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Research Article

A Simulation Approach on the Techno-economic Feasibility of Wells in Depleted Oil Reservoirs for Geothermal Well Systems in the Niger Delta

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Abstract

Majority of matured and abandoned wells in depleted oil reservoirs in the Niger Delta are becoming economically unviable. Recently, application of geothermal well system has gained acceptance in the re-use of wells in depleted oil reservoirs. Unfortunately, there are limited studies in the conversion of matured and abandoned wells into geothermal well system in the Niger Delta. Therefore, this study evaluates the techno-economic feasibility of applying geothermal well systems (GWS) in wells in depleted oil reservoirs in the Niger Delta. In this study, characterization and screening of the gathered data from wells in depleted oil reservoirs were performed for GWS application, considering a reservoir temperature above 80 ℃ (176 ℉) and a water cut of more than 85%. The screened well data were modelled using petroleum production software, PROSPER™, to evaluate their performances and estimate geothermal gradients. A model was developed from a simple regression technique in Microsoft Excel software to predict fluid flowing temperature gradient, using the simulated geothermal data. From the result, the temperature gradient varies by 0.011 ℉/ft. Estimation of overall heat recovery was then calculated with a simplified heat model, considering an open loop vertical coaxial single geothermal well system. The estimated overall heat recovery ranged from 0.1 MW to 8 MW, for the wells under study. Sensitivity analyses were also conducted to assess the impact of various operating parameters on the overall heat recovery. Finally, economic analyses were performed to evaluate the economic viability of converting matured and abandoned oil wells into geothermal well systems; the simplified economic analyses, considering net present value (NPV), showed geothermal well system with heat capacity above 5 MW to be economically viable. The study demonstrates that wells in depleted oil reservoirs in the Niger Delta can be effectively repurposed for geothermal electricity generation.

Keywords

Geothermal Well Systems, Abandoned Wells, Niger Delta, Re-use of Oil Wells, Heat Recovery from Oil Wells

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1. Introduction

The global imperative to reduce dependence on fossil fuels has galvanized stakeholders to pursue innovative strategies for sustainable energy systems, with particular emphasis on decarbonizing heating and cooling in the built environment [23]. Geothermal energy also referred to as ground source energy has emerged as a technically robust and environmentally advantageous solution, offering consistent, low-carbon heating and cooling by exploiting the Earth's stable subsurface temperatures. Compared to conventional air source heat pumps, ground source heat pump (GSHP) systems exhibit superior efficiency and reliability due to their reliance on the relatively invariant thermal properties of the ground [3].

In the category known as hot sedimentary aquifer (HSA), the heat source is the normal geothermal gradient or possibly a local decaying radiogenic granite heating the aquifers in permeable rocks, for example, commonly from Mesozoic carbonates to Plio-Pleistocene fluvial sediments. HSA are mostly in subsided basins (for example, North of Alpes, Hungary, and Utah in the USA, Paris and Aquitaine Basins in France, Australia, and China). Medium temperature (MT) reservoir temperatures range from 100 ℃ to 190 ℃, and they can be hosted in volcanic and sedimentary formations [2]. MT fields are relatively widespread at both the plate boundaries and intraplates such as in California and Utah, South America, Philippines, Azores, New Zealand, Kenya, Hawai, Europe (Croatia), and Central East China [10]. High temperature (HT) resources are the most sought-after as their reservoir temperature is 190 ℃ to 374 ℃, and they are high enthalpy. These convective systems are generally found down to 3 km, and occasionally > 3.5 km depth. HT resources are mostly in young porous volcanic rocks at active plate boundaries (e.g., Iceland, Indonesia, East Africa, Turkey, and New Zealand), and occasionally in intraplate context above a hotspot such as Yellowstone in the USA [35].

There is a growing body of research focusing on the repurposing of abandoned and depleted oil and gas wells for geothermal exploitation [13]. Traditionally, the high capital expenditure associated with drilling and completion has been a limiting factor in geothermal project economics. However, the strategic reutilization of existing well infrastructure significantly mitigates upfront costs by obviating the need for new drilling and surface facility installation [20]. Furthermore, leveraging hydrocarbon wells for geothermal applications aligns with the principles of circular economy and infrastructure optimization.

As global oil markets face volatility and declining production in mature fields, petroleum operators are increasingly investigating alternative revenue streams including geothermal co-production and field conversion to optimize asset value and extend field life cycles. This paradigm shift is supported by emerging research on integrated reservoir management that combines hydrocarbon extraction with sustainable geothermal development [24].

