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Geothermal Potential Assessment of the Agadem Petroleum Basin (Eastern Niger) and Energy Evaluation

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Abstract

The Agadem Basin is located in the southeastern part of the Republic of Niger. The structural setting is dominated by faulted and tilted blocks arranged in networks of horsts, grabens, and half-grabens, which have favored both hydrocarbon accumulation and deep fluid circulation. These characteristics also make the area potentially suitable for geothermal resource development. This study assesses the geothermal resources of the Agadem Basin through the analysis of petroleum-well data, particularly bottom-hole temperatures. The geothermal gradients investigated in the Dibeilla, Fana, and Koulele oil fields indicate geothermal potential. This is particularly the case in the Dibeilla field, where bottom-hole temperatures range from 161-171°C after application of the Harrison correction, with geothermal gradients ranging from 40.5 to 48.3°C/km. These values indicate that some wells may be capable of generating electricity at sufficient depth. Accordingly, a simulation was performed by assuming a fixed depth of 3,000 m for selected wells. The cumulative recoverable geothermal energy of the wells potentially suitable for electricity generation is estimated at 32.13

million MWh using a recovery factor of 20%. The recoverable thermal power, calculated over a ten (10)-year period, is estimated at 372 MW.

Keywords: Agadem Basin, Geothermal Gradient, Bottom-Hole Temperature, Geothermal Energy, Oil Wells

Introduction

Geothermal energy is a renewable, clean, and sustainable form of energy stored as heat beneath the Earth's surface (Procesi et al. 2019). It is experiencing rapid growth within the renewable energy sector. Estimates indicate that there are large numbers of abandoned oil and gas wells worldwide, including 3.2 million in the United States alone (Raimi et al. 2021) and more than 200,000 in China (Bu et al. 2012). Although these wells may no longer be economically viable for hydrocarbon production because of their high water content, they retain substantial heat, making them valuable potential geothermal resources. Geothermal energy, in the form of natural steam and hot water, has been used for decades for building heating as well as electricity generation (Bu et al. 2012). It is attracting increasing interest, particularly in regions where geological data from petroleum exploration are already available. In this respect, the Agadem Basin has a notable advantage because of the extensive geophysical and geological information acquired during exploration campaigns. The development of geothermal resources represents a sustainable alternative that could contribute to Niger's future energy mix. This study therefore combines a scientific approach aimed at assessing the geothermal resources of the Agadem Basin with a strategic perspective focused on the development of local energy resources.

Data and Methods

Data

In this study, drilling data, including bottom-hole temperatures from eighteen (18) wells in the Dibeilla, Fana, and Koulele oil fields, were used (Table 1).

Table 1: Bottom-hole temperature data

Field	Well	Depth (m)	Bottom-hole temperature (°C)
Fana	F-1	1782	69
	F-2	1913	83
	F-3	1999	81
	F-4	1630	75
	F-5	1889	72
	F-6	2030	76
	K-1	2055	72
	K-2	2363	77

Koulele	K-3	2283	79
	K-4	2295	79
	K-5	2300	83
	K-6	2397	91
Dibeilla	D-1	1951	99
	D-2	1765	100
	D-3	1757	105
	D-4	1880	107
	D-5	1782	105
	D-6	1795	108

Methods
Temperature Correction

Mud circulation during drilling operations disturbs the thermal equilibrium of the surrounding rock by temporarily cooling it (Jessop, 1990). Temperature measurements obtained during well logging are generally recorded shortly after drilling has ended, before the surrounding formation has had sufficient time to return to thermal ekvilibrium (Walpes & Ramly, 2001). Consequently, measured bottom-hole temperatures are underestimated (Jessop, 1990; Harrison, 1983). Several empirical temperature-correction methods can be used to estimate the undisturbed subsurface temperature, including the Horner, Harrison, and Waples and Ramly corrections. In this study, the Harrison correction was applied; it relates the temperature correction to the measurement depth according to the following equation:

$$Tc = TBHT + \Delta T \quad (1)$$

Where Tc is the corrected temperature (°C), TBHT is the measured bottom-hole temperature (°C), and ΔT is the temperature correction (°C).

$$\Delta T = -16{,}51 + (1{,}827x10^{-2}Z) - (2{,}345x10^{-6}Z^2) \quad (2)$$

ΔT is the temperature correction to be added to the measured temperature (°C), and Z is the depth (m).

