aquifer range from 136°C to 145°C.



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		Mission Canyon Fm.	Madison Aquifer T 114 to 129 C
			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

Figure 12: Stratigraphy, hydrostratigraphy, and aquifer temperatures of the Williston Basin throughout the Missouri River. Modified after Ricker and Gosnold, 2014.



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
		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
Mississippian	U	Big Snowy Group	Mississippian Aquitard
		Madison Group: Charles Fm.	
	L	Madison Group: Mission Canyon Fm.	Madison Aquifer
		Madison Group: Lodgepole Fm.	
Devonian	U	Bakken Fm.	Bakken/Three Forks Aquitard
		Three Forks Fm.	
		Jefferson Group (Duperow Fm. & Birdbear Fm.)	Minor Devonian Aquifer
	M	Manitoba Group (Dawson Bay Fm. & Souris River Fm.)	
		Prairie Fm.	Prairie Aquiclude
		Winnipegosis Fm.	Winnipegosis Aquifer
		Ashern Fm.	Basal Aquitard
Silurian		Interlake Fm.	
Ordovician	U	Red River Fm.	Basal Aquifer
	M	Winnipeg Group	
	L		
Cambrian	U	Deadwood Fm.	
	M		
Precambrian		Superior Province & Trans-Hudson Orogenic Belt	Lower Boundary

Figure 13: Cross section of Williston Basin in North Dakota and stratigraphic column. Blue arrows indicate aquifer systems with temperatures in the 90 ºC to 100 ºC range. Red arrows indicate aquifer systems with temperatures above 100 ºC. (Gosnold et al 2017).

METHODS AND RESULTS

Site Selection

Williston State College is close to two fields – The Williston field and the Catwalk field. These fields have 110 (59 for Williston and 51 for Catwalk wells); 75 wells are active, and 35 wells are not from either being plugged and abandoned, permit now cancelled, dry, inactive, and abandoned. We focus on plugged and abandoned wells and the reason for using abandoned wells is to reduce cost since a great portion of the cost for a geothermal plant is drilling. It is believed that by repurposing existing wells, we save a lot of money. I picked a well with NDIC File Number 7290 currently known as B.P.O.E 1 as the production well while for the injection well I selected NDIC File Number 2476 currently known as W. C. SVEEN ET UX 1. Well, #7290 is a plugged and abandoned oil and gas well with a total depth of 9650ft (2941.32m) and its distance from the Williston State College is 1.19miles (1915.11m) while the injection well is a saltwater disposal which suits the purpose of injection with its distance from the production well as 0.64miles (1029.98m).

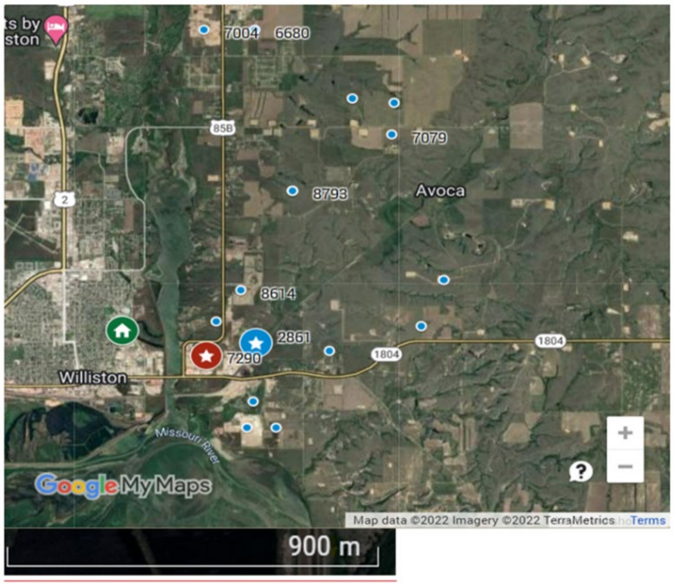
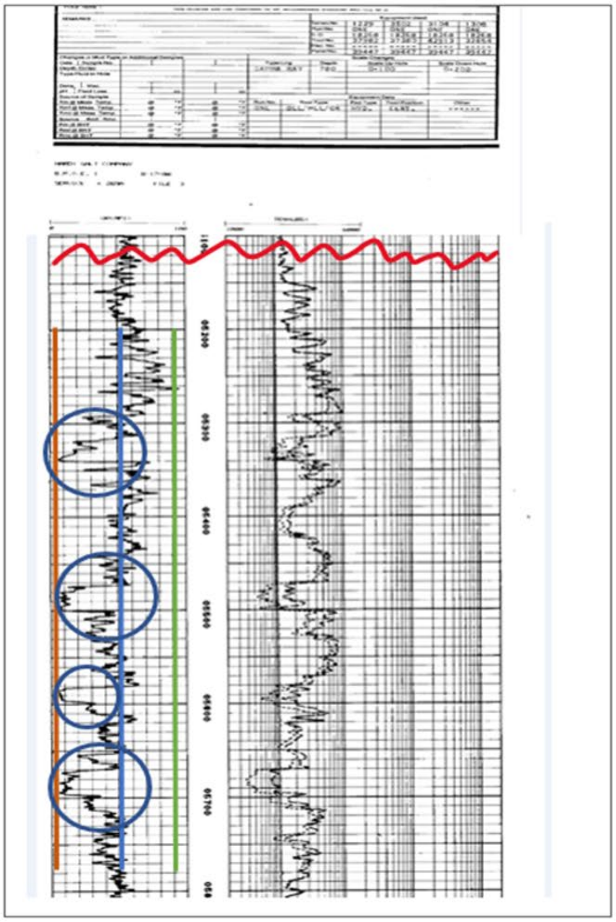


Figure 14: Abandoned Oil wells around Williston City show target area, production, and injection wells.

Resource Assessment

The Dakota and Pennsylvanian aquifers at depths of approximately 5000+ft and 7000ft respectively are two shallow aquifers with temperatures 90°C -100°C while others are above 100°C. Since our interest is in direct use we focus on the shallower formation as its temperature is adequate for our use. The Dakota aquifer, which is the Dakota Group has Newcastle, Skull Creek, and the Inyan Kara Formations. The Inyan Kara formation is the target formation for two reasons, it is a shallow aquifer and also has the required temperature.

According to the journal by Jeffery W. Bader (2017), The Iyan Kara has its sediments deposited in a coastal setting adjacent to the Cretaceous Seaway from approximately 115 to 105 million years ago. Numerous rivers flowed across the coastal plain to the sea. Sea-level variations caused shoreline shifts; with the coastline moving landward during transgression, and seaward during regression. Major sea-level fluctuations occur due to tectonic events such as the uplift of mountain ranges, global sea-level changes based on water volume in the oceans, or both, combining for a net relative change in sea level. Inyan Kara sediments were deposited over western North Dakota during two of these transgressive/regressive cycles as relative sea levels fluctuated.



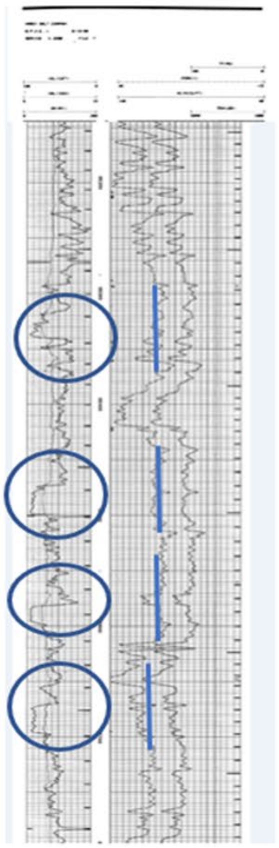


Figure 15: Dual laterology of well 7290 showing the Gamma Ray Showing the sandstone and shale divide

Figure 16: Acoustic log for well 7290 showing the porosity and GR for the Sandstone reservoir

The lithology of the production well (#7290) is a combination of shale and sandstones with a combined total thickness of 580ft (176.8m). The shale thickness was calculated from logs available from the NDIC website to have 220ft (67m) while the sandstone thickness is 360ft (109.7m). The porosity of the sandstone thickness is found to be 0.21 and the permeability is 100mD from the available logs.

