PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

Probabilistic Assessment and Uncertainty Quantification of a Geothermal Resource, Red River Formation, North Dakota

Emmanuel Gyimah, Olusegun Tomomewo, William Gosnold, Adesina Fadairo, Charles Kporxah, Jerjes Porlles, Abdesselem Dehdouh

Gorecki Center, 3501 University Ave Stop 8357, Grand forks 58202

Emmanuel.gyimah@und.edu , Olusegun.tomomewo@und.edu

Keywords: Geothermal energy, probabilistic assessment, uncertainty quantification, Beaver Lodge field, arithmetic mean

ABSTRACT

Geothermal energy stands out as a sustainable green energy that complements the global energy transition away from fossil fuels. The immense potential of geothermal resources in deep sedimentary basins in North Dakota makes it an attractive and alternative source of energy. Effective utilization of geothermal resources requires a good understanding of inherent uncertainties and variabilities. This study incorporates the application of geo-statistical methods on geothermal reservoir engineering principles for evaluating uncertainty parameters within a geothermal reservoir. Uncertainty analysis quantifies the variability and ambiguity of subsurface parameters to better evaluate resource utilization and project feasibility. This study accounts for uncertainties in field data inputs from the Red River Formation that are essential to assess the geothermal energy potential, reduce risk associated with geothermal energy exploration and promote sustainable development. Probabilistic assessment and uncertainty quantification of geothermal resources are crucial in informed decision making and successful reservoir utilization. In this study of the Beaver Lodge field in the Red River Formation, we found that arithmetic means for total geothermal resources, aquifer geothermal resources and producible geothermal resources are: 4.0×10^{18} J, 2.5×10^{17} J and 4.8×10^{16} J respectively. We found that relative impact plot shows total geothermal resource is sensitive to the gross thickness and volume of the reservoir, aquifer geothermal resource is sensitive to the porosity and water saturation of the reservoir and lastly, the producible geothermal reservoir is sensitive to the fluid flowrate and formation permeability.

1. INTRODUCTION

1.1 Geothermal energy in North Dakota

Geothermal energy is a clean and sustainable energy source that uses the thermal properties of the earth's crust to generate energy for heating and cooling as well as electricity generation. Primordial heat produced billions of years ago and radioactive decay are the main sources of this energy. It is divided into two categories: moderate to low temperature resources (< 150°C), which are typically found in deep sedimentary strata or shallow subsurface rocks, and high temperature resources (> 150°C), which are found in areas of significant tectonic activity (Dickson et al., 2004). This heat can be used for various applications, including electricity generation and direct heating. Geothermal energy is estimated to currently supply, for direct heat use and geothermal heat pumps, approximately 21,700 TJ/yr (6029 GWh/yr) of energy through direct-heat applications in the United States (Ufondu, 2017). Geothermal energy in North Dakota, particularly in the western region, has significant potential for electricity generation and heating. Several empirical correlations have been utilized for permeability modelling and heat flow studies have been done on the Red River Formation to highlight the geothermal potential (Gyimah et al., 2023a). Machine learning has been used to improve subsurface characterization within the Red River Formation to classify it as a geothermal hotspot (Koray et al, 2023). The state's favourable conditions for Enhanced Geothermal Systems (EGS) are being explored using data from deep oil wells (Ouadi et al, 2023). The deeper formations of the Williston basin have been estimated to have high geothermal resource systems and great geothermal storage systems (Gyimah et al, 2023b) (Gosnold et al, 2017) (Vashaghian et al, 2023). From Merzoug's studies on existing oil and gas wells, they could be repurposed in North Dakota to geothermal wells (Merzoug et al, 2023). Geothermal heat pumps are increasingly used in homes, schools, and public buildings to provide efficient heating and cooling. Geothermal resources in the Williston Basin in North Dakota occur as thermal waters in at least four regional aquifers, i.e., the Inyan Kara (Cretaceous), Madison (Mississippian), Duperow (Devonian), and Red River (Ordovician). According to the U.S. Energy Information Administration (EIA), exploration and production risk stands out as a pivotal factor contributing to the gradual development of Enhanced Geothermal Systems (EGS) resources (Lowry et al, 2016). Mufer et al, 1978 employed a volumetric approach coupled with probabilistic analysis to calculate the thermal energy content and analyze the recoverable energy for electricity generation. In a study focused on the Dikili-Izmir region in Turkey, Turan et al, 2021 conducted probabilistic heat in place calculations, revealing that there is a 50% probability of generating 75 MW of net electrical power. Wang et al, 2022 ingeniously constructed proxy numerical models utilizing Experimental Design and Response Surface Methodology in conjunction with the Monte Carlo Simulation technique. Their approach provided a probabilistic assessment of the thermal energy potential in the Maichern Sag area in South China.

