A Study of Geothermal Energy Prospect from Abandoned Oil and Gas Wells in Nigeria

Blessed Oghenevieze Usuolori, Nkemakolam Chinedu Izuwa, Anthony Kerunwa, Ngozi Claribelle Nwogu, Chukwuebuka Francis Dike*, Petroleum Engineering Department, Federal University of Technology Owerri. Owerri, Nigeria

Abstract

The repurpose of depleted oil and gas wells for geothermal energy extraction represents an efficient and sustainable approach to harnessing geothermal resources from these formations. Abandoned wells have significant potential to contribute to the growing global energy demand while mitigating the environmental issues associated with traditional energy sources. This study evaluates the geothermal energy potential of abandoned oil and gas wells in the Niger Delta region of Nigeria. The analysis is based on the heat in place, extractable heat quantity, and heat loss using water vapor and carbon dioxide (CO_2) as working fluids.

The results indicate that the Niger Delta wells possess substantial geothermal energy potential, with heat in place ranging from 0.0489×10^{15}BTU to 0.0677×10^{15} BTU. In terms of heat extraction efficiency, CO_2 outperformed water vapor as a carrier fluid, with heat extraction rates ranging from 3.96×10^{11} BTU/day to 2.01×10^{11} BTU/day, compared to water vapor's range of 3.76×10^{10} BTU/day to 3.08×10^{10} BTU/day. Additionally, CO_2 demonstrated lower heat loss compared to water vapor, further confirming its superior performance as a heat carrier fluid.

These findings highlight the viability of utilizing abandoned oil and gas wells in the Niger Delta for geothermal energy production. The study underscores the potential of CO^2 as an efficient working fluid for geothermal systems and provides a foundation for future research and development in this field.

Introduction

The global demand for energy is projected to grow significantly over time (Roksland et al. 2017), driven by the direct correlation between energy availability and a nation's economic development. Conventional energy sources derived from fossil fuels are not only finite and costly but also pose substantial environmental challenges (Ahmad et al. 2002). To meet the energy needs of an increasing population while ensuring environmental sustainability, renewable and eco-friendly energy sources must be prioritized over non-renewable alternatives. Among the renewable energy options — such as solar, wind, biogas, and geothermal — geothermal energy has gained considerable global attention due to its reliability and sustainability.

The term "geothermal" originates from the Greek words ‘geo’ (earth) and ‘therme’ (heat), referring to the heat stored within the Earth’s crust. Historically, geothermal energy has been utilized for centuries in regions like Japan, Rome, and China, primarily through hot springs. Today, it is one of the fastest-growing renewable energy sources, with significant potential for harnessing heat from abandoned oil and gas wells—a largely untapped resource for power generation (Okoroafor 2024). Repurposing these wells not only mitigates the economic waste

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*Corresponding author: dike.chukwuebuka@futo.edu.ng

associated with decommissioned infrastructure but also creates opportunities for sustainable energy production (Betkowski 2022).

Geothermal power generation systems are widely used globally; however, their commercial viability depends on several factors, including reservoir characteristics, drilling technology, resource availability, durability, and local energy costs (Caulk and Tomac 2017). Repurposing abandoned wells for geothermal energy extraction can reduce project costs by 42-95%, as these wells provide direct access to subsurface heat and eliminate the need for new drilling (Tester et al. 1994). Oil and gas wells offer valuable geophysical, geological, and geochemical data, enabling efficient heat extraction from deep reservoirs (Wang et al. 2018a; Mehmood and Yao 2017). Globally, mature oilfields with high water cuts and declining production rates are prime candidates for geothermal energy exploitation (Wang et al. 2018b). For a well to be suitable, it must exhibit reliable wellbore integrity, high bottom-hole temperatures (Moustafa et al. 2022), and significant production potential. These requirements have spurred interest in retrofitting existing wells for geothermal applications.