Thermostratigraphy

From the literature review and thermostratigraphy estimation (TSTRAT) (Eqn.2) from Gosnold et al., 2012 to quantify the Inyan Kara formation temperatures for our production well at a depth of 5230ft (1594.104m) we calculated the temperature to be 82.5ºC.

$$T(z) = T_0 + \sum_{i=1}^{n} \frac{qz_i}{\lambda_i} \qquad Eq\ 2$$

Depth, z = 1,583.4m

Thermal Conductivity for Inyan Kara, λ_i = 1.60 (W m^{-1} K^{-1}) (Gosnold et al. 2012)

Mean surface temperature, T_0 = 5 ºC

Heat flow Q = 51 mW/m^2 (Gosnold et al. 2012)

Temperature at depth z, T(z) = 82.5ºC

Stratigraphy	Temperature (^{o}C)	Depth(m)
		0.00
Brule Fm	7.8	0.00
Chadron Fm	7.8	0.00
Golden Valley Fm	7.8	0.00
Sentinel Butte	7.8	0.00
Slope Fm.	11.3	66.83
Cannonball Fm.	14.6	130.40
Ludlow Fm	18.6	207.01
Hell Creek	22.9	289.33
Fox Hills	28.1	388.76
Pierre	36.1	554.74
Niobrara	39.1	616.68
Carlile	43.5	716.11
Greenhorn	71.6	1352.09
Belle Fouche	78.2	1439.30
Mowry	77.3	1470.36
Newcastle	79.4	1514.86
Skull Creek	81.0	1549.90
Inyan Kara	82.5	1583.44
Swift	88.8	1760.22
Rierdon	95.5	1900.12
Piper	97.4	1951.12
Spearfish	101.8	2075.69
Minnekahta Fm	105.3	2173.22
Opeche Fm	105.5	2182.37
Broom Creek Fm	108.8	2249.42
Amsden Fm	109.5	2279.42
Tyler Fm	109.9	2305.81
Big Snowy	111.3	2371.95
Kibbey Fm	113.6	2478.02
Madison Unconformity	114.5	2521.92
Mission Canyon Fm	115.3	2556.86
Ratcliffe Interval	118.9	2711.20
Base of Last Salt	119.4	2733.45

Table 7: Well Data showing various formations' temperature, depth, and thermal conductivity

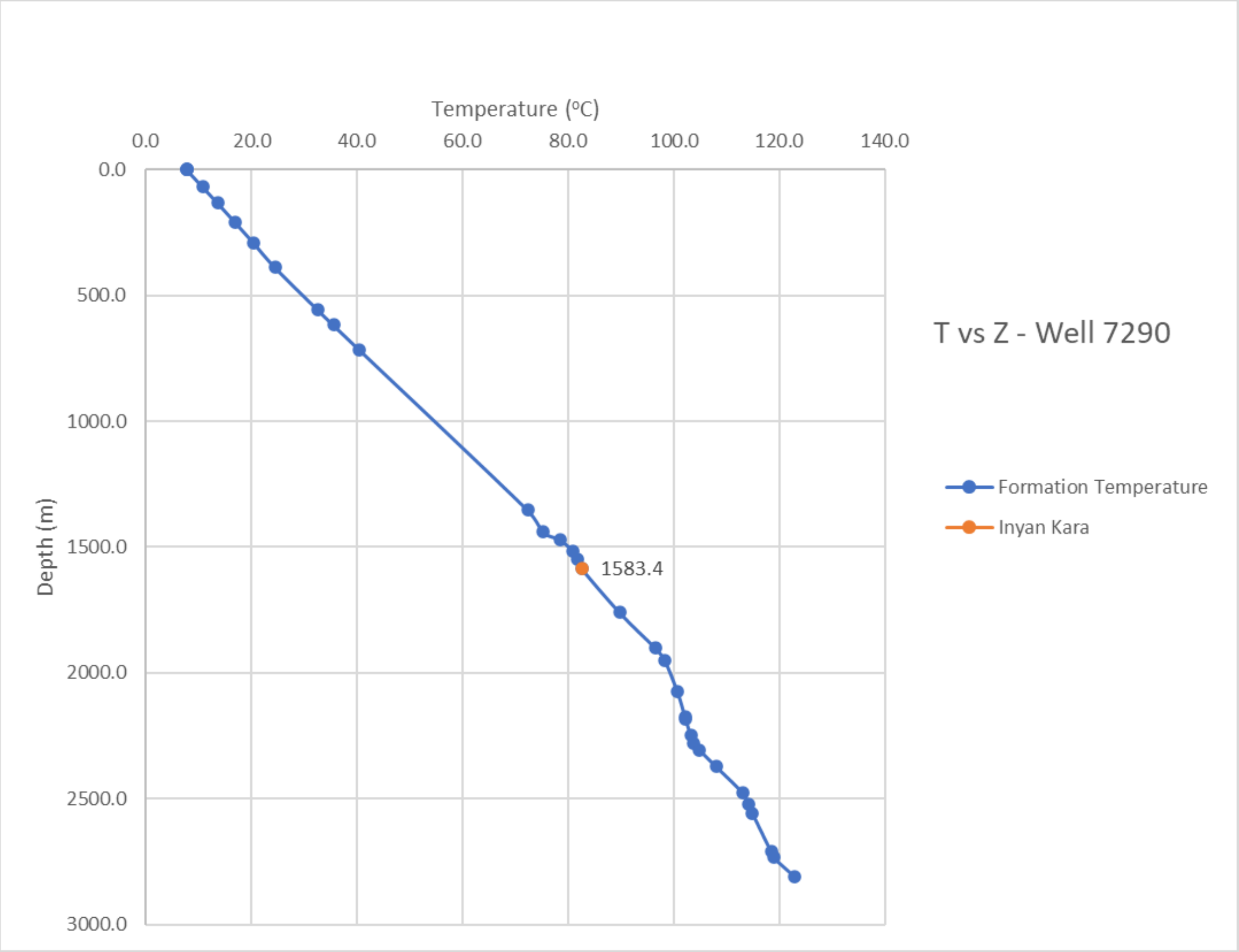


Figure 17: Calculated temperature – formation depth plot of well #7290 with the Inyan Kara formation highlighted in orange at 82.5ºC using the T-strat.

Estimation of Productivity Index

Chu M.H. (1988), suggested that the methods of Jones et al (1976) or Fetkovich (1973) can provide more accurate flow rate predictions than those estimated with the productivity index (PI) method. However, Chu M.H. (1991), due to the unavailability of flow test data, used the PI method for flow rate predictions of the Inyan Kara formation for four major cities: Williston city, Watford City, New Town, and Dickson. The PI is the ratio of the flow rate to the pressure drawdown at the producing interval. Thus, a geothermal well's productivity index can be calculated by using; Equation 3

$$PI = \frac{7.08Kh}{\mu B\ \left[ln\left(\frac{\gamma_e}{\gamma_w}\right) - 0.5\right]}$$

where:

PI = Productivity Index (bbl./day/psi)

K = formation permeability (Darcies)

h = net pay thickness (ft)

μ = fluid viscosity, (cP)

B = water formation volume factor

γ_e= external drainage radius (ft)

γ_w= well-bore radius (ft)

Assumptions made for the calculations of geothermal flow rate are it is in radial flow; the formation flow is a single-phase, and the producing well is located at the center of a circular reservoir.

For the Inyan Kara Formation water, the water formation volume factors are in the range of 0.9972 to 1.02 (Chu M.H, 1991, Kutasov, 1989).

For the water formation volume factor, we use the mean of the said range by Chu 1991 for Inyan Kara. Therefore, for well 7290, we have :

B = 1.0086, μ = 1 Cp, k = 100mD = 0.1, H = 360ft

γ_e = 3379.2ft

γ_w= 9in = 0.75ft

PI = (7.08*0.1*360)/((1*1.0086)[In(3379.2/0.75)-0.5])

PI = 254.88/(1.0086)[In(4505)-0.5])

PI = 254880/7.981129

PI = 31.935 bbl./day/psi

The maximum estimated pressure drawdown possible, MPDP(psi) = hydraulic pressure gradient * formation depth

Maximum pressure drawdown possible = 0.43 * 5195 = 2233.85psi

Production from well 7290 = PI * MPDP

Production rate = 31.935 bbl./day/psi * 2233.85psi = 71,338.74bbl./day.

Estimation of Original Water in Place

Chen M.H. 1991 also estimated the volume of water in the reservoir using equation 4 below

$$OWIP = 7758 * \emptyset * S_W * h * A \qquad Eq\,4$$

where:

OWIP = original water in place (bbl.)

7758 (bbl./acres ft)

$\emptyset$ = average porosity, (%)

h = net pay thickness (ft)

A = reservoir area (acres)

S_W = water saturation (in this case, S_w, = 1).

An assumption made for the calculations of the original water in place is that the reservoir is a homogeneous reservoir with uniform reservoir properties such as pay zone, thickness, porosity, and water saturation.

For Well 7290, the OWIP for the Inyan Kara is calculated as:

$\emptyset$ = 0.21

h = 360 (ft)

A = well spacing *arbitrary width = 3379.2 * 5905.512 = 19955906.2ft^2 = 458.125acres

S_W = water saturation (in this case, S, = 1).

OWIP = 7758*0.21*360*458.125*1

OWIP = 2.687 x10^{8}barrels.

Thermal energy

The Total Thermal Energy can be calculated by using the energy equation

$$E_{th} = \rho_W * V * C_{P\,W} * \Delta T \quad Eq\ 5$$ (Gosnold et al 2017)

where E_{th}= Total Thermal Energy, (J), ρ_W= density of water (kg m^{-3}),

$C_{P\,W}$ is the heat capacity of water (J kg^{-1} K^{-1}), V is the volume in m^3, and ΔT (ºC) is the temperature difference.

Computing the values for the equation below :

ρ_W = 1000kg m^{-3} , $C_{P\,W}$= 4182J kg^{-1} ºC $^{-1}$

ΔT = 62.5 ºC (82.5-20) , V = 268,692,257.70 OWIP(bbl) = 42,717,370.06 m^3

$$E_{th} = \rho_W * V * C_{P\,W} * \Delta T$$

E$_{th}$ = [1000*42717370.06*4182*62.5]

E$_{th}$ = 1.12x10^{16} , Converting to BTU = E$_{th}$ /1055

E$_{th}$ = 10,583,177,819,367.30BTU = 10.5x10^{12} BTU for the available resource.