1.2 Red River Formation

The Red River Formation in the Williston Basin of North Dakota has a thickness of over 214m, temperatures exceeding 140°C and its permeability is 0.1–38 mD (Hartig, 2018). The formation is divided into upper and lower subunits. The lower subunit makes up two thirds of the Red River portion in the middle basin and is composed of fossiliferous wackestone that has been burrow-mottled. Towards the margins of the basin, the lower Red River becomes less fossiliferous, less burrow-mottled, and grades into dense dolostone. The lithologies of each upper Red River cycle are as follows, in ascending order: nodular to laminated anhydrite, laminated microcrystalline dolostone, burrowed lime mudstone to fossil wackestone, and a thin argillaceous dolomitic mudstone (Sippel, 1998). The Red River Formation has excellent potential projected to produce 3.4×10^{22} J of thermal energy (Porro and Augustine 2014).

2. METHODOLOGY

2.1 Reservoir Parameters Determination

From the North Dakota Industrial Commission (NDIC), reservoir core data were collected for the Beaver Lodge field as shown in Tables, 1, 2 and 3. The mean and standard deviation were calculated from five wells and were used as representative reservoir variables for probabilistic assessment and uncertainty quantification. The representative reservoir variables are crucial in characterizing the subsurface reservoir of the Beaver Lodge field within the Red River Formation. The parametric probabilistic method which works on the principle for statistical distribution was used to generate the expectation curve and uncertainty quantification. Typically, probabilistic assessment and uncertainty quantification methods have been applied on oil and gas reserves (Asante et al, 2021; Ampomah et al, 2016; Morgan et al, 2021).

2.2 Probabilistic method for Geothermal Resource

This paper seeks to quantify the geothermal resource and analyze the uncertainties within the Beaver Lodge field in the Red River Formation in North Dakota. The geothermal resource quantified is sub-divided into three categories: total geothermal resource, aquifer geothermal resource and producible geothermal resource. Probabilistic method can handle large and complex dataset and engineering problems. The parametric method is an analytical procedure that utilizes the mean and standard deviation to generate probabilistic outcomes and uncertainty results. The methodology for the parametric method is displayed in Fig, 1. After generating the mean and standard deviation for the reservoir variables, the first step for the parametric method is to convert them into lognormal mean and lognormal standard deviation. The geothermal resource in lognormal forms is then summed up for lognormal mean and lognormal variance to generate the probabilistic outcome.

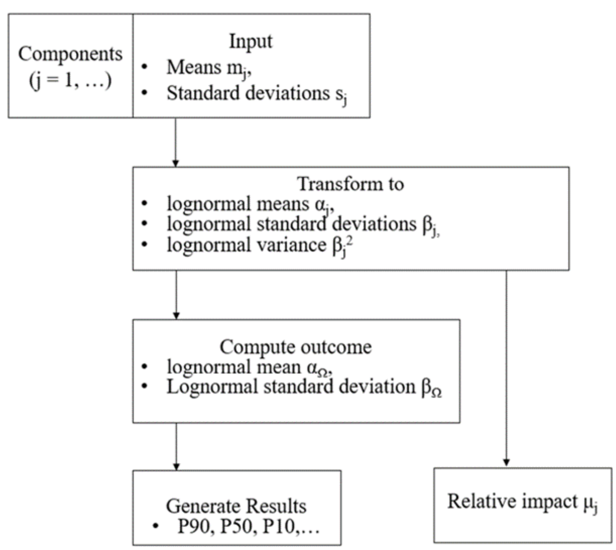

Figure 1: Flow chart for Probabilistic methods

Reservoir Variable	Mean	Standard deviation
Area (m^2)	52609133	0
Gross thickness (m)	205.435	28.65
Density (kg/m^3)	2600	100
Temperature (°C)	150	10
Heat capacity (J/kg/K)	950	30