Geothermal Gradient Calculation

The geothermal gradient is a variable used to evaluate heat flow and subsurface temperatures. Expressed in degrees Celsius per meter (°C/m) or degrees Celsius per kilometer (°C/km), the geothermal gradient represents the change in subsurface temperature as a function of depth.

The TBHTc value used is the undisturbed bottom-hole temperature, i.e., the temperature obtained after application of the Harrison correction.

The surface temperature considered in this study is the mean annual temperature obtained from meteorological data.

$$GT = \frac{TBHTc - Ts}{Z} \tag{3}$$

Where GT is the geothermal gradient (°C/km), TBHTc is the corrected bottom-hole temperature (°C), Ts is the surface temperature (°C), and Z is the depth (m).

Geothermal Energy Calculation

Geothermal resources are estimated by calculating the heat-in-place, i.e., the amount of thermal energy stored within a given volume of rock. The total thermal energy in place is a function of the temperature and volume of the rock considered (Muffler & Cataldi, 1978; Williams et al. 2008).
It is calculated as follows:

$$E_T = E_R + E_F \tag{4}$$

$$E_R = (1 - \emptyset) x C_R x \rho_R x S x H (T_R - T_S) \tag{5}$$

$$E_F = (\emptyset) x S_W x C_F x \rho_F x S x H (T_R - T_S) \tag{6}$$

Where:

- E_T is the total energy (kJ);
- E_R is the energy stored in the rock (kJ);
- E_F is the energy stored in the fluid (kJ);
- $\emptyset$ is the porosity (%);
- C_R is the specific heat capacity of the rock (kJ/kg/°C);
- C_F is the specific heat capacity of the fluid (kJ/kg/°C);
- *S is the reservoir area (m^2);*
- *H is the reservoir thickness (m);*
- T_R is the reservoir temperature (°C);
- T_S is the surface temperature (°C);
- ρ_F is the fluid density (kg/m^3);
- ρ_R is the rock density (kg/m^3);
- S_W is the fluid saturation (%).

Recoverable Geothermal Energy Calculation

The recoverable thermal energy from the total stored energy is calculated using the following formula:

$$E_{rec} = E_T \text{ x } RF \quad (7)$$

Where: E_{rec} = recoverable energy and RF = recovery factor.

Recoverable Thermal Power Calculation

Thermal power corresponds to the amount of heat produced per unit time. It is calculated using the following equation:

$$P = \frac{Erec}{t} \quad (8)$$

Where:
– Erec = recoverable thermal energy;
– t = project lifetime;

Results and Discussion

Analysis of Bottom-Hole Temperature Data

The initial (uncorrected) bottom-hole temperatures range from 69-108°C. Application of the Harrison correction made it possible to estimate the actual formation-equilibrium temperatures by removing the effects associated with drilling-mud circulation. The corrected temperatures therefore range from 77.6 to 116.7°C (Table 2). The spatial distribution map of bottom-hole temperatures (Figure 1) reveals a complex thermal system characterized by temperatures between 90°C and 110°C, indicating significant subsurface thermal heterogeneity. Three (3) thermal domains can be distinguished:

- Hot domain (above 110°C): mainly located in the western and northeastern parts of the area;
- Intermediate domain (90–110°C): occupies a large part of the central region;
- Relatively cold domain (below 90°C): occurs around several closed anomalies in the central and southeastern parts of the area.