Converting to BTU/bbl, we take the ratio of Total thermal Energy (BTU) to the Total Volume (OWIP, in barrels)

$$E_{th} = \frac{10.5x^{12}BTU}{2.687x10^{8}bbl} = 39{,}387.73BTU/bbl$$

The heat generated by the production well is then calculated by the product of Energy(BTU/bbl) and the production rate (bbl/day), Therefore, The heat produced by Well 7290 per day =

$$\frac{39{,}387.73BTU}{bbl} * \frac{71{,}338.74bbl}{day} = \frac{2{,}809{,}871{,}031.36BTU}{day} = 2.8\,x10^{9}BTU/day$$

Productivity Index (bbl/day/psi)	**Production rate (bbl/day)**	**OWIP (bbl)**
31.93	71,338.74	2.69E+08
Total Thermal Energy (J)	**Total Thermal Energy (BTU/bbl)**	**Heat Produced (BTU/day)**
1.12E+16	39,387.73	2.81E+09
Formation depth (m)	**Porosity (%)**	**Permeability (mD)**
1594.104	21	100
Producing well	**Formation temperature (°C)**	**Formation thickness(m)**
NDIC # 7290	82.5	176.8

Table 8: Resource Data.

Temperature, Heat Exchanger, Downhole pumps, and Distribution pipes

In Williston, the summers are warm; the winters are freezing, snowy, and windy; and it is partly cloudy year-round. Over the year, the temperature typically varies from 4°F to 86°F and is rarely below -19°F or above 97°F.

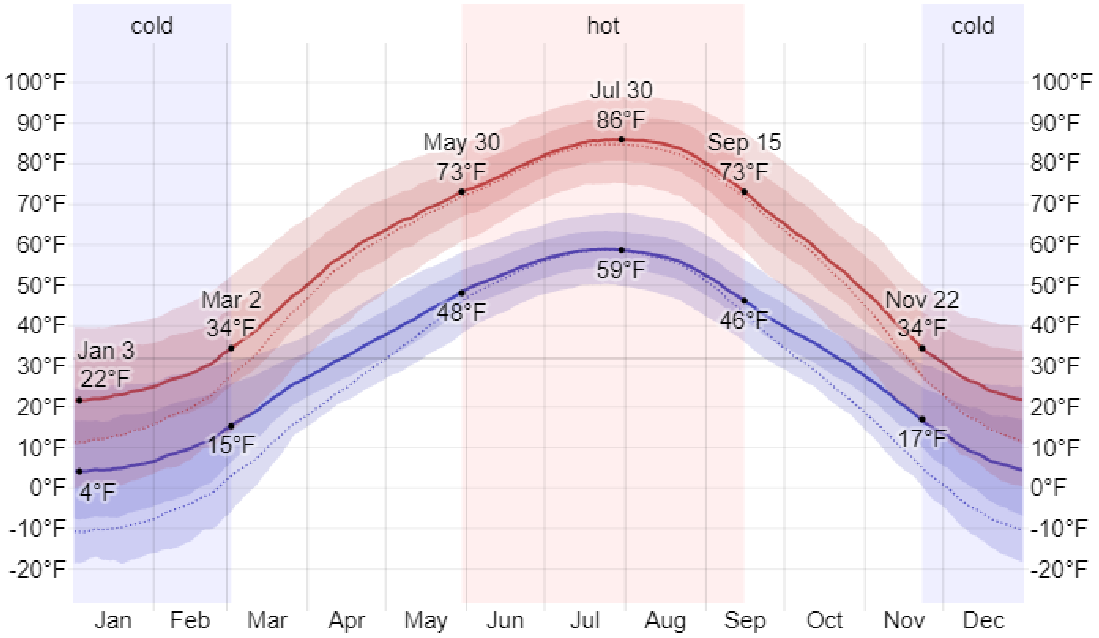
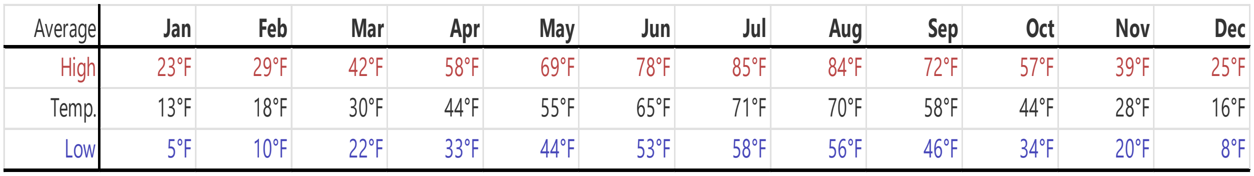


Figure 18: Average High and Low temperature in Williston. (Weathersparks.com). The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures.



Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High	23°F	29°F	42°F	58°F	69°F	78°F	85°F	84°F	72°F	57°F	39°F	25°F
Temp.	13°F	18°F	30°F	44°F	55°F	65°F	71°F	70°F	58°F	44°F	28°F	16°F
Low	5°F	10°F	22°F	33°F	44°F	53°F	58°F	56°F	46°F	34°F	20°F	8°F

Table 9: Average High and Low temperature in Williston. (Weathersparks.com)

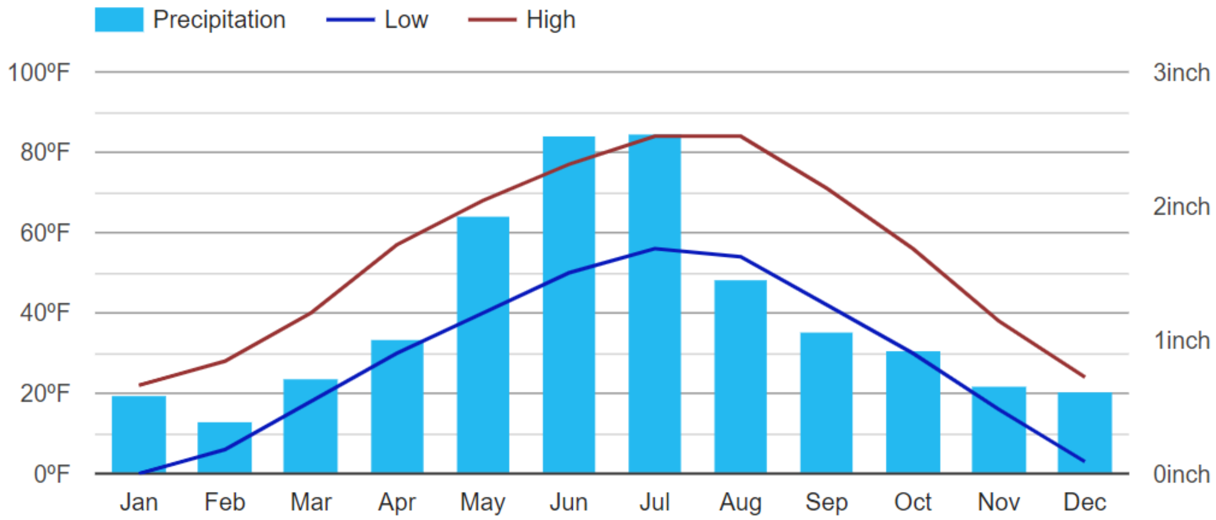
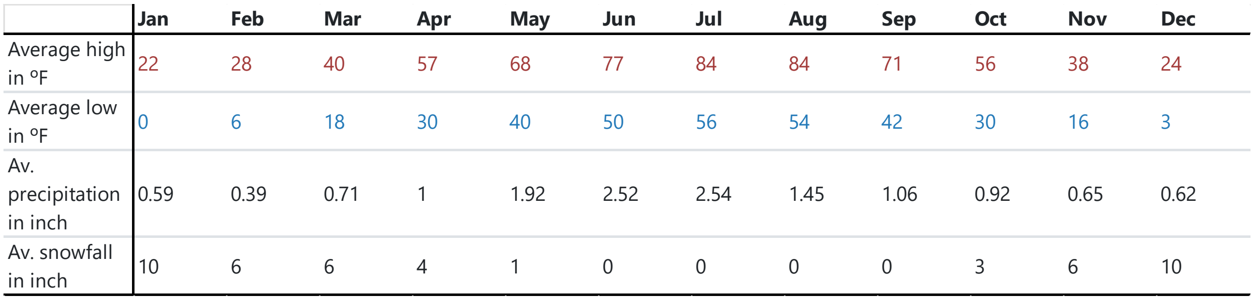


Figure 19: Williston Climate Graph (usclimatedata website)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average high in ºF	22	28	40	57	68	77	84	84	71	56	38	24
Average low in ºF	0	6	18	30	40	50	56	54	42	30	16	3
Av. precipitation in inch	0.59	0.39	0.71	1	1.92	2.52	2.54	1.45	1.06	0.92	0.65	0.62
Av. snowfall in inch	10	6	6	4	1	0	0	0	0	3	6	10

Table 10: Williston Climate data (usclimatedata. website)

A heat exchanger is a system used to transfer heat between two or more fluids. Heat exchangers are used in both cooling and heating processes. A solid wall may separate the fluid to prevent mixing, or they may be in direct contact. They are widely used in space heating, refrigeration, air-conditioning, PowerStation, chemical plants, petrochemical plants, petroleum refineries, natural-gas processing, and sewage treatment. The principal heat exchangers used in geothermal systems are the plate, shell-and-tube, and downhole types. The plate heat exchanger consists of a series of plates with gaskets held in a frame by clamping rods. The counter-current flow and high turbulence achieved in plate heat exchangers provide for efficient thermal exchange in a small volume. In addition, compared to shell-and-tube exchangers, they have the advantage of occupying less space, can easily be expanded when additional load is added, and are typically 40% cheaper. The plates are usually made of stainless steel, but titanium can be used when the fluids are especially corrosive. Plate heat exchangers are commonly used in geothermal heating systems in the United States. For Williston State College our focus is the heating as the temperatures here are suitable for cooling.