Several studies have explored the potential of abandoned wells for geothermal energy extraction. Sliwa (2014) proposed using borehole heat exchangers to exploit abandoned reservoirs near urban areas. Dijkshoorn et al. (2013) developed a mathematical model for deep coaxial heat exchanger systems in Aachen, Germany, though the high cost of inner piping limited economic feasibility. Caulk and Tomac (2017) established a mathematical correlation for predicting geothermal energy generation from wells deeper than 1,000 meters with temperatures exceeding 40°C and gradients of 7°C/100 meters. Kohl et al. (2002) investigated the performance of deep borehole heat exchangers and proposed numerical methods to analyze heat transfer phenomena. Kujawa (2006) introduced a computational approach to assess geothermal potential and recommended insulating inner pipes to minimize heat loss. Zhang et al. (2008) evaluated the feasibility of extracting energy from depleted petroleum wells, while Davis and Michaelides (2009), Bu et al. (2012), and Templeton et al. (2014) studied the sensitivity of variables affecting geothermal energy recovery for electricity generation.

Recent advancements include Nian and Cheng (2018), who assessed geothermal energy extraction from depleted wells, and Macenić and Kurevija (2017), who demonstrated the economic viability of closed circulation systems in deep dry wells. Mehmood et al. (2019) evaluated heat production potential in the Indus Basin, Pakistan, concluding that depleted gas wells could yield commercially viable geothermal energy over their lifetime. Ojaghi et al. (2023) identified key challenges, including heat loss along pipelines, low geothermal gradients, and the high costs of insulation and thermal facility installation. Li et al. (2023) highlighted that while retrofitting abandoned wells reduces drilling-related environmental impacts, long-term operation is necessary to achieve significant environmental benefits.

This study focuses on the geothermal energy potential of abandoned oil and gas wells in the Niger Delta, Nigeria. By analyzing heat in place, extractable heat quantities, and heat loss using water vapor and carbon dioxide (CO_2) as working fluids, the research aims to provide insights into the feasibility and efficiency of repurposing these wells for sustainable energy production.

Overview of Nigeria’s Geothermal Profile

Nigeria’s geological sequence consist of the sedimentary basins of different ages and crystalline basement complex. Studies show that there is a prospect for geothermal energy of reservoir within the country. The temperature profile derived from several drilling activities in the oil and gas industry in deep basins have been between 100^oC to 175^oC, and geothermal gradients of $5^oC/100m$ around the Chad Basin, though the basin is rift-related basin with recognized faults arrangement. The warm springs located in Ruwan Zafi and Akiri in Nigeria has the temperature range of about 54^oC indicating the prospect of some geothermal variation. Despite these prospects, there is little technical expertise, information and exposure on the geothermal energy potential of the country in general, and this owing to public outreach and acceptance.