Table 1: Reservoir Variables for Total Geothermal Resource

Reservoir Variable	Mean	Standard deviation
Area (m^2)	52609133	0
Gross thickness (m)	205.435	28.65
Density (kg/m^3)	2600	100
Temperature (°C)	150	10
Heat capacity (J/kg/K)	950	30
Water saturation (stb/rb)	0.73	0.05
Porosity	0.084	0.0086

Table 2: Reservoir Variables for Aquifer Geothermal Resource

Reservoir Variable	Mean	Standard deviation
Area (m^2)	52609133	0
Gross thickness (m)	205.435	28.65
Density (kg/m^3)	2600	100
Temperature (°C)	130	10
Heat capacity (J/kg/K)	950	30
Water saturation (stb/rb)	0.73	0.05
Porosity (frac.)	0.084	0.0086
Flow rate (m^3/h)	0.223	0.068

Table 3: Reservoir Variables for Producible Geothermal Resource

$$V_j = {}^{s_j}/_{m_j} \quad (1)$$

Where V_j is the coefficient of variation, s_j is the standard deviation and m_j is the mean.

$$\beta^2 = In(1 + V_j^2) \quad (2)$$

Where β^2 is the lognormal variance.

$$u_j = {}^{\beta_j^2}/_{\sum \beta_j^2} \quad (3)$$

Where u_j is the Relative impact

$$\alpha_j = In(m_j) - 0.5 \times \beta_j^2 \quad (4)$$

Where α_j is the lognormal mean

$$P90 = \exp(\alpha - 1{,}281\beta) \quad (5)$$

Where P90 is the Probability at least 90%

$$P50 = \exp(\alpha) \quad (6)$$

Where P50 is the Probability at least 50%

$$P10 = \exp(\alpha + 1{,}281\beta) \quad (7)$$

Where P10 is the Probability at least 10%

$$E_P = \rho\, c_p\, \mathrm{v}\, \mathrm{q}\, \Delta\mathrm{T}\, (T_f \text{ - } 20°\mathrm{C}) \quad (8)$$

Where E_P is the Producible geothermal resource, ρ is density (kg/m^3), c_p is heat capacity (J/kg/K), v is volume (m^3), q is flowrate (m^3/h), T_f is the reservoir fluid temperature (°C) and T_a is annual mean temperature (°C).

$$E_A = \phi\, \rho\, S_w\, c_p\, \mathrm{v}\, \Delta\mathrm{T}\, (T_f \text{ - } T_a) \quad (9)$$

Where E_A is the Aquifer geothermal resource, S_w is water saturation and ϕ is porosity (frac)

$$E_T = \rho\, c_p\, \mathrm{v}\, \Delta\mathrm{T}\, (T_f \text{ - } T_a) \quad (10)$$

Where E_T is the Total geothermal resource

3. RESULTS AND DISCUSSION

3.1 Probabilistic assessment of geothermal reservoir parameters

From the expectation curve, probabilistic estimation of geothermal energy details large accessible energy output within the subsurface of the Red River Formation. As expected, the total geothermal resource which is the energy within the formation is the largest followed by the aquifer geothermal resource and lastly the producible geothermal resource, shown in Fig, 2 and Fig, 3. The aquifer geothermal resource refers to the energy from only the formation fluid therefore its lower energy output compared to the total geothermal resource. The producible geothermal resource is the energy practically utilized at the surface after considering heat loss and fluid flow rate, hence the lowest energy output. For P90 of total, aquifer and producible geothermal resource are: 3.2 $\times 10^{18}$ Joules, 1.9 $\times 10^{17}$ and 2.7 $\times 10^{16}$ respectively. For P50 of total, aquifer and producible geothermal resource are: 3.9 $\times 10^{18}$ Joules, 2.4 $\times 10^{17}$ and 4.4 $\times 10^{16}$ respectively. For P10 of total, aquifer and producible geothermal resource are: 4.8 $\times 10^{18}$ Joules, 3.1 $\times 10^{17}$ and 7 $\times 10^{16}$ respectively. From our studies on the Beaver Lodge field in the Red River Formation, the arithmetic mean for total geothermal resources, aquifer geothermal resources and producible geothermal resources are: 4.0 $\times 10^{18}$ J, 2.5 $\times 10^{17}$ J and 4.8 $\times 10^{16}$ J respectively.