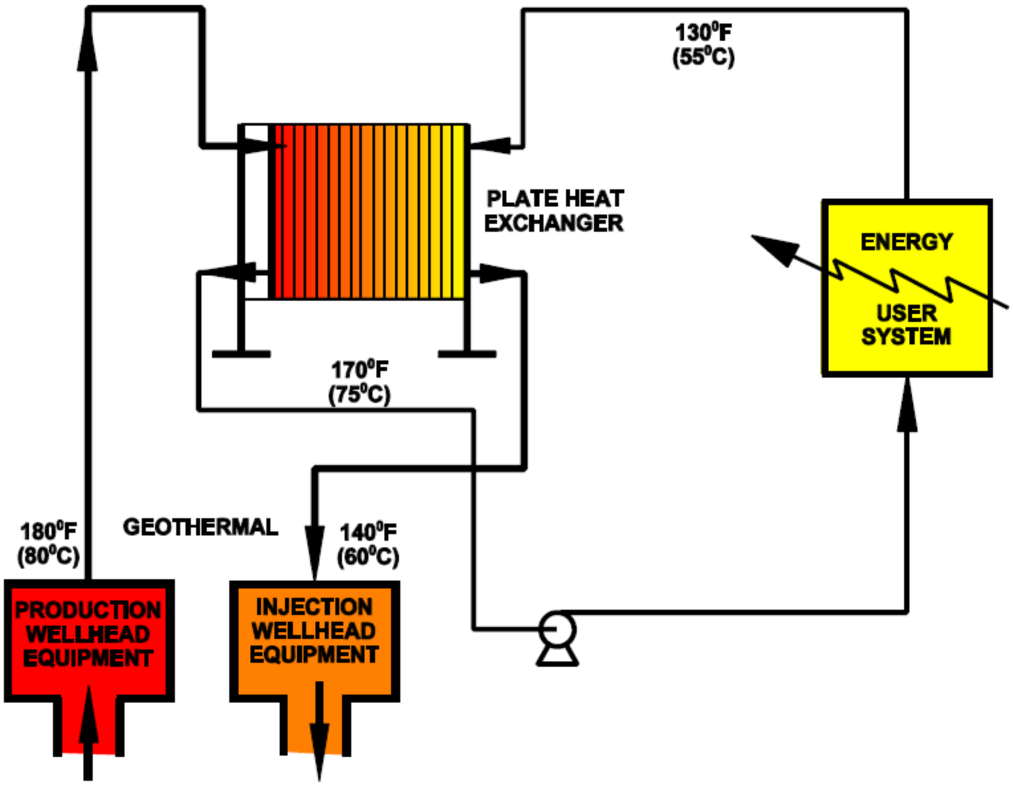


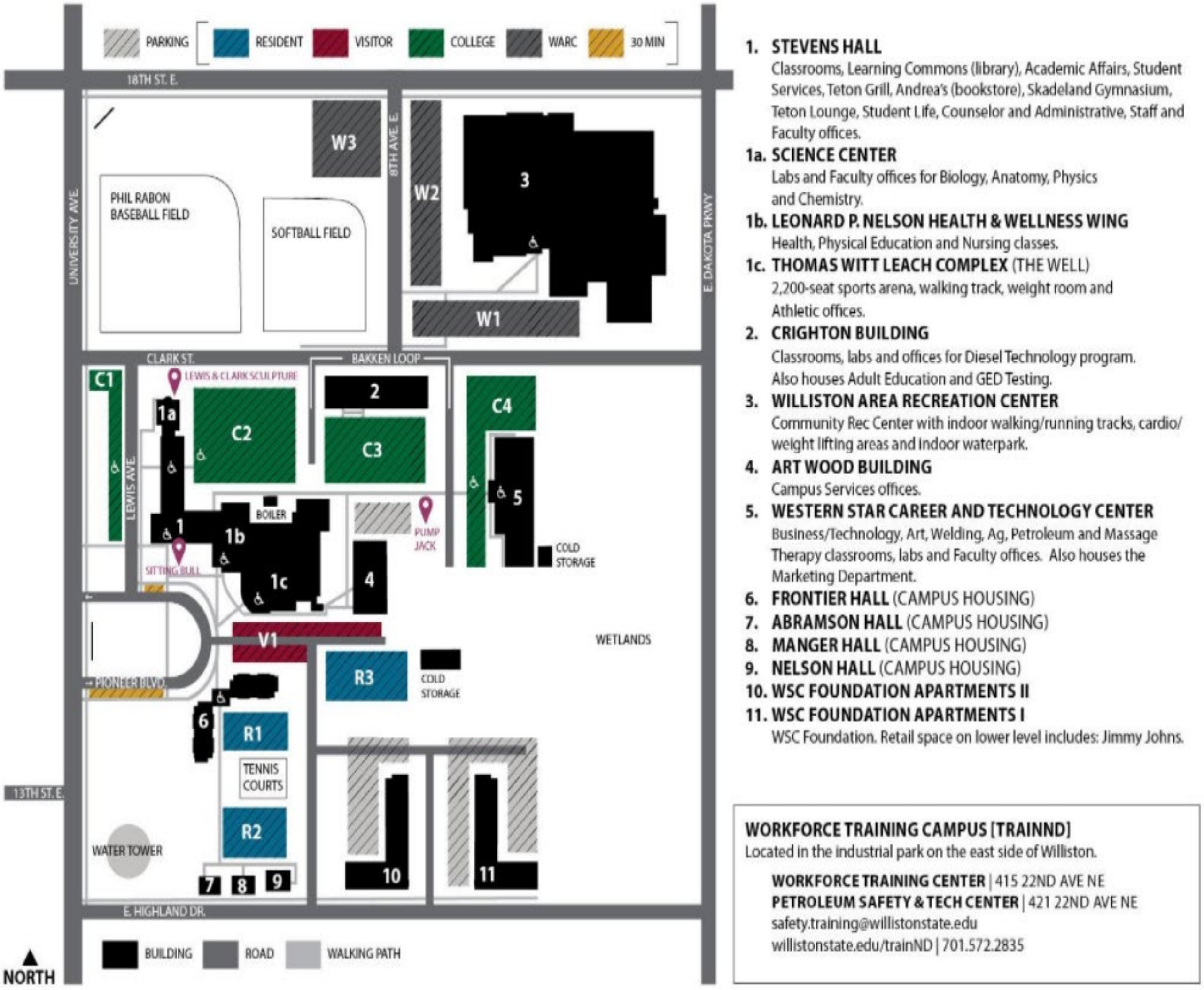
Figure 20: Geothermal direct utilization system using a heat exchanger. (Lund, 1998).

Downhole pumps

Submersible and lineshaft pump systems have been used for pumping cold water and recently geothermal wells as they are the most common downhole pumps. A submersible pump is preferred in this project because the depths of the Inyan kara (5230ft) exceed 850ft at which depth is a problem for lineshaft pump systems due to thermal expansion. The electric submersible pump system consists of a multi-stage downhole centrifugal pump, a downhole motor, a seal section (also called a protector) between the pump and motor, and an electric cable extending from the motor to the surface electricity supply.

Distribution pipes

Pipes for supply and distribution can be either steel, Polyvinyl chloride (PVC), High-density polyethene (HDPE) pipes or fiberglass-reinforced plastic can all be used for projects which is a low-temperature application. The distribution network in this project will be a single-pipe system which is a once-through system where the fluid is disposed of/reinjected after use.



1. **STEVENS HALL**
   Classrooms, Learning Commons (library), Academic Affairs, Student Services, Teton Grill, Andrea's (bookstore), Skadeland Gymnasium, Teton Lounge, Student Life, Counselor and Administrative, Staff and Faculty offices.

1a. **SCIENCE CENTER**
   Labs and Faculty offices for Biology, Anatomy, Physics and Chemistry.

1b. **LEONARD P. NELSON HEALTH & WELLNESS WING**
   Health, Physical Education and Nursing classes.

1c. **THOMAS WITT LEACH COMPLEX** (THE WELL)
   2,200-seat sports arena, walking track, weight room and Athletic offices.

2. **CRIGHTON BUILDING**
   Classrooms, labs and offices for Diesel Technology program. Also houses Adult Education and GED Testing.

3. **WILLISTON AREA RECREATION CENTER**
   Community Rec Center with indoor walking/running tracks, cardio/weight lifting areas and indoor waterpark.

4. **ART WOOD BUILDING**
   Campus Services offices.

5. **WESTERN STAR CAREER AND TECHNOLOGY CENTER**
   Business/Technology, Art, Welding, Ag, Petroleum and Massage Therapy classrooms, labs and Faculty offices. Also houses the Marketing Department.

6. **FRONTIER HALL** (CAMPUS HOUSING)

7. **ABRAMSON HALL** (CAMPUS HOUSING)

8. **MANGER HALL** (CAMPUS HOUSING)

9. **NELSON HALL** (CAMPUS HOUSING)

10. **WSC FOUNDATION APARTMENTS II**

11. **WSC FOUNDATION APARTMENTS I**
    WSC Foundation. Retail space on lower level includes: Jimmy Johns.

WORKFORCE TRAINING CAMPUS [TRAINND]
Located in the industrial park on the east side of Williston.