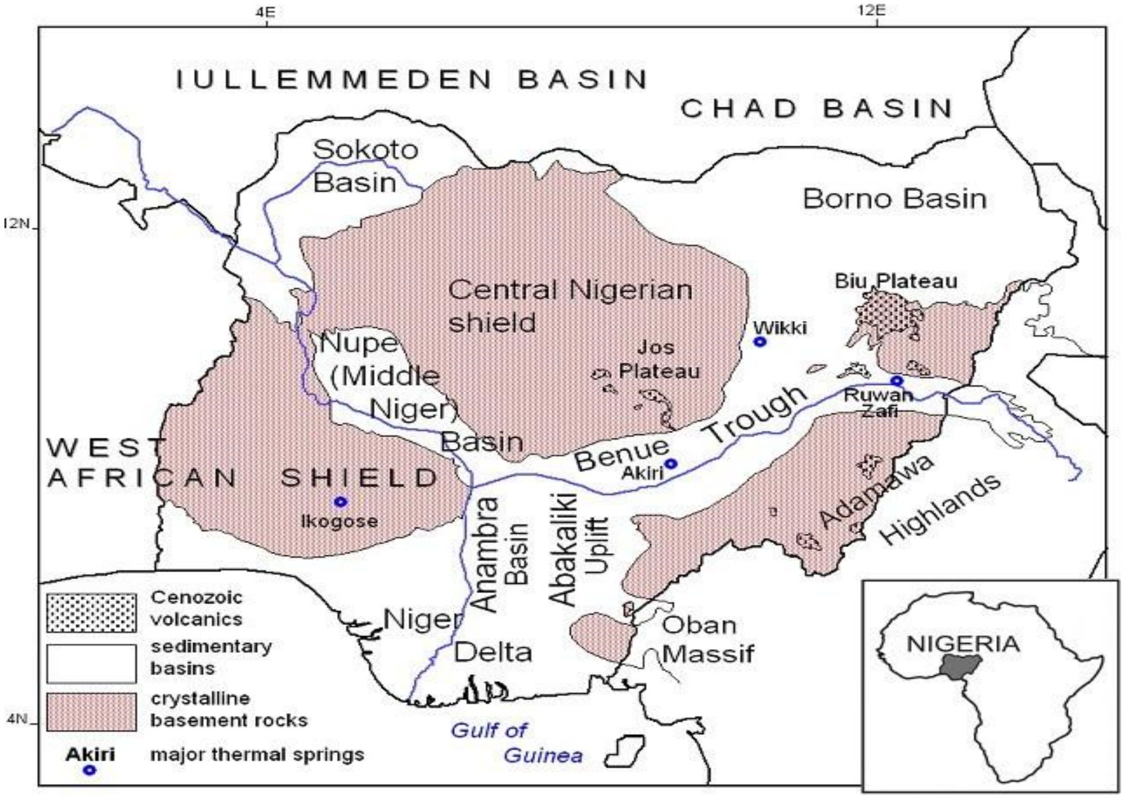

Figure 1—Geological setting and location of areas with major geothermal anomaly in Nigeria (Okeifufe et al. 2020) .

Materials and Methods

Materials. The materials utilized include the datasets, Tough2 software, HYSYS simulator and MATLAB. The datasets utilized for the study is the reservoir data and heat transfer data depicted in **Tables 1** and **2**. The reservoir data includes reservoir temperature, well depth, reservoir pressure, porosity, area, pay thickness, solution gas oil ratio (GOR), oil rate and gas rate. The heat transfer data includes thermal conductivities across formation, cement sheath, casing and tubing, radius across formation, cement sheath, casing and tubing, fluid convection, thermal diffusivity, radiative fluid transfer and fluid production time.

Table 1—Reservoir properties of the various wells.

Wells	**Temp.^{o} C**	**Depth, m**	**Pressure, psia**	**Porosity, %**	**Area, m ^{2}**	**Pay thickness, m**	**Water Sat. ,%**	**Water mass heat capacity (KJ/Kg^{o}C)**	**Water density (kg/m ^{3})**
Well 1	104	1828.80	3992	25	576320995.59	500	90	4.344	956.5
Well 2	96	2438.40	3992	25	576320995.59	500	90	4.33	962.6
Well 3	102	2438.40	3992	25	576320995.59	500	90	4.34	958
Well 4	112	2438.80	3992	25	576320995.59	500	90	4.36	950.3
Well 5	91	1828.80	3992	25	576320995.59	500	90	4.322	966.5

Table 2—Other simulation data.

Parameters	Unit	Value
The height of fluids from the producing depth	ft	8000
Thermal conductivity of the earth	Btu/hrft°F	1.4
The outside radius of the casing	ft	0.359
Temperature at the cement formation interface	ºF	325
The outside radius of the tubing	ft	0.229
The inside radius of the tubing	ft	0.204
The radius of the tubing insulation	ft	0.292
The inside radius of the casing	ft	0.322
The radius of the cement/formation interface	ft	0.448
The thermal conductivity of the tubing wall	Btu/hrft°F	24.957
The thermal conductivity of the tubing insulation	Btu/hrft°F	0.0116
The thermal conductivity of the casing wall	Btu/hrft°F	24.957
The thermal conductivity of the cement	btu/hrft°F	0.595
Convective heat transfer coefficient b/w the fluid film in tubing and the tubing wall	Btu/(hr ft2 °F)	99.9
Convective heat transfer coefficient of fluid inside annulus	Btu/(hr ft2 °F)	99.9
Radiative heat transfer coefficients of fluid inside annulus	Btu/(hr ft2 °F)	2
the production time	days	75
The thermal diffusivity of the earth	ft2/day	0.96