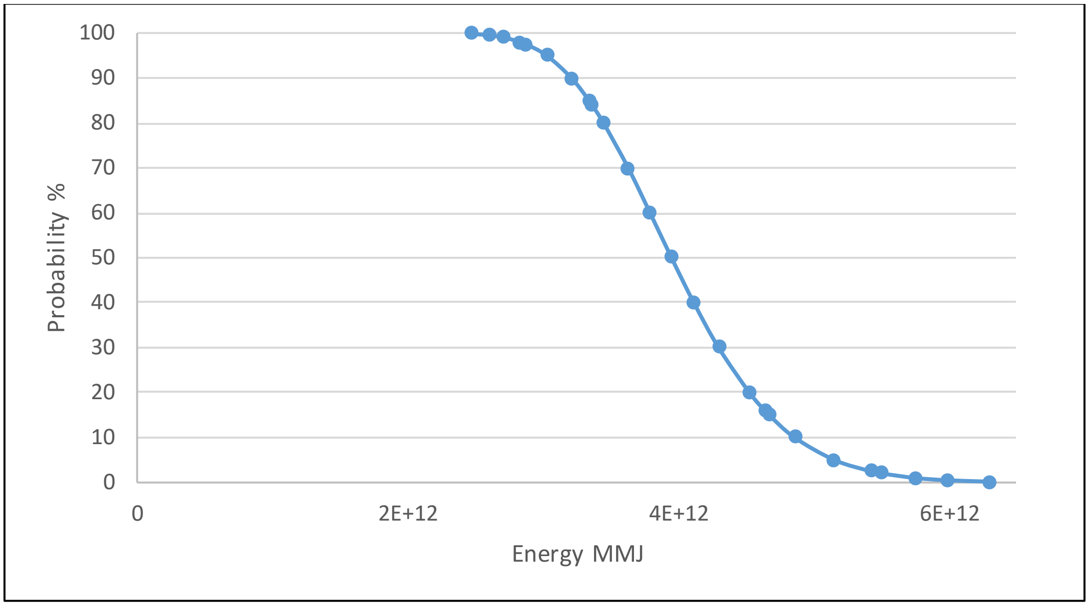

Figure 2: Probabilistic Expectation Curve for Total Geothermal Resource, Beaver Lodge field