WORKFORCE TRAINING CENTER | 415 22ND AVE NE
PETROLEUM SAFETY & TECH CENTER | 421 22ND AVE NE
safety.training@willistonstate.edu
willistonstate.edu/trainND | 701.572.2835

Figure 21: Map of the Williston State College campus map. (WSC website)

Greenhouse Aquaponics

Heating the Williston State campus is the primary plan, adding a greenhouse for aquaponics is included. Aquaponics is a farming method that combines the benefits of aquaculture and hydroponics. A nitrifying bacteria convert the wastes that fish produce. They then serve as an organic nutrient source for the plants. This is a great idea for the College to make money whereby floras and faunas can be added to the system, providing vegetables, shrimp, and fish for the College to sell to the locals and improve the agricultural produce in the locale. This aquaponics will be a source of finance for the college and a form of training facility for the student to learn about greenhouse farming and produce.

According to Go Green Aquaponics (2022), Water temperature is one of the most critical parameters that an aquaponics grower must maintain consistently to maintain a healthy aquaponics system, the water temperature must be kept in the range that is safe for the fish, plants, and bacteria growing in your aquaponics system. Fish can be categorized into cold water, cool water, and warm water fish. Warm-water fish like catfish, carp, and tilapia thrive in high water temperatures of 71-89 °F (22-32°C) but cold-water fish such as trout prefer a colder temperature of 50 - 64°F (10-18 °C) to thrive while some cool water or temperate water fish such as largemouth bass and common carp have wider ranges and can tolerate the temperature range of 41 - 86°F (5-30°C). Some vegetables like lettuce and cucumber grow at 46-68°F (8-20°C), other vegetables Like basil are better at 62-86°F (17-30°C) while Leafy Greens are 78°F (26°C).

Water temperature is essential for bacterial growth, the optimal water temperature range for healthy bacterial growth and productivity in an aquaponics system is 62-93°F (17-34°C). The bacterial growth rate will decrease when the temperature is below 64°F (18°C) and will die when the temperature is lower than 32°F (0°C). These temperatures can be harnessed from the existing heat and used for the aquaponic greenhouse. The exiting heat can also be used for Pavement/sidewalk heating too can also be done to help melt off the snow that has been formed during winter.

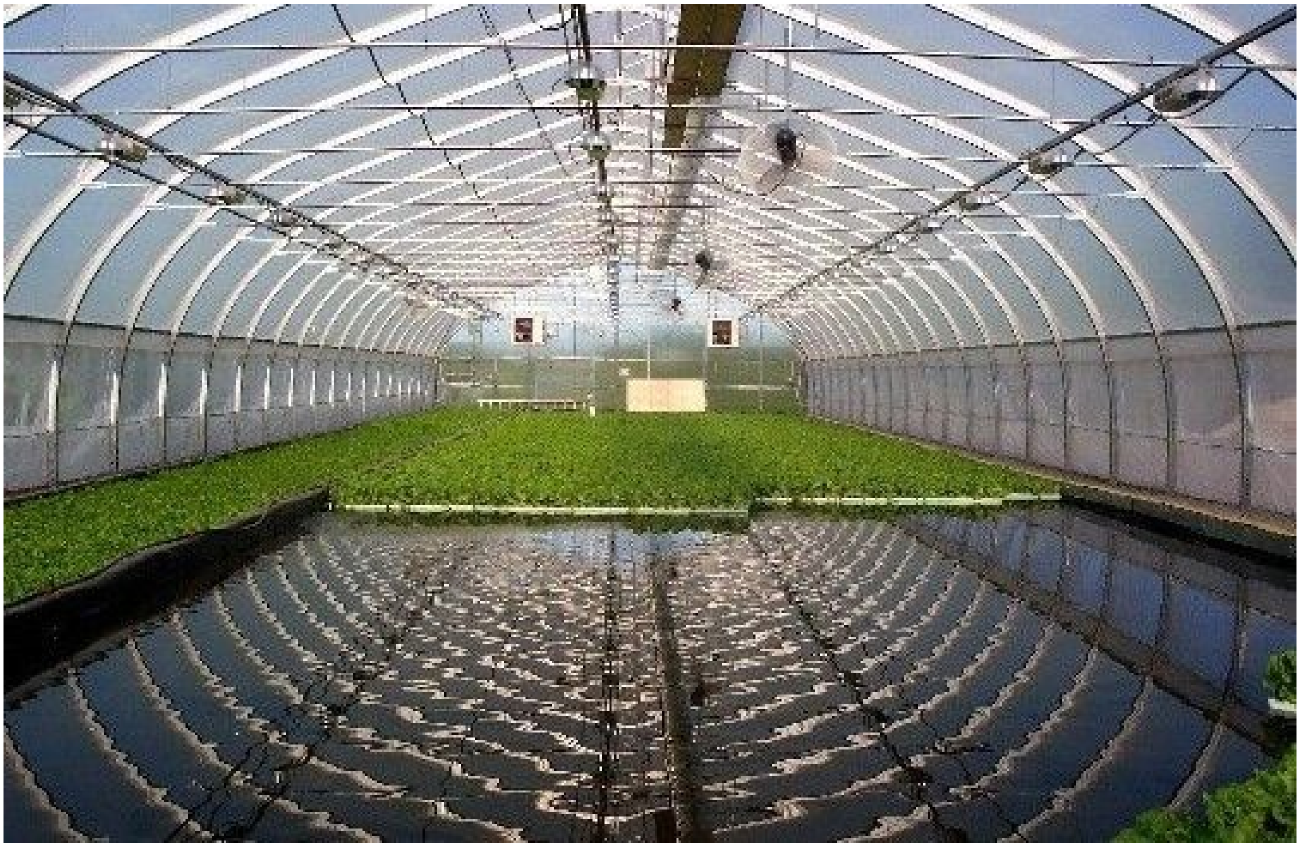


Figure 22: A typical example of an aquaponics farm (AFN website)

Recreation Centre

Williston Area Recreation Centre (ARC) - Located on campus, the ARC opened in the Spring of 2014 and is a world-class 250,000-square-foot community recreation center. The ARC has indoor walking/running tracks, turf fields, a golf simulator, tennis courts, batting cages, cardio/weightlifting areas, multi-sport courts, a 50m Olympic-size pool, a teaching pool, a water park, a lazy river, and kid areas. This center can also be heated up with geothermal, especially the 4-water-related activity in the center. These events will bring many people to the center and generate funds for the school.

Figure 23: Photos of the Williston Area Recreation Centre (ARC) (WSC Website)

Risks

Like every project, the Williston State College project has risks. Using the ‘Georisk tool’ – a worksheet established to cover risks associated with the development and the operation of a geothermal plant (Georisk, 2019) to analyze the associated risk for this project and resolve the risk in the project based on the high likelihood in the Risk Index.

- **Changes in policies, laws, taxes, and regulations:** Government policies affect projects a lot. Whilst the Federal Government is pro-green energy and is encouraging the use of alternate forms of energy to reduce carbon footprint (USGBC, 2022) North Dakota ranks second in the nation, after Texas, in both proved crude oil reserves and crude oil production (USEIA, 2021) making its earnings from fossil fuels so being pro-fossil fuels is only normal. Currently, there is no defined ownership of the geothermal resources available in North Dakota and this might create a problem for the project in the future if the lawmakers decide to pass a law that will not favor the landowners as the crude oil ownership does (NDGS, 2013). Lack of government support can be in form of no incentives or tax credits to encourage private investors to invest in such ventures or unfavorable policies and laws
- **Financing:** Many factors influence the cost of a geothermal project. Financing a project includes seeking partnerships – be it Private or Public-Private Partnerships. A geothermal resource is an expensive resource to tap. A project cannot be fully funded by debt financing because the risk remains too high. At the same time, the expenditure needed is high enough that it is not easy to find investors willing to take on all the risk. So, securing project financing is a high priority.

- **Public opposition/Low social acceptance:** The residents where the project is to be sited can have a huge effect on the project. Their collective acceptance can make or mar a project. Opposition can range from ‘ not in my backyard ’ (NIMBY) to ancestral land to just outright rejection of drilling in the area by the locals and their representatives due to previous dealings with other companies who never kept their end of the bargain or due to contamination of their aquifer system or general environmental degradation from previous projects.
- Time-sensitive requirements for maintaining a concession or license, imposed by regulatory authorities, are not compatible with the time it takes to raise the investment capital that is needed to fund the required activities (GeoCom, 2015).
- **Geological Lithology/stratigraphy difference:** There is a high possibility of having stratigraphic variation in a proposed site when drilling a well which poses a great risk for geothermal projects, observation of wells to know the geology is important.
- **Porosity, permeability, temperatures, and flow rate:** These factors are important for geothermal projects and are critical when decisions are made on drilling, naturally an observation well will be drilled to determine the necessary data/values of these factors.
- **Scaling in the Geothermal Loop:** Most pipelines have a scaling issue and geothermal pipelines encounter the same issue. With the observed high total dissolved solids encountered at the target formation (Buurink et al, 2014), the possibility of scaling is high.
- Induced seismicity is also a potential risk during drilling.