Estimation of Geothermal Energy in Place. The estimation of geothermal energy in place (GIP) is key when considering renewability in terms of geothermal power plant. This is viewed as the ability to maintain the installed capacity of power plant overtime without reduction in the resource. Sustainability is the ability to keep the installed capacity economically constant over the useable period of a power plant by reinjecting geothermal fluids to avoid pressure drawdown and cooling (Sanyal 2005; Rybach 2003). The greatest hurdles lie in learning the thermal energy and size of the rock-surface as well as the limiting factors to the exploitation of the thermal energy. Several parameters are required to predict or forecast the geothermal energy potential (GEP). The temperature variation as a function of data was used to derive the GEP of the reservoir (Mendrinos 2008; William 2004). The GEP of a particular area means majorly the study of pressure (P_{geo}) and temperature (T_{geo}) of the geothermal fluid and at the highest mass flow rate (m_{geo}) that can be exploited to maintain the thermal properties of rock formation overtime. This GEP can be derived using volumetric approach. This is done using estimated heat in place using rock and fluid features, estimated reservoir volume, and temperature variation between average and reference temperature.

Heat stored in the geothermal reservoir, q_R, is given by:

$$q_R = V\overline{\rho_C}\,(T_R - T_r), \tag{1}$$

$$\overline{\rho_C} = \varphi\rho_w C_\omega + (1 - \varphi)\rho_r C_r, \tag{2}$$

where C_w is the heat capacity of water, C_r is the heat capacity of rock, A is reservoir area, H is reservoir thickness, T_r is reference (or rejection) temperature, T_R is the verage reservoir temperature, V the reservoir volume (=AH), φ is porosity, $\overline{\rho_C}$ is volumetric heat capacity of fluid saturated rock, ρ_w is density of water, ρ_r is density of rock.

Prediction Heat Loss. The potential for heat extraction from both water and supercritical CO_2 was evaluated in this section using the TOUGH2 simulation software with Petrasim GUI. EOS2 module was used to simulate injection of water and supercritical CO_2. The study employed a geothermal reservoir model representative of various wells with dimensions of 5000 m x 3000 m x 500 m in the X, Y, and Z directions. Various geothermal reservoirs within Nigeria were evaluated individually to ascertain their energy production prospects. These reservoirs are characterized by permeability of 200mD and porosity of 0.25 in all direction to create a homogenous system. The heat conductivity, rock density and specific heat capacity of 2.1W/m.K, 2323kg/m^3 and 950J/kg.C respectively. Temperature variation of 58-139^oC and Reservoir Pressure of 3992psi, an inverted five-spot pattern comprising of 4-edge based producers and 1-center based injector were utilized for simulating geothermal heat recovery. The wells were comprehensive designed using reservoir rock and fluid property. **Figure 2** depict the static model configuration before production and injection.

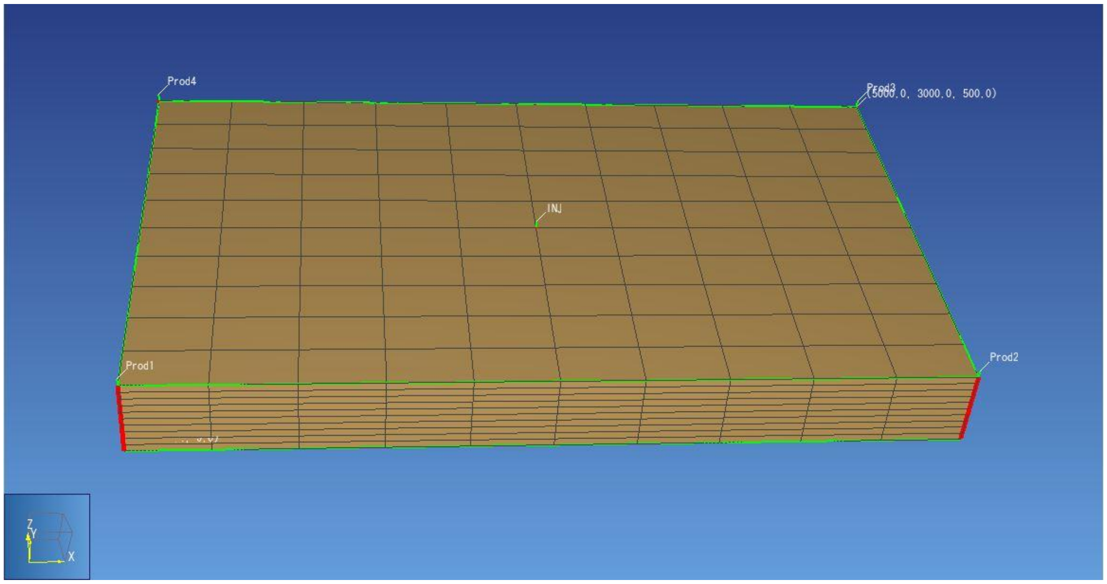

Figure 2—3D geothermal reservoir simulation model with an inverted 5 spot pattern.