Li and Zhang [14] were among the first to systematically propose the conversion of abandoned oil reservoirs for geothermal power production, introducing technical models for heat extraction and power conversion. A notable milestone was achieved when Wang *et al*. [33] documented the commissioning of a geothermal power plant utilizing oil wells with formation temperatures of approximately 99 ℃. For such low- to medium-enthalpy geothermal resources, power generation is typically accomplished through Organic Rankine Cycle (ORC) technology and, in some cases, thermoelectric modules, both of which are optimized for efficient energy conversion at moderate temperature gradients [19].

Extensive global studies corroborate the technical and economic viability of harnessing waste heat from oil and gas fields. For example, McKenna *et al*. [16] estimated that coproduced fluids from Gulf Coast oilfields could generate over 1 GW of electrical power. Similarly, Bennett and Horne [4] demonstrated that Los Angeles oilfields possess a net electrical production potential exceeding 7.4 MW. In the context of China, Wang *et al*. [33] reported a recoverable geothermal resource on the order of 4.24 million joules from oilfield operations. These findings are complemented by a global survey of oilfield geothermal reuse, including Austria’s long-standing use of abandoned well water for spa heating since the 1970s and greenhouse heating applications in Albania, as well as industrial and district heating projects in China and Hungary [21]. The feasibility and scale of geothermal utilization are fundamentally governed by the thermal regime (temperature, pressure, flow rate) of the reservoir, which is a function of local geothermal gradient, well depth, and petrophysical characteristics such as permeability [20]. This underscores the necessity of site-specific screening to optimize geothermal resource development.

Wen-Long *et al*. [28] investigated the problem of geothermal power generation from abandoned oil wells in Texas. It develops a mathematical model accounting for masses, energy, and momentum conservation equations for fluid flows in the well. Isobutane is chosen as a working fluid. One more approach is described by Davis and Michaelides [6]. The authors suggested using water as a well fluid. The wellbore is used as a heat exchanger which enables the generation of electricity through the binary cycle unit.

Wen-Long *et al*. [29] researched on the evaluation of working fluids for geothermal power generation from abandoned oil wells. The authors suggested using freon as a working fluid. Modern binary turbines allow for using low-grade heat of the medium. These technologies are used by RASER operating in Alaska. The design of wells is described by Mukhametshin [17]. Depending on the formation structure, various well construction designs are developed.

Wight and Bennett [26] propose a numerical model of energy production from abandoned oil wells in Iran. The mathematical model accounts for the geometrical parameters of the casing wells and exact temperature gradients. The simulation results were optimized for the flow rate of the input and output fluid and temperatures. The use of the Rankine organic cycle in abandoned wells shows the efficiency of the studies [18]. The authors analyze different liquids for different temperature gradients. Well, depths and their temperature gradients are classified. Based on this classification, working fluids were selected.

Wei and Guo [27] advanced the evaluation of geothermal potential in abandoned oil and gas wells by developing a robust mathematical model that simulates heat transfer dynamics from geothermal zones to surface wellheads. Their model incorporates variables such as pipe and wellbore insulation, fluid flow characteristics, and reservoir temperature distributions. Results demonstrate that adequate insulation is critical in maintaining high return fluid temperatures, thereby improving the overall energy conversion efficiency of retrofitted geothermal wells. These findings underscore the importance of system design optimization in maximizing geothermal energy recovery from existing hydrocarbon infrastructure. Topor *et al*. [24] researched on assessing the geothermal potential of selected depleted oil and gas reservoirs based on geological modeling and machine learning tools. Advanced modeling techniques were employed to analyze the studied formations' heat, storage, and transport properties. The obtained results were then used to calculate the heat in place (HIP) and evaluate the recoverable heat (Hrec) for both water and CO_2 as working fluids, considering a geothermal system lifetime of 50 years.

Gabdrakhmanova *et al*. [8] developed a new approach to the selection of resource-attractive wells. They developed a mathematical model that is determined by the temperature gradient, well depth, bottom, and coolant temperatures. Depending on the depth and temperature gradients, these nomograms determine injection rates. Based on these nomograms, it is possible to predict what thermal power can be obtained from a certain well at a given coolant injection rate.