Solutions

- As much as government laws and policies affect projects, it can also be receptive to projects that tend to improve the lives of its people. North Dakota state government will support fossil fuels more than green energy as they make money from fossil fuels but engaging with government officials and other stakeholders in seeing the benefits of geothermal energy is a way of making the desired progress for Geothermal energy. It is believed that once a geothermal project can be achieved and the government can witness its operation and viability, they will make laws and policies to favor geothermal.
- Finance is the most critical part of project execution and getting investors is not an easy task. Reusing an existing but abandoned well has reduced the financial needs of the project by a considerable proportion. Although it is not easy to find investors on high-capital projects willing to take all the risk, we can manage this risk with Government assistance, public-private partnerships, or joint ventures. It is important to seek long-term investors as the outlay finance can be recouped as part of a long-term investment and due to the homogeneity of products derived from geothermal energy (power and heat) it does not command a price premium and the break-even period for investors might be long term.
- There is a fair amount of distrust between locals and companies when it comes to how the companies manage their environment. As such, people tend to vote against companies doing any projects in their area. To solve this problem, Stakeholder engagement is critical and communication with the locals is essential to build trust
- Making realistic plans for the development of the geothermal project is necessary. It is important to start thinking simultaneously about the technical, administrative and financial needs of the project to allow for contingencies in time and budget in areas where there is

uncertainty to be prepared for unexpected results in some aspects of the development because they are almost certain to occur. (GeoCom, 2015)

- For most geothermal projects, an exploration well with multiple tests and data records is the norm. But numerous studies of the geothermal resources of the Williston Basin and much data exist on the North Dakota Industrial commission's (NDIC) website about wells close to our area of interest. Thus, one can predict with a high degree of certainty the geology of our proposed site, lithology, and temperature of our target formation.
- There is a possibility of encountering high concentrations of total dissolved solids at the target formation. High TDS raises the possibility of scaling, but it can be handled with the mechanical process of pigging or the chemical process of scaling inhibitors.
- For Induced seismicity – North Dakota is in a stable region and as such the chances are low but with continuous injection and reinjection of fluids into the formation to generate the heat, the potentials are there, hence geophones/detectors should be installed to monitor the area and seismic activity there. Local and regional faulting/tectonic evaluation will also be conducted. There exist other risks but with experienced hands in the project and no cutting of corners, the chances of occurrence are low.

Geophires

According to Beckers and McCabe (2018,2019), GEOPHIRES is an acronym that stands for GEOthermal energy for Production of Heat and electricity (“IR”) Economically Simulated, with “IR” representing electric current and resistance and referring to the electricity mode. It is a computer code (python) that performs techno-economic simulations of geothermal energy systems. Input parameters are given, and the tool simulates the wellbore, subsurface and surface plants by using models that are built-in or user provided. Possible end-use configurations are direct-use heat (e.g., for district heating or an industrial process), electricity, and cogeneration or combined heat and power (CHP). Ground-source heat pumps are not considered. The simulated output includes the reservoir production temperature and instantaneous and lifetime surface plant heat and/or electricity production. Combined with capital, operation, and maintenance (O&M) cost correlations, GEOPHIRES applies Levelized cost models to estimate the overall required investment and Levelized cost of electricity and/or heat (LCOE and LCOH). The GEOPHIRES v2.0 is an upgraded version of the v1.0 by Beckers et al (2013).

Selecting the 1-D linear heat sweep model for the reservoir model which is for Direct Use Heat and keying in some of the input parameters from my data while some other parameters are allowed to be the default settings on the GEOPHIRES. The parameters set include Porosity at 21%, thermal conductivity at 1.4 W/m/K, the flow rate at 85.6kg/s, and maximum drawdown at 30%. Surface Technical parameters are the surface temperature at 6 ^{o}C, Utilization factor of 90%, and efficiency factor at 90%. Financial parameters include a plant lifetime of 30 years, a 5% discount rate and an assumed zero inflation during construction. Other parameters are left as is from the tool.

	units	
Williston elevation	m	572
Well elevation	m	583
Gradient	deg C/Km	51.75
Maximum temperature	deg C	82.5
Number of Production Wells	-	1
Number of Injection Wells	-	1

Table 11: Input Parameters for GEOPHIRES

Summary of Simulation Results	
End-Use Option	= Direct-Use Heat
LCOH	= 12.0 $/MMBTU
Economic Model Used	= Standard Levelized Cost Model
Maximum Net Heat Production	= 9.42 MW_{th}
Average Net Heat Production	= 4.28 MW_{th}
Minimum Net Heat Production	= 2.14 MW_{th}
Initial Net Heat Production	= 9.37 MWth
Average Annual Heat Production	= 33.64 GWh
Average Pumping Power	= 1.96 MWe
Discount Rate	= 5.00%

Table 12: GEOPHIRES Simulation Result

DISCUSSION AND CONCLUSION

Williston State College is a prime site for the direct use of geothermal energy using repurposed oil and gas infrastructure.

- Temperature is a factor necessary for direct use. Using the thermostratigraphy method which has been applied in various assessments of geothermal resources in the Williston basin (Lachenbruch; 1970; Gosnold, 1984, 1991, 1999; Gosnold et al., 2010, 2012, 2013, 2014, 2015, 2016, 2017, 2019, 2020; Crowell and Gosnold, 2011; Crowell et al., 2011) on the Inyan Kara formation, which is the formation of interest, we calculate that the temperature is 82.5°C.
- Formations with fluids according to Gosnold et al 2017 are 11 formations with 6 regional aquifers for the Williston basin. Although other formations exist with temperatures capable of direct use, the Inyan Kara formation is the shallowest formation with porosity and permeability capability for the easy extraction of formation water with adequate temperature.
- Oil and Gas infrastructure plays a great role in geothermal use. Data from existing wells helps in decision-making in citing plants, porosity, and permeability of formations. Abandoned Oil and Gas wells are also repurposed for geothermal purposes saving a lot of capital expenditure that will occur from drilling a new well.

The factors above play great roles in geothermal direct use. In addition to those factors, nearness to a user community is important as it is used locally. Other factors include porosity and permeability, Thermal energy in the production well, and volumetrics of the reservoir.

Well-7290 and 2476 were selected as production and injection wells not just for their heat production capabilities but also due to them being close to the College thereby saving cost through the reduction of transmission pipes.

As the temperature of the Inyan Kara formation is at 82.5ºC, porosity is at 21%, permeability at 100mD, Original water in place at 268692257.70bbl, Productivity Index at 31.93bbl/day/psi and Heat produced at 2,809,871,031.36 BTU/day, we can calculate the heat produced per year and compare to the heat used in Williston State College per year.

Therefore,

According to the USEIA report 2016, Educational buildings of over 100,000sqft consumes 72K BTU/ square foot per year.

Williston ARC = 250,000 sqft

Campus buildings = 250,000 sqft

Total square footage = 500,000 sqft

WSC Energy consumptions = 500,000 sqft * 72,000BTU/sqft per year = 3,680,000,000BTU/year

The heat generated by the well = Heat produced per day * 365 days

Heat generated by well = 2,809,871,031.36 BTU/day * 365 days/year

The heat generated by the well = 1,025,602,926,446.69 BTU/year.

From the above calculations, the well is adequate to perform the functions of providing heat for the Williston State College campus while also adding heat for the proposed aquaponics greenhouse and the Williston ARC - all of which will be beneficial to the community at large.

According to the stimulation by GEOPHIRES, the LCOH is 12.0 $/MMBTU while the current price of propane in North Dakota is $1.889 per gallon (EIA 2022). Converting the price of propane to Million BTU we have propane price at $20.7/MMBTU thereby showing that it is cheaper to use the heat from the well. We acknowledge that the 1-D stimulation has fixed values and parameters that are different from that of the Williston Basin. Government tax-waiver incentives and the proposed income coming from the aquaponics greenhouse or the heating up of the pools in the ARC on campus have not been considered.

In conclusion, the energy from that well will be enough to heat Williston State College. Matching its demand, creating jobs and income via the aquaponics greenhouse, heating recreational facilities, and generating income, reduce dependency and use of fossil fuels while also decarbonizing the environment by replacing the use of fossil fuels for heating purposes.

Limitations

Limitations from this research will include but are not limited to

- Finance: Initial funding for a geothermal project is expensive due to the costs of drilling and/or well workover and completion.
- The GEOPHIRES built-in parameters are not valid for every region. Sedimentary basins vary in rock types and physical and thermal properties reducing the robustness of the economic feasibility estimate.
- Wells: Repurposing wells seem like an innovative idea, but most plugged and abandoned wells are over 30 years old putting well integrity to question.
- Convincing the state government to go green when they make money off fossil fuel is going to be difficult.

Future Work

Williston State College is supposed to be a test run on the acceptability and possibility of repurposing an abandoned oil well in North Dakota. The success of this run will open doors to expanding the process to the entire Williston city and western North Dakota where the geothermal gradient is high.

REFERENCES

Adam Zoet et al, (2011) Geothermal 101: The Basics and Applications of Geothermal Energy.

AFN (2022) : https://agfundernews.com/aquaponics-the-next-big-thing-in-agriculture

Ahern, J. L. & Turcotte, D. L. (1979). Magma migration beneath an ocean ridge. Earth Planet. Sci. Lett. 45, 115–22.

Blackwell, D., M. Richards, Z. Frone, J. Batir, A. Ruzo, R. Dingwall, and M. Williams, (2011), Temperature at 6.5km depth maps for the conterminous US and geothermal resource estimates, GRC Transactions, 35 (GRC1029452)

Blackwell, D.D., and M. Richards, (2004). "Geothermal Map of North America", U.S. Subset. Amer. Assoc. Petroleum Geologists, Tulsa, OK, scale 1:6,500,000

Buursink, M.L., Merrill, M.D., Craddock, W.H., Roberts-Ashby, T.L., Brennan, S.T., Blondes, M.S., Freeman, P.A., Cahan, S.M., DeVera, C.A., and Lohr, C.D., (2014), "Geologic framework for the national assessment of carbon dioxide storage resources—Williston Basin, Central Montana Basins, and Montana Thrust Belt study areas, chap. J of Warwick, P.D., and Corum, M.D., eds., Geologic framework for the national assessment of carbon dioxide storage resources: U.S. Geological Survey Open-File Report 2012–1024–J, 40 p.," http://dx.doi.org/10.3133/ofr20121024J https://pubs.usgs.gov/of/2012/1024/j/pdf/ofr2012-1024j.pdf

Bodri L., Cermak V., (2007) "Borehole Climatology: a new method how to reconstruct climate" Elsevier Science 9780080453200.