The enthalpy of CO_2 and water was derived to be 343.45KJ/kg and 153.814KJ/kg using TOUGH-2 simulation. 100kg/s of supercritical CO_2 and water were consistently injected, at a pressure of 80bar and temperature of 35^oC, for 100year period under two scenarios. Simulation study was carried out to derive the heat extraction rates profiles and production well temperature profiles as function of time, directly exploited from the results derived through the TOUGH-2 simulator. The flow pattern for the heat transfer and heat transfer properties of a geothermal formation influences the heat exploitation rate of the formation. The rock-type fracture network derives the heat transfer feature which control conductive rate of heat transfer rock surface. The thermos-physical features are weighted values with respect to mass fraction of underground water. This can be forecasted from the pore fluid (10%) and rock matrix (90%).

Estimation of the Possible Heat Loss from the Various Geothermal Wells. The simulation of the wellbore heat loss for geothermal heat extraction using water and CO_2 as geofluids are performed in this section. Reservoir fluid properties, including mass density and heat capacity at different temperatures and pressures, were determined using Hysys v11 software. Wellbore heat transfer models were simulated using MATLAB R2014 software, involving scripts that considered heat losses, fluid temperature changes from the reservoir to the surface, and wellbore heat transfer.

Figure 3 illustrates the workflow and key components of the study, which includes data gathering, wellbore fluid temperature analysis, heat loss simulation, and results analysis. The figure provides a visual representation of the methodology employed to evaluate the geothermal energy potential of abandoned oil and gas wells in the Niger Delta. The phase of data gathering involves collecting wellbore data, including temperature gradients, reservoir properties, and geological information, to assess the geothermal potential of the wells. The step of wellbore fluid temperature analysis focuses on analyzing the temperature profiles of fluids within the wellbore to determine the heat extraction potential. In the phase of heat loss simulation, numerical simulations are conducted to model heat loss during the extraction process, ensuring accurate predictions of energy efficiency. The final phase presents the findings, including heat in place, extractable heat quantities, and the performance of different working fluids (e.g., water vapor and CO_2).

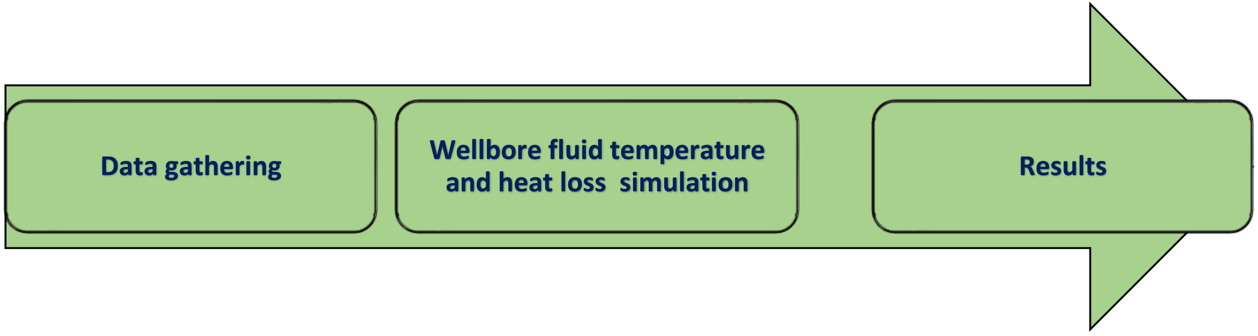

Figure 3—Simulation procedure utilized for estimating the possible heat loss.