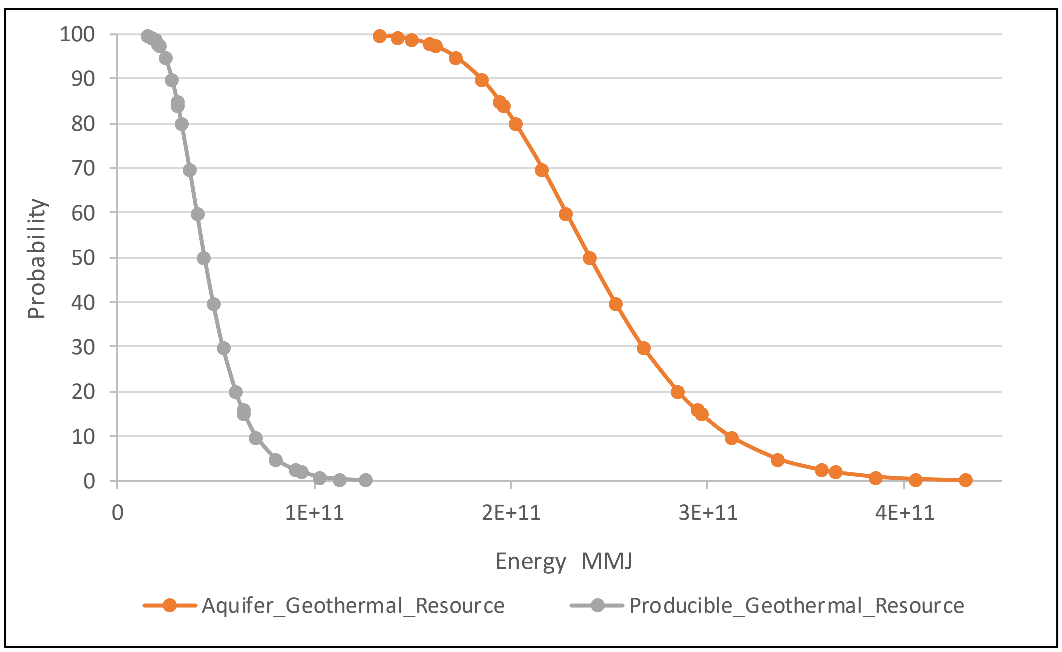

Figure 3: Probabilistic Expectation Curve for both Aquifer Geothermal Resource and Producible Geothermal Resource, Beaver Lodge field

3.2 Uncertainty and relative impact of geothermal reservoir parameters

From the relative impact plot of the reservoir variables, we are able to quantify the uncertainty for the geothermal resource. Firstly, the total geothermal resource has gross thickness (74%) as the most contributing factor to uncertainty followed by temperature (17%), density (6%) and heat capacity (4%) respectively, Fig. 4. This shows the essence of areal extent and thickness collectively bulk volume in determining the total geothermal resource. The Aquifer geothermal resource has its uncertainty outcome as gross thickness (47%), porosity (25%), water saturation (11.4%) and temperature (10.7%), Fig. 5. Since fluids occupy the porous spaces within the formation, water saturation and porosity are sensitive factors to the aquifer geothermal resource. Lastly, producible geothermal resource has its uncertainty outcome dominated by the fluid flowrate (68%), then gross thickness (15%), Fig. 6. Fluid flowrate within subsurface of formation depends on the formation permeability, thereby highly permeable formations allow fluids to flow through quickly.