Cataldi, R., Hodgson, S. F., Lund, J. W (1999), "Stories from a Heated Earth – Our Geothermal Heritage", Geothermal Resources Council International Geothermal Association, Sacramento, California, (1999), 569 p.

Chu, M.H. 1988, Inflow performance relationships for geopressured geothermal wells. Houston, Geothermal Resources Council Transactions, **v.** 12, October 1988, p. 437-440.

Chu M.H, 1991 Study of the geothermal production potential in the Williston basin, North Dakota. Engineering Final Report

Crowell, A. M., and Gosnold, W. D., (2011), Correcting Bottom-Hole temperatures: A Look at the Permian Basin (Texas), Anadarko and Arkoma Basins (Oklahoma), and Williston Basin (North Dakota), Geothermal Resources Council Transactions, Vol. 35, pp. 735-738.

Crowell, A. M., Klenner, R., and Gosnold, W. D., (2011), GIS Analysis for the Volume and Available Energy of Selected Reservoirs: Williston Basin, North Dakota, Transactions: Geothermal Resources Council Vol. 35, pp. 1581-1585.

Davies, J.H. and Davies, D.R. (2010) “Earth’s surface heat flux” Solid Earth, 1, 5–24, 2010.

Energy efficiency and renewable energy (2022) https://www.energy.gov/eere/geothermal/electricity-generation

Esource.com (2022) “Colleges and Universities” https://esource.bizenergyadvisor.com/article/collegesanduniversities#:~:text=Colleges%20and%20universities%20in%20the,2%20)%20of%20floorspace%20each%20year.

Fetkovich, J.J., 1973, "The Isochronal Testing of Oil Wells," paper SPE 4529. presented at the SPE 48th Annual Fall Meeting, Las Vegas, NV.

Fox D. B., Sutter D., Beckers K. F., Lukawski M. Z., Koch D. L., Anderson B. J., and Tester, J. W. (2013). “Sustainable Heat Farming: Modeling Extraction and Recovery in Discretely Fractured Geothermal Reservoirs”. Geothermics 46, pp. 42- 54.

Georisk (2019) https://www.georisk-project.eu/georisk-tool/

GeoCom (2015) https://geothermalcommunities.eu/assets/elearning/9.17.COSTS.pdf

Go Green Aquaponics (2022) “The Effects of Water Temperature in Aquaponics” https://gogreenaquaponics.com/blogs/news/the-effects-of-water-Temperature-in-aquaponics#:~:text=The%20water%20Temperature%20range%20for,fish%20thrive%20in%20this%20range.

Gosnold Will, Michael Mann, and Hossein Salehfar (2017) “The UND-CLR Binary Geothermal Power Plant” GRC Transactions, Vol. 41, 2017

Gosnold, W.D., McDonald, M.R., Klenner, R., Merriam, D., (2012). Thermostratigraphy of the Williston Basin. GRC Transactions 36, 8.

Gosnold, W., Lefever, R., Klenner, R., & Mann, M. (2010). Geothermal Power form Coproduced Fluids in the Williston Basin. GRC Transactions, 34(GRC1028702).

Gosnold, W.D., Jr., (1999b), “Basin-Scale groundwater flow and advective heat flow: An example from the northern Great Plains”, in Geothermics in Basin Analysis, Forster and Merriam, Eds., Kluwer Academic/Plenum, p. 99-116.

Gosnold, W.D., Jr., (1991), “Subsurface Temperatures in the Northern Great Plains”, in Slemmons, D.B., E.R. Engdahl, M.D. Zoback, and D.D. Blackwell, eds., Neotectonics of North America; Boulder, Colorado, Geological Society of America, Decade Map vol. 1.

Gosnold, W. D., (1990), “Heat flow in the Great Plains of the United States”, Journal of Geophysical Research, vol. 95, no. B1, p. 353-374.

Gosnold Jr., W. D., (1984), “Geothermal Resources in the Williston Basin: North Dakota”. Transactions of the Geothermal Resources Council, vol. 8, p. 431-436.

Grame Ross Beardsmore, J. P. Cull, (2001) "Crustal Heat Flow: A Guide to Measurement and Modelling", Cambridge University Press 2001.

Greenberg, R., Wacker, J. F., Hartmann, W. K., & Chapman, C. R. (1978). Planetesimals to planets: Numerical simulation of collisional evolution. *Icarus* **35**, 1–26.

Hulen, J.B., et al. (2001) "Geothermal Energy: Clean Sustainable Energy for the Benefit of Humanity and the Environment." University of Utah Energy and Geoscience Institute. May 2001

Jeffery W. Bader (2017) "Mapping sandstones of the Inyan Kara Formation for saltwater disposal in North Dakota" https://www.researchgate.net/publication/332100379.

Jeffery W. Bader (2019) "A Sequence Stratigraphic Model for the Inyan Kara Formation North Dakota" https://www.researchgate.net/publication/334400947

Jones, L.G. Blount, E.M. and Glaze, O.H., 1976, "Use of Short-Term Multiple Rate Flow Tests to Predict Performance of Wells Having Turbulence" paper SPE 6133, presented at the SPE 51st Annual Fall Meeting, New Orleans, LA.

Koenraad F. Beckers, Maciej Z. Lukawski, Timothy J. Reber, Brian J. Anderson, Michal C. Moore, Jefferson W. Tester (2013). " Introducing GEOPHIRES v1.0: software package for estimating Levelized cost of electricity and/or heat from enhanced geothermal systems" PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 11-13, 2013 SGP-TR-198.

Koenraad F. Beckers and Kevin McCabe (2018) "Introducing GEOPHIRES v2.0: Updated Geothermal Techno-Economic Simulation Tool" PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, 2018 SGP-TR-213.

Koenraad F. Beckers and Kevin McCabe (2019) "GEOPHIRES v2.0: updated geothermal techno-economic simulation tool" Geotherm Energy (2019) 7:5 https://doi.org/10.1186/s40517-019-0119-6

Koenraad F. Beckers, Amanda Kolker, Hannah Pauling, Joshua D McTigue , Devon Kesseli, (2021) "Evaluating the feasibility of geothermal deep direct-use in the United States" Energy Conversion and Management 243 (2021) 114335

Kutasov, I.M. 1989, Water FV factors at higher pressures and temperatures: Oil and Gas Journal, March 20, 1989, p. 102-104.

Lachenbruch, A.H., (1970), "Crustal temperature and Heat Production: Implications of the Linear Heat-Flow Relation", Journal of Geophysical Research, vol. 75, no. 17, p. 3291-3300

Levin, B. J. (1972). Origin of the Earth. In *The Upper Mantle*, pp. 7–30, ed. A. R. Ritsema.

Elsevier, Amsterdam

Lund, J.W. (1998) “Geothermal direct-use equipment overview”. GHC Bulletin, March 1998

Lund, J.W., Leif Bjelm, Gordon Bloomquist, and Anette K. Mortensen (2008) “Characteristics, development and utilization of geothermal resources – a Nordic perspective” https://www.researchgate.net/publication/238784790

Lund, J.W. (2016) “Direct utilization of geothermal energy 2015 worldwide review”

Mary H. Dickson, Mario Fanelli (2003) “Geothermal Energy Utilization and Technology”.

McCabe, K., Gleason, M., Reber, T., and Young, K. R. (2016): “Characterizing U.S. Heat Demand for Potential Application of Geothermal Direct Use”, Proceedings, 40th GRC Annual Meeting, Sacramento, California (2016).

McKenna, J., Blackwell, D., and Moyes, C., (2005), “Geothermal power supply possible from Gulf Coast, Midcontinent oil field waters”, Oil & Gas Journal, p. 34-40.

Michael K. Nord (2022) “Personal Communications”

Moore, J. and Simmons, S.(2013). “More power from below”. Science, 340(6135): 933– 934.

Muffler, L. (1979). “Assessment of geothermal resources of the United States”, 1978. United States. https://doi.org/10.2172/6870401

The National Renewable Energy Laboratory (NREL)(2022) https://www.nrel.gov/research/re-geo-elec-production.html

North Dakota Geological Survey: Geothermal Resource Development Regulation (2013) https://www.dmr.nd.gov/ndgs/geothermal/2013CenturyCode.asp

Safronov, V. S. (1969). Evolution of the Protoplanetary Cloud and Formation of the Earth and Planets. Nauka, Moscow, Translation by the Israel Program for Scientific Translation, 1972. (1978). The heating of the Earth during its formation. Icarus **33**, 3–12.

Schubert, G., Cassen, P., &Young, R. E. (1979a). Subsolidus convective cooling histories of terrestrial planets. Icarus 38, 192–211.

Schubert, G., Cassen, P., &Young, R. E (1979b). Core cooling by subsolidus mantle convection. Phys. Earth Planet. Int. 20, 194–208.

Schubert, G., Stevenson, D., & Cassen, P. (1980). Whole planet cooling and the radiogenic heat source contents of the Earth and Moon. J. Geophys. Res. 85, 2511–8.