Results and Discussion

Estimation of the Geothermal Heat in Place. Table 3 presents the geothermal heat in place for Well-1, Well-2, Well-3, Well-4, and Well-5. The results indicate significant geothermal energy potential across all wells, with heat in place values of 0.0622×10^{15} BTU, 0.0563×10^{15} BTU, 0.0606×10^{15} BTU, 0.0677×10^{15} BTU, and 0.0489×10^{15} BTU for Well-1, Well-2, Well-3, Well-4, and Well-5, respectively.

As observed in Table 3, the geothermal heat in place exhibits a positive correlation with reservoir temperature. This relationship aligns with the findings of Sullivan and Edmondson (2008), demonstrating that higher reservoir temperatures correspond to greater geothermal gradients. The wells investigated in this study all exhibit high geothermal heat in place, underscoring their potential for sustainable energy extraction.

Table 3—Reservoir properties of the various wells.

Wells	Temp. °C	Depth, m	Pressure, psia	Heat in Place, $\times 10^{18}$J	Heat In Place, EJ	Heat in Place, E-BTU
Well 1	104	1828.8	3992	65.44	65.44	0.0622
Well 2	96	2438.4	3992	59.39	59.39	0.0563
Well 3	102	2438.4	3992	63.92	63.92	0.0606
Well 4	112	2438.8	3992	71.47	71.47	0.0677
Well 5	91	1828.8	3992	55.61	55.61	0.0489

Heat Extracted from the Various Wells Using CO_2 and Water. Well-5 using supercritical carbon dioxide (CO_2) and water vapor as carrier fluids. The results demonstrate that CO_2 outperforms water vapor in terms of heat extraction efficiency. Specifically, the heat extracted using CO_2 was 3.21×10^{11} BTU, 2.48×10^{11}BTU, 2.96×10^{11} BTU, 3.96×10^{11} BTU, and 2.01×10^{11}BTU for Well-1, Well-2, Well-3, Well-4, and Well-5, respectively. In contrast, the heat extracted using water vapor was 3.5×10^{10} BTU, 3.27×10^{10} BTU, 3.44×10^{10} BTU, 3.76×10^{10}BTU, and 3.08×10^{10}BTU for the same wells.

As observed, CO_2 extracted significantly more heat than water vapor across all wells. This superior performance is attributed to the unique properties of supercritical CO_2, which enable it to absorb and transport thermal energy more efficiently than water (Thippeswamy and Kumar 2020). These findings align with the study by Cabeza et al. (2017), which highlighted the advantages of CO_2 as a working fluid in geothermal systems due to its high thermal conductivity and low viscosity in supercritical states.