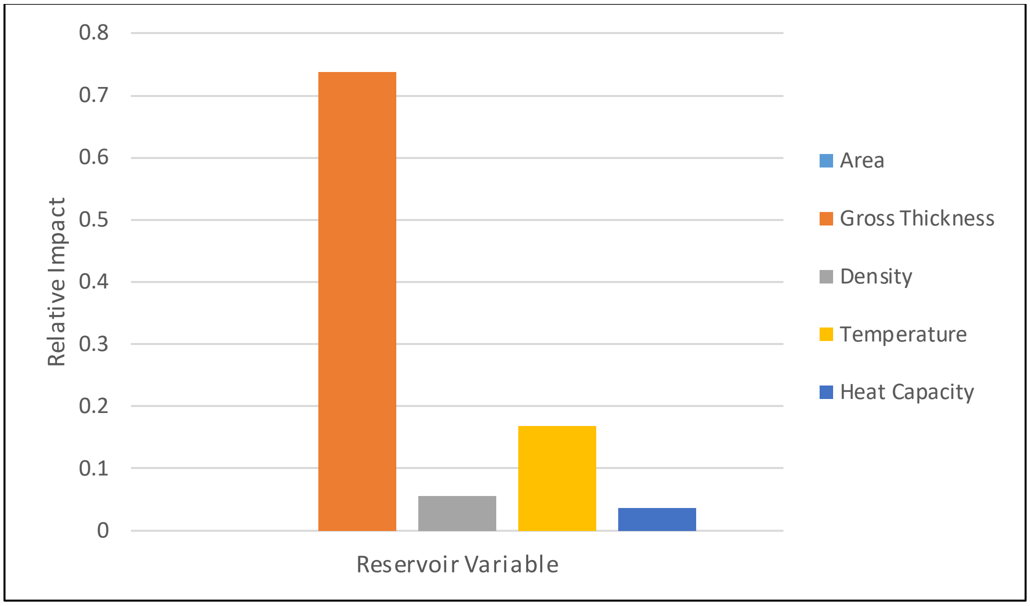

Figure 4: Relative Impact Plot for Total Geothermal Resource, Beaver Lodge field

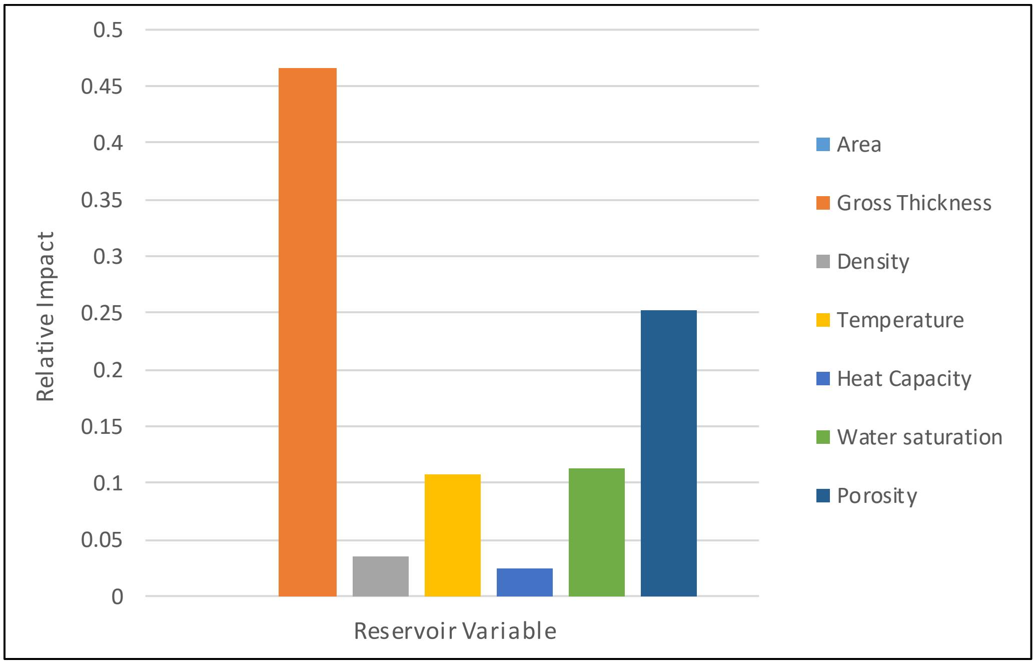

Figure 5: Relative Impact Plot for Aquifer Geothermal Resource, Beaver Lodge field

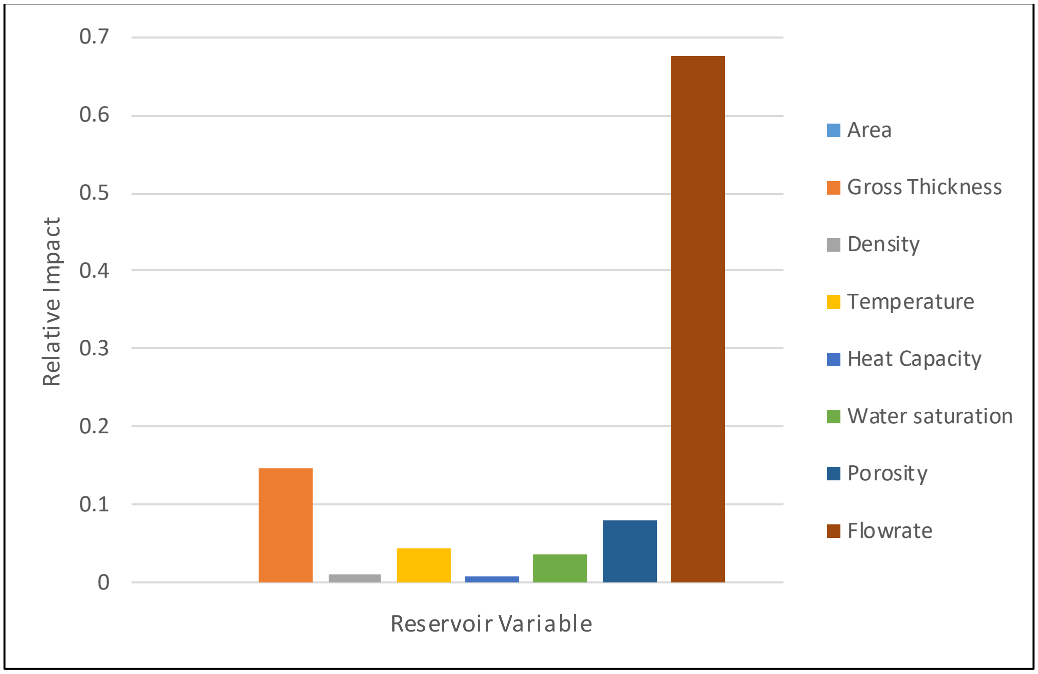

Figure 6: Relative Impact Plot for Producible Geothermal Resource, Beaver Lodge field