Table 2: Bottom-hole temperatures corrected

Well	Depth (m)	Measured temperature (°C)	Corrected temperature (°C)
F-1	1782	69	77,6
F-2	1913	83	92,8
F-3	1999	81	91,6
F-4	1630	75	82
F-5	1889	72	81,6
F-6	2030	76	87
K-1	2055	72	83
K-2	2363	77	90,5
K-3	2283	79	92
K-4	2295	79	92
K-5	2300	83	96

K-6	2397	91	105
D-1	1951	99	109
D-2	1765	100	108
D-3	1757	105	113
D-4	1880	107	116,5
D-5	1782	105	113,6
D-6	1795	108	116,7

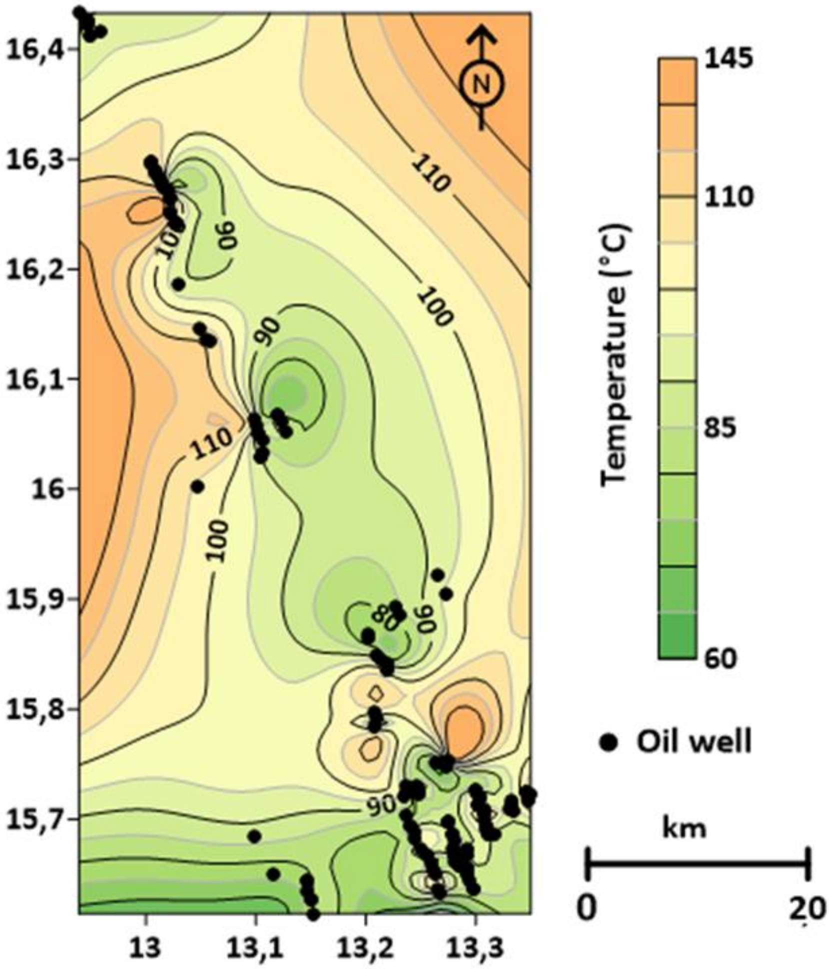

Figure 1: Bottom-hole temperature map of the study area

Geothermal Gradient Analysis

The geothermal-gradient map shows strong spatial variability. The highest values (above 40°C/km) occur mainly in the western part of the study area (Figure 2). Intermediate values (30–40°C/km) occupy most of the central area, while low values (below 20°C/km) occur in the southwest. This distribution indicates that heat flow is not homogeneous across the region.

Thus, the map reveals a highly contrasted thermal regime characterized by:
- A major geothermal anomaly in the west (40–45°C/km);
- Several secondary positive anomalies in the central and southeastern areas (30–40°C/km);
- A cold anomaly in the southwest (below 20°C/km).