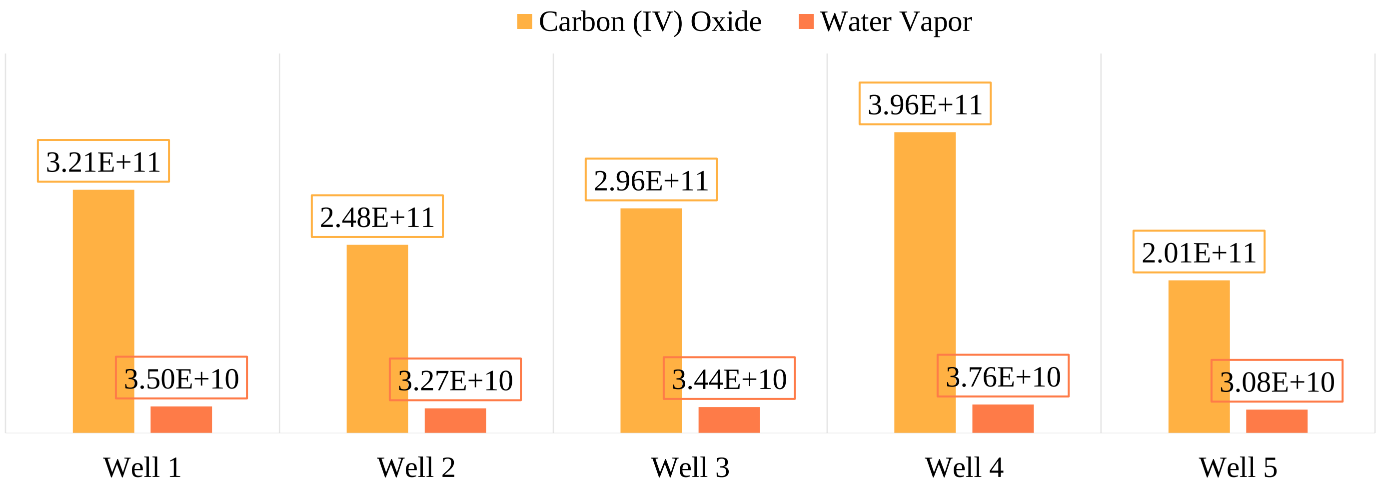

Figure 4—Heat Extracted Using Carbon (IV) Oxide and Water Vapour.

Heat Loss from the Various Geothermal Wells. Figure 5 presents the heat loss observed when carbon dioxide (CO2) and water vapor were utilized as carrier fluids in Well-1, Well-2, Well-3, Well-4, and Well-5. As shown in the figure, the heat loss when CO_2 was used as the carrier fluid was 1.51×10^5 BTU, 1.8×10^5 BTU, 2.0×10^5 BTU, 2.2×10^5 BTU, and 1.41×10^5 BTU for Well-1, Well-2, Well-3, Well-4, and Well-5, respectively. In comparison, the heat loss when water vapor was used as the carrier fluid was 1.514×10^5 BTU, 1.82×10^5 BTU, 2.05×10^5 BTU, 2.3×10^5 BTU, and 1.42×10^5 BTU for the same wells.

As observed in Figure 5, CO_2 exhibited lower heat loss compared to water vapor across all wells. This can be attributed to CO_2's superior ability to retain heat over longer distances (Wetenhall et al. 2017) and its excellent heat transfer coefficient. The heat transfer efficiency of CO_2 is particularly high when the operating pressure is close to the critical point, the mass flow rate is high, and the temperature is near the pseudocritical temperature. These properties make CO_2 a more effective carrier fluid for geothermal energy extraction, minimizing energy losses and enhancing overall system efficiency.

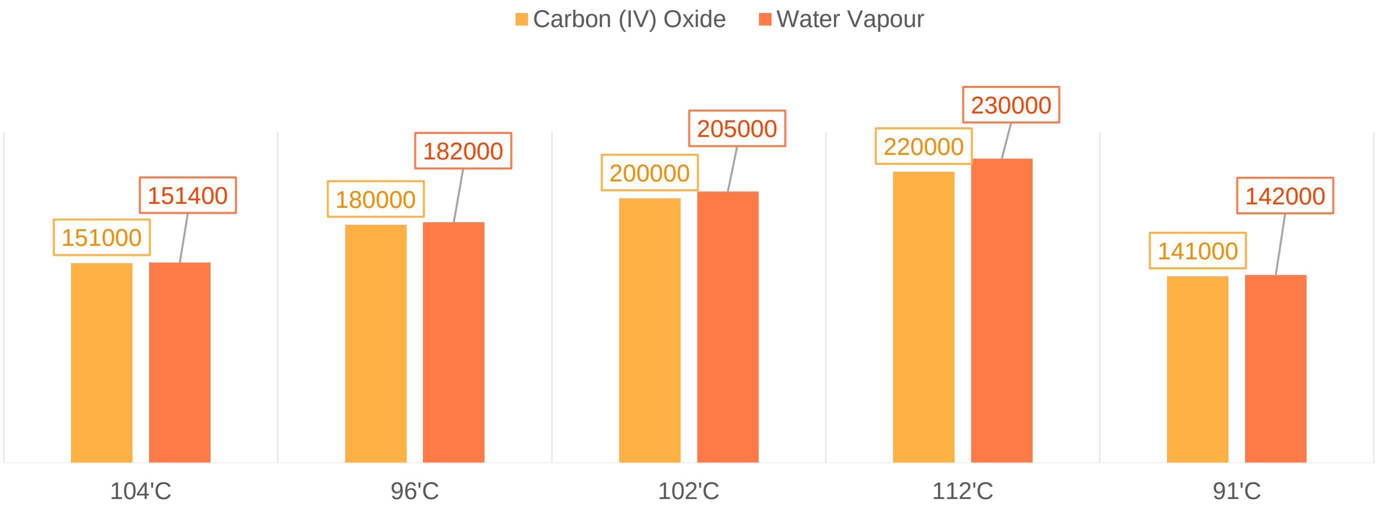

Figure 5—Heat loss using carbon (IV) oxide and steam.