Gudmundsdottir and Horne [9] used the feedforward model (MLP) and recurrent neural network (RNN) models to predict tracer concentrations in the production well to investigate the breakthrough in the synthetic fractured reservoir. They found that the MLP model performed better and faster in training compared to the RNN model.

Yan *et al*. [34] developed a robust general thermal decline model for geothermal reservoirs. They integrated it with deep learning (DL) and multi-objective optimization for geothermal reservoir management considering uncertainties in reservoir property. They also used the Fourier neural operator to predict the geothermal temperature field over time with a heterogeneous fracture aperture field in EGS with high precision and further performed reservoir optimization for temperature control based on a control neural network (NN) or stochastic gradient descent method. Kalogirou *et al*. [12] developed thermal maps at three different depths such as 20, 50, and 100 m using artificial NNs.

Regions characterized by intense tectonic activity exhibit elevated geothermal gradients, leading to higher temperatures at shallower depths in contrast to regions with normal geothermal gradients (about 1.5 ℃ every 100 meters). Although high-temperature regions are optimal for generating power, their isolated locations frequently present substantial obstacles to development. Electricity generation is technically and economically impractical at temperatures below 80 ℃. Conventional geothermal power facilities of significant size necessitate reservoir temperatures that surpass 150 ℃ [21]. There are a significant number of abandoned oil and gas wells globally, with around 3.2 million in the United States alone [20] and over 200,000 in China [5]. Many wells in the Niger Delta are reaching their economic limits and abandoned wells are growing in numbers, with potentially few of them already experiencing varying degrees of leakage, thereby causing environmental hazards. Though, applications of geothermal well system has gained acceptance in the re-use of depleted oil reservoirs in some countries, however, there are limited studies (and no field application to the est of our knowledge) on the conversion of depleted oil reservoirs into a geothermal well system in the Niger Delta.

This study intends to explore the technical feasibility and economic analysis of converting depleted oil reservoirs in the Niger Delta region into a geothermal well system. The specific objectives will be to characterize and screen wells in depleted oil reservoirs for geothermal system development in the Niger Delta; model the well performances of some Niger Delta wells in depleted oil reservoirs for geothermal gradient estimation; model and evaluate geothermal well systems in some depleted oil reservoirs; perform sensitivity analysis to assess the impact of different operating parameters on overall heat recovery; and evaluate the economic feasibility of converting wells in depleted oil reservoirs in the Niger Delta into geothermal wells.

2. Data Used for the Study and Methodology

The Niger Delta is one of the most productive deltaic petroleum systems, with decades of oil and gas exploration and exploitation activities, in the world. It has over 12,000 m of sediments, which is composed of three diachronous siliciclastic units: the deep-marine pro-delta Akata Group, the shallow-marine delta-front Agbada Group and the continental, delta-top Benin Group [11].

Lithologically, the Niger Delta is stratified into three major formations: the Akata, Agbada, and Benin Formations [7, 25]. Thermal conductivity in the Niger Delta formations typically ranges between 1.2-2.5 W/(m K), depending on lithology. Formation water in Agbada formation typically has densities of 1,050-1,170 kg/m^3 and salinities that can exceed 35,000 ppm [1]. The Benin sands serve as the region's main aquifer, with groundwater densities around 1,000 kg/m^3 and relatively low total dissolved solids compared to deeper formations.

In the Nigerian oil and gas sector, as at 2023, there were over 200 fields, more than 1200 reservoirs and over 2500 wells with records of technical allowable rates [15]. The dataset used in this study was sourced from a confidential report provided by the reservoir management database of a major oil-producing company operating in the Niger Delta. The dataset underwent rigorous quality assurance and validation using established petroleum engineering protocols to ensure data integrity and reliability. Key parameters assessed included detailed rock and fluid properties, as well as comprehensive well characteristics.

2.1. Methodology

The approach adopted in this study involves characterization and screening the gathered well data, well performance simulation, overall heat estimation from the well and economic analysis.

2.1.1. Characterization and Screening

Characterization and screening of wells in depleted oil reservoirs for use for GWS were carried out using a dataset of 110 wells obtained from the Niger Delta. Figure 1 depicts the temperature distributions of the wells, showing a reservoir temperature from 90 ℉ to 265 ℉. According to Riney [21], electricity generation for GWS is technically and economically impractical at temperatures below 80 ℃ (176 ℉). Therefore, over 50 wells from the gathered wells were candidates for GWS development. Figure 2 presents the candidate wells