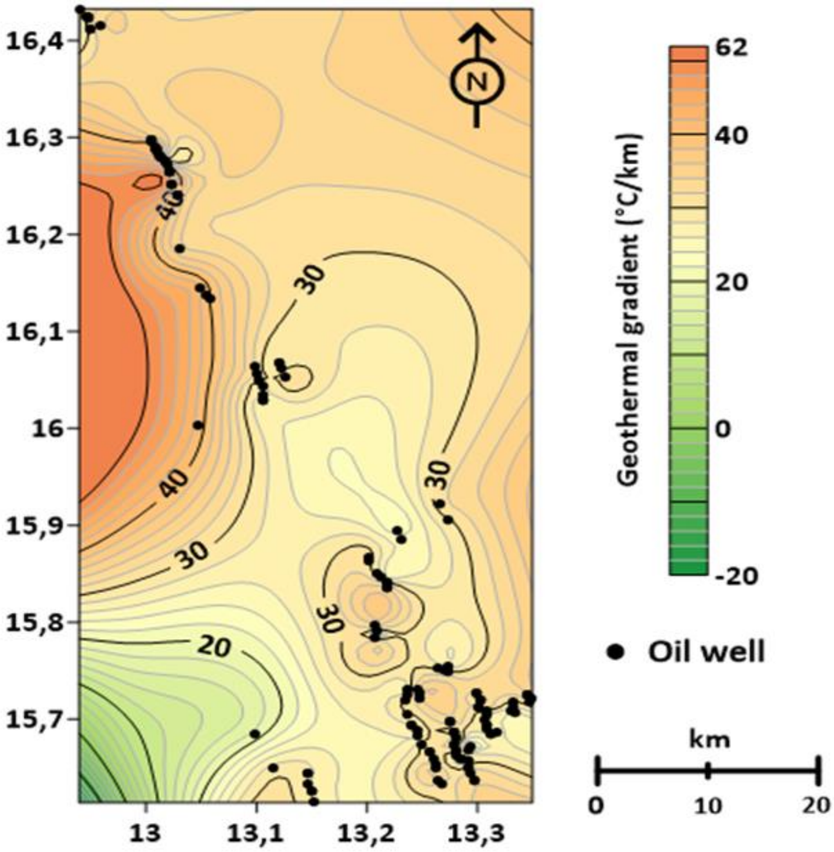

Figure 2: Geothermal-gradient map of the study area

Analysis of the calculated geothermal-gradient values (Table 3) shows that wells D-3, D-5, and D-6 have the highest geothermal gradients, at 47.2, 46.9, and 48.3°C/km, respectively. These values are well above the global average of approximately 30°C/km, indicating significant geothermal interest for these three wells.

Table 3: Geothermal-gradient results

Field	Well	Depth (m)	Bottom-hole temperature (°C)	Geothermal gradient (°C/km)
Fana	F-1	1782	77,6	27,8
	F-2	1913	92,8	32,8
	F-3	1999	91,6	30,8
	F-4	1630	82	31,9
	F-5	1889	81,6	27,3

	F-6	2030	87	28
Koulele	K-1	2055	83	25,8
	K-2	2363	90,5	25,6
	K-3	2283	92	27,1
	K-4	2295	92	27
	K-5	2300	96	28,7
	K-6	2397	105	31,3
Dibeilla	D-1	1951	109	40,5
	D-2	1765	108	44,2
	D-3	1757	113	47,2
	D-4	1880	116,5	46
	D-5	1782	113,6	46,9
	D-6	1795	116,7	48,3

Figure 3 shows the superposition of well depth and geothermal gradient. Well depths generally increase from west toward the south-central part of the map, from approximately 1,900 m to more than 2,600 m. The map indicates an inverse relationship between geothermal gradient and well depth. Thus, the western part of the map shows relatively shallow depths (approximately 1,900 m) associated with higher gradients (40–45°C/km), whereas in the southwest the wells are deeper (up to 2,600 m) and the gradients are low (15–20°C/km).