Conclusion

In summary, the study highlights the significant geothermal energy potential of abandoned oil and gas wells in the Niger Delta. CO_2 emerges as a more efficient carrier fluid compared to water vapor, offering higher heat extraction rates and lower heat losses. Based on the simulation study conducted, the following conclusions can be drawn. These findings underscore the viability of repurposing abandoned wells for sustainable geothermal energy production, contributing to the global transition towards renewable energy sources.

1. The Niger Delta wells exhibit significant geothermal energy potential, with heat in place values ranging from 0.0489×10^{15} BTU to 0.0677×10^{15}BTU. This indicates that these wells are highly suitable for geothermal energy extraction.
2. Carbon dioxide (CO_2) demonstrated superior heat extraction performance compared to water vapor. Specifically, CO_2 achieved heat extraction rates ranging from 3.96×10^{11} BTU/day to 2.01×10^{11} BTU/day, while water vapor recorded lower rates of 3.76×10^{10} BTU/day to 3.08×10^{10}BTU/day. This is attributed to CO_2's excellent thermal properties in its supercritical state.
3. CO_2 also outperformed water vapor in terms of heat retention, exhibiting lower heat loss across all wells. This is due to CO_2's ability to retain heat over longer distances and its high heat transfer coefficient, particularly when operating near the critical pressure and pseudocritical temperature.

Conflicting Interests

The author(s) declare that they have no conflicting interests.

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Blessed Usuolori Oghenevieze is Ph.D Student at the Department of Petroleum Engineering, Federal University of Technology Owerri, with interest in Drilling, Production, Production and Alternative Energy Sources. He has a bachelor's degree and master's degree in petroleum engineering from the Department of Petroleum Engineering, University of Port Harcourt.

Nkemakolam Chinedu Izuwa is an Associate Professor at the Department of Petroleum Engineering, Federal University of Technology, Owerri. He also spent sabbatical leave at Covenant University, Ota and is currently serving as a visiting Associate Professor. Dr. Izuwa holds a Bachelor's Degree in Petroleum Engineering, Master's Degree in Natural Gas Engineering and Ph.D in Petroleum Engineering. Dr. Izuwa is involved in teaching, student development / mentorship and research. His research areas include but are not limited to formation evaluation, enhanced oil recovery, drilling fluids engineering, Geothermal Engineering, Surface Active Agents and Gas Engineering. Currently, he is handling research on Green Hydrogen production.

Anthony Kerunwa is an Associate Professor at the Department of Petroleum Engineering, Federal University of Technology Owerri with Research Interest in drilling, production, reservoir engineering and petroleum economics. Kerunwa holds a bachelor's degree in petroleum engineering from Federal University of Technology Owerri, a master's degree in petroleum engineering from Federal University of Technology Owerri, and a PhD degree in Petroleum Engineering from Centre for Oilfield Chemicals Research, IPS, University of Port Harcourt.

Ngozi Claribelle Nwogu is Senior Lecturer at the Department of Petroleum Engineering, Federal University of Technology Owerri, with interest in Drilling, Natural Gas Engineering and Renewable Energy. She has a bachelor's degree from Department of Petroleum Engineering, Federal University of Technology Owerri, and master's degree in petroleum engineering from Department of Petroleum Engineering, Federal University of Technology Owerri, and PhD degree in Petroleum Engineering (Gas Option) from Robert Gordon University, Aberdeen, Scotland, United Kingdom. She was also Post-Doctoral Research Fellow at the School of Engineering, Robert Gordon University, Aberdeen, Scotland, United Kingdom.

Chukwuebuka Francis Dike is a Research Technologist at the Department of Petroleum Engineering, Federal University of Technology Owerri. He has research interest in Drilling Fluids Technology, Reservoir Engineering, Enhanced Oil Recovery and Flow Assurance. Dike Holds a bachelor's degree and master's degree in petroleum engineering from Federal University of Technology Owerri.