Sidike A. (2020) “Geothermal Energy from Repurposed Oil and Gas Wells in Western North

Dakota”. Master’s degree thesis.

Snyder D, Beckers K, Young K. (2017) “Update on Geothermal Direct-Use Installations in The United States.” Proceedings, 42nd Workshop on Geothermal Reservoir Engineering, Stanford University

Smith, S. A., Beddoe, C. J., Mibeck, B. A. F., Heebink, L. V., Kurz, B. A., Peck, W. D., & Jin, L. (2017). “Relative Permeability of Williston Basin CO_2 Storage Targets”. Energy Procedia, 114, 2957–2971. 10.1016/j.egypro.2017.03.1425

Stein, C.A. and Stein, S. 1992 “A model for the global variation in oceanic depth and heat flow with lithospheric age” Nature. Vol. 359. 10 September 1992.

Stevenson, D. J., Spohn, T., & Schubert, G. (1983). Magnetism and thermal evolution of the terrestrial planets. Icarus 54, 466–89.

Tester, J. W., Anderson, B., Batchelor, A., Blackwell, D., DiPippo, R., Drake, E., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksoz, N., Veatch, R., Augustine, C., Baria, R., Murphy, E., Negraru, P., Richards, M. (2006). “The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century”. Massachusetts Institute of Technology, DOE Contract DE-AC07-05ID14517 Final Report, 374p.

Tester, J.W. (2011). “Lessons Learned from Energy Use in the U.S”. Energy and Environmental Science 4, pp. 3729–3730.

Williston State College https://www.willistonstate.edu/students/Campus-Life/Williston-ARC/

United States Energy Information Administration (USEIA), (2017). “Primary Energy Overview”. http://www.eia.gov/beta/MER.

United States Energy Information Administration (USEIA), (2020). “North Dakota Profile State Profile and Energy Estimates” https://www.eia.gov/state/index.php?sid=ND

United States Energy Information Administration (USEIA), (2021). “Energy-Related CO2 Emission Data Tables” https://www.eia.gov/environment/emissions/state/

United States Energy Information Administration (USEIA), (2021). “North Dakota Energy Consumption by End-Use Sector 2019” https://www.eia.gov/state/index.php?sid=ND#tabs-2

United States Energy Information Administration (USEIA), (2021). https://www.eia.gov/state/analysis.php?sid=ND

US Climate Data (2022) https://www.usclimatedata.com/climate/williston/north-dakota/united-states/usnd0372

U.S. Green Building Council (USGBC) (2022) https://www.usgbc.org/articles/biden administration-takes-shape-around-sustainability

Vraa, H., Picklo, M., Hertz, E., & Gosnold, W. (2019). "Geothermal Energy Utilization of Multi-Well Oil Pads via the Application of Organic Rankine Cycle Systems". Geothermal Resources Council Transactions, 43.

Weathersparks.com (2022) https://weatherspark.com/y/4085/Average-Weather-in-Williston-North-Dakota-United-States-Year-Round#Figures-Temperature.

APPENDIX

Geophires Output

```
Python 3.9.7 (default, Sep 16 2021, 16:59:28) [MSC v.1916 64 bit (AMD64)]
Type "copyright", "credits" or "license" for more information.
IPython 7.29.0 -- An enhanced Interactive Python.
In [1]:         'C:/Users/nngob/OneDrive/Desktop/Geophires/GEOPHIRES-v2-master/
GEOPHIRESv2.py'      ='C:/Users/nngob/OneDrive/Desktop/Geophires/GEOPHIRES-v2-
master'
Warning: No valid fracture area provided. GEOPHIRES will assume default fracture area
(250,000
m2)
Warning: No valid number of fractures provided. GEOPHIRES will assume default number
of
fractures (10)
Warning: No valid reservoir volume provided. GEOPHIRES will assume default reservoir
volume
(1.25E8 m3)
Warning: No valid water loss fraction provided. GEOPHIRES will assume default water
loss
fraction (0)
----------------------------
GEOPHIRES Simulation Results
----------------------------
1. Simulation Metadata
----------------------
GEOPHIRES Version = 2.0
GEOPHIRES Build Date = 2018-01-02
Simulation Date = 2022-07-01
Simulation Time = 23:57
Calculation Time = 0.960 s
2. Summary of Simulation Results
--------------------------------
End-Use Option = Direct-Use Heat
Average Net Heat Production = 4.28 MWth
LCOH = 12.0 $/MMBTU
Economic Model Used = Standard Levelized Cost Model
Discount Rate = 5.00%
3. Reservoir Simulation Results
-------------------------------
Reservoir Model = 1-D Linear Heat Sweep Model
Number of Production Wells = 1
Number of Injection Wells = 1
Number of Times Redrilling = 0
Well Depth = 1471.2 m
Flow Rate per Production Well = 86 kg/s
Initial Reservoir Temperature = 82.5°C
Maximum Production Temperature = 82.2°C
Average Production Temperature = 66.3°C
Minimum Production Temperature = 59.6°C
Initial Production Temperature = 82.1°C
Average Reservoir Heat Extraction = 4.75 MWth
Production Wellbore Heat Transmission Model = Ramey Model
```

```
Average Production Well Temperature Drop = 0.2°C
Total Average Pressure Drop = 17942.9 kPa
Average Injection Well Pressure Drop = 239.9 kPa
Average Reservoir Pressure Drop = 17549.4 kPa
Average Production Well Pressure Drop = 239.9 kPa
Average Buoyancy Pressure Drop = -86.3 kPa
1
4. Surface Equipment Simulation Results
---------------------------------------
Maximum Net Heat Production = 9.42 MWth
Average Net Heat Production = 4.28 MWth
Minimum Net Heat Production = 2.14 MWth
Initial Net Heat Production = 9.37 MWth
Average Annual Heat Production = 33.64 GWh
Average Pumping Power = 1.96 MWe
5. Capital and O&M Costs
------------------------
Total Capital Cost = 15.05 M$
Wellfield Cost = 4.76 M$
Surface Plant Cost = 3.37 M$
Exploration Cost = 3.04 M$
Field Gathering System Cost = 2.37 M$
Stimulation Cost = 1.51 M$
Total O&M Cost = 1.15 M$/year
Wellfield O&M Cost = 0.14 M$/year
Surface Plant O&M Cost = 0.25 M$/year
Make-Up Water O&M Cost = 0.00 M$/year
Average annual pumping costs = 0.77 M$/year
6. Power Generation Profile
---------------------------
YEAR THERMAL GEOFLUID PUMP NET
DRAWDOWN TEMPERATURE POWER HEAT
(-) (deg C) (MWe) (MWth)
0 1.0000 82.07 1.9587 9.3730
1 1.0008 82.14 1.9587 9.3929
2 1.0011 82.17 1.9587 9.4027
3 1.0013 82.18 1.9587 9.4078
4 1.0014 82.19 1.9587 9.4110
5 1.0015 82.20 1.9587 9.4135
6 1.0016 82.21 1.9587 9.4153
7 1.0017 82.21 1.9587 9.4169
8 1.0017 82.21 1.9587 9.4182
9 1.0017 82.22 1.9587 9.4193
10 1.0018 82.22 1.9587 9.4202
11 1.0018 82.22 1.9587 9.4211
12 1.0018 82.23 1.9587 9.4219
13 0.7638 62.69 1.9570 3.1235
14 0.7626 62.59 1.9570 3.0920
15 0.7614 62.49 1.9570 3.0607
16 0.7603 62.40 1.9570 3.0298
17 0.7591 62.30 1.9570 2.9991
18 0.7580 62.21 1.9569 2.9687
19 0.7568 62.12 1.9569 2.9386
20 0.7557 62.02 1.9569 2.9088
21 0.7546 61.93 1.9569 2.8793
```

```
22 0.7535 61.84 1.9569 2.8501
23 0.7524 61.75 1.9569 2.8211
24 0.7513 61.66 1.9569 2.7924
25 0.7502 61.57 1.9569 2.7640
26 0.7492 61.49 1.9569 2.7359
27 0.7481 61.40 1.9569 2.7081
2
28 0.7471 61.31 1.9569 2.6805
29 0.7460 61.23 1.9569 2.6532
30 0.7450 61.15 1.9569 2.6262
31 0.7440 61.06 1.9569 2.5994
32 0.7430 60.98 1.9569 2.5729
33 0.7420 60.90 1.9568 2.5467
34 0.7410 60.82 1.9568 2.5207
35 0.7401 60.74 1.9568 2.4950
36 0.7391 60.66 1.9568 2.4695
37 0.7381 60.58 1.9568 2.4443
38 0.7372 60.50 1.9568 2.4193
39 0.7363 60.43 1.9568 2.3946
40 0.7353 60.35 1.9568 2.3701
41 0.7344 60.28 1.9568 2.3459
42 0.7335 60.20 1.9568 2.3219
43 0.7326 60.13 1.9568 2.2982
44 0.7317 60.06 1.9568 2.2746
45 0.7308 59.98 1.9568 2.2514
46 0.7300 59.91 1.9568 2.2283
47 0.7291 59.84 1.9568 2.2055
48 0.7283 59.77 1.9568 2.1829
49 0.7274 59.70 1.9568 2.1605
50 0.7266 59.63 1.9568 2.1384
C:\Users\nngob\OneDrive\Desktop\Geophires\GEOPHIRES-v2-master\GEOPHIRESv2.py:1471:
RuntimeWarning: overflow encountered in multiply
Tresoutput = Twnd*(Trock-Tinj) + Tinj
In [2]:
3
```