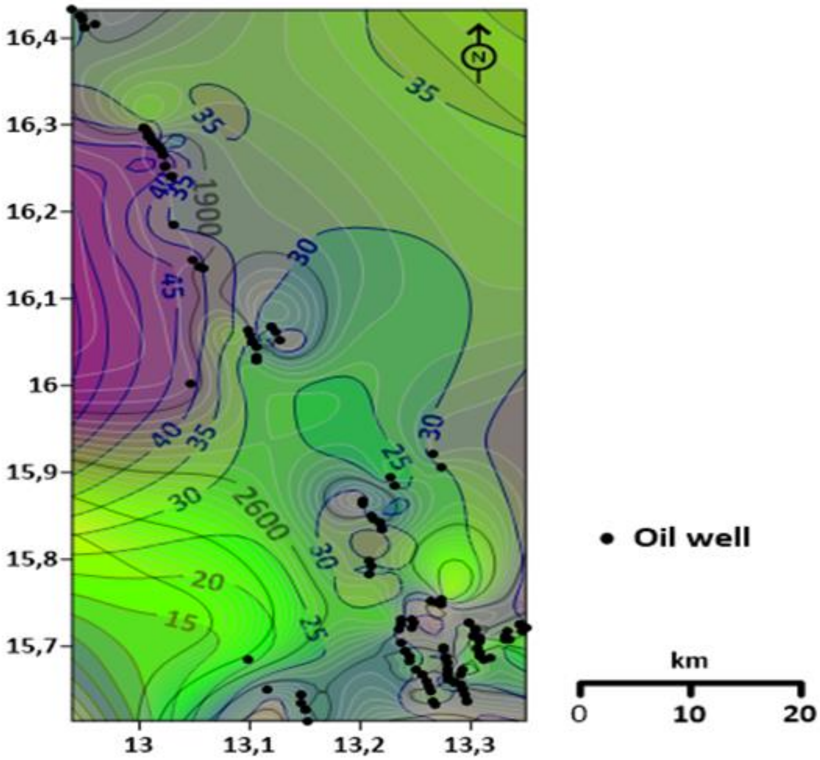

Figure 3: Superposition of well depth and geothermal gradient

Although the geothermal gradient is higher in the Dibeilla area, the current bottom-hole temperature data do not support electricity generation because the temperatures are below 150°C.

For electricity generation, the bottom-hole temperature should be greater than or equal to 150°C (Horner, 1951). To reach this temperature, the wells must attain a depth of at least 3,000 m. Based on the geothermal-gradient data and assuming a uniform depth of 3,000 m, the Dibeilla wells selected for this study yield the following bottom-hole temperatures (Table 4).

Table 4: Bottom-hole temperatures at 3,000 m

Field	Well	Depth (m)	Geothermal gradient (°C/km)	Bottom-hole temperature (°C)
Dibeilla	D-1	3000	40,5	161,8
	D-2	3000	44,2	161,44
	D-3	3000	47,2	165
	D-4	3000	46	169
	D-5	3000	46,9	171
	D-6	3000	48,3	159,7

All wells show temperatures above 150°C. These values indicate that the Dibeilla wells studied could potentially generate electricity from geothermal energy if their depths are greater than or equal to 3,000 m. However, wells D-3, D-4, and D-5 were selected as candidate wells for geothermal-resource estimation because of their particularly high temperatures.

Geothermal Resource Assessment Results

Wells D-3, D-4, and D-5 have among the highest geothermal gradients. They were selected in this study as candidate wells for estimating the geothermal resources of the Agadem Basin. First, the total thermal energy stored in the rock was calculated using parameters such as the heat capacities of the rock and fluid and their respective densities (Table 5).

Table 5: Physical parameters used for geothermal-energy estimation

Well	CR (kJ/kg·°C)	CF (kJ/kg·°C)	ρR (kg/m³)	ρF (kg/m³)	TR (°C)	TS (°C)	Sw (%)	Ø (%)	S (10^6 m²)	H (m)
D-3	4,315	3,96	2400	1000	165	40	0,43	25	3,88	59
D-4	4,307	3,95	2400	1000	169	40	0,38	25	4,47	38
D-5	4,312	3,96	2400	1000	171	40	0,13	25	4,47	36

Assuming an average porosity of 25%, the total thermal energy stored in the rock is obtained from Equation (4). The results are presented in the table below.