4. CONCLUSIONS

Geothermal energy, a sustainable and large untapped energy resource was estimated in large energy quantities within the Red River Formation in the Williston Basin. From the probabilistic method (parametric), geothermal energy output was estimated for total geothermal resource, aquifer geothermal energy and producible geothermal resource. Large energy reserves within the Formation in the form of geothermal energy are accessible to the energy industry. From the relative impact plot, sensitive reservoir variables are depicted to assist in decision making for future viable projects. The geothermal energy assessment provides notable information for resource potential and quantification. The probabilistic method (parametric) was successfully used to estimate the geothermal resource and its sensitive reservoir variables. The quantification of geothermal reserves is very complex due to uncertainty with data precision and heterogeneity hence probabilistic method is another technique utilized to quantify project feasibility and total uncertainty. To conclude, exploration of the geothermal resource within the Williston basin would boom the energy industry.

REFERENCES

Ampomah et al. Probabilistic reserves assessment and evaluation of sandstone reservoir in the Anadarko Basin, SPE, Houston, TX, USA, May 2016

Asante et al. Probabilistic Assessment and Uncertainty Analysis of CO_2 Storage Capacity of the Morrow B Sandstone, Farnsworth Field Unit, Energies 2021

Dickson, Mary and Mario Fanelli. (2004) 'What is Geothermal Energy?' International Geothermal Association

Hartig C. M. (2018) Porous media of the Red River Formation, Williston Basin, North Dakota: a possible Sedimentary Enhanced Geothermal System. International Journal of Earth Sciences, 107, 103-112.

Gosnold et al (2017) The UND-CLR Binary Geothermal Power Plant, Transactions – Geothermal Rising Council 41:1824-34

Gyimah et al. Heat Flow Study and Reservoir Characterization Approach of the Red River Formation to Quantify Geothermal Potential. GRC Transactions, Vol 47, 2023

Gyimah et al (2023) A Conceptual Assessment of Geologic Thermal Storage Systems in North Dakota. 57^{th} US Rock Mechanics / Geomechanics Symposium, Atlanta, Georgia

Koray et al. Assessment of the Red River Formation as a Geothermal Hotspot in North Dakota: A Machine Learning Approach. GRC Transactions, Vol 47, 2023

Lowry et al (2016) A Probabilistic Assessment of Enhanced Geothermal Systems, Uncertainty and Levelized Cost of Electricity

Merzoug Ahmed and Rita Esuru Okorafor. Selection Criteria for Repurposing Oil and Gas Well to Geothermal Heat Extraction. SPE ATCE, San Antonio, Texas, USA

Morgan et al. A Gate-to-Gate Life Cycle Assessment for the CO_2 EOR Operations at Farnsworth Unit, Energies 2021

Mufer et al (1978) Methods for Regional Assessment of geothermal reservoirs, Geothermics 7:53-89

Ouadi et al. Numerical Investigation of Fishbone Well Design Impact on Geothermal System Enhancement in North Dakota. GRC Transactions, Vol 47, 2023

Ouadi et al. (2023) Design and Performance Analysis of Fishbone Wells in Solution Gas Drive Reservoirs for Drilling Decarbonisation. 57^{th} US Rock Mechanics / Geomechanics Symposium, Atlanta, Georgia

Ufondu L. S. (2017). Assessment of the potential heat stored in the deep aquifers of the Williston Basin for geothermal energy production (Doctoral dissertation, University of Saskatchewan)

Vashaghian et al. Petro-physical Characterization of Lodgepole Formation as a Geothermal Reservoir. GRC Transactions, Vol 47, 2023

Sippel, M. A., Luff, K. D., Hendricks, M. L., & Eby, D. E. (1998). Reservoir characterization of the Ordovician Red River Formation in southwest Williston Basin Bowman County, ND and Harding County, SD (No. DOE/BC/14984-14). Luff Exploration Co., Denver, CO (United States).

Turan et al (2021) Probabilistic Assessment of geothermal resource and their development in Dikili-Izmir region

Wang et al (2022) Probabilistic Geothermal Assessment in Maichen Sag, South China