Table 6: Total thermal energy stored for each well

Well	ER (10^{12} kJ)	EF (10^{12} kJ)	ET (10^{12} kJ)
D-3	222,25	12,85	235,1
D-4	169,87	8,7	178,57
D-5	163,62	2,86	166,48

The thermal energy stored in the rock is not entirely recoverable because of various technical constraints that arise during exploitation. A single average recovery factor of 20% was adopted. It represents the fraction of energy that can be extracted from the total rock volume considered. The recoverable thermal energy is presented in the table below.

Table 7: Recoverable thermal-energy results

Well	ET (10^{12} kJ)	FR (%)	Erec (10^{12} kJ)
D-3	235,1	20	47,02
D-4	178,57	20	35,71
D-5	166,48	20	33,29

For easier interpretation of the results, recoverable geothermal energy was converted to megawatt-hours (MWh), using 1 kJ = 2.777×10^{-7} MWh.

Table 8: Recoverable thermal energy expressed in MWh

Well	Erec (10^{12} kJ)	Erec (10^{6} MWh)
D-3	47,02	13,02
D-4	35,71	9,89
D-5	33,29	9,22
Total	116,02	32,13

The results indicate a cumulative recoverable geothermal energy of 116.02×10^{12} kJ, equivalent to 32.13 million MWh, for the three (3) candidate wells. Well D-3 has higher recoverable thermal energy than wells D-4 and D-5, with a value of 13.02 million MWh. The geothermal energies of wells D-4 and D-5 are 9.89 million MWh and 9.22 million MWh, respectively. However, despite the higher bottom-hole temperatures of wells D-4 (169°C) and D-5 (171°C) compared with well D-3 (165°C), their thermal energies are lower than that of D-3. This demonstrates that geothermal energy does not depend solely on bottom-hole temperature. It also depends on rock volume and water content. The greater these parameters, the greater the geothermal energy.

Based on the recoverable geothermal energy, the thermal power of wells D-3, D-4, and D-5 was calculated over a ten (10)-year operating period (Table 9). It therefore depends on the project lifetime. Well D-3 has a thermal power of 150.75 MW, higher than those of wells D-4 and D-5, which are 114.5 and 106.75 MW, respectively. The cumulative thermal power of the three wells is estimated at 372 MW, indicating substantial thermal-energy potential for continuous electricity-generation applications.

This energy can only be utilized by installing appropriate equipment, such as heat exchangers at the wellheads concerned.

Table 9: Thermal power (MW)

Well	Erec (10^6 MWh)	Power (MW)
D-3	13,02	150,75
D-4	9,89	114,5
D-5	9,22	106,75
Total	32,13	372

Conclusion

Geothermal energy is a clean energy source with a relatively low environmental impact. It can be used for various applications, including direct use and electricity generation depending on the available temperature. The geothermal gradient of the Dibeilla oil field indicates potential for direct-use applications and even electricity generation. The study identified an above-average geothermal gradient in the Dibeilla area and relatively low geothermal gradients in the Fana and Koulele fields. At an extrapolated depth of 3,000 m, the bottom-hole temperatures of the investigated Dibeilla wells exceed 150°C, a temperature considered suitable for electricity generation. However, the current depths of wells D-3, D-4, and D-5 do not allow such temperatures to be reached; their depths were therefore extrapolated to 3,000 m. Under this assumption, wells D-3, D-4, and D-5 show bottom-hole temperatures exceeding 160°C. Such temperatures are technically favorable for electricity generation. The parameter analysis also shows that geothermal energy does not depend solely on bottom-hole temperature; it also depends on rock volume and water content. These parameters significantly influence the geothermal potential of petroleum wells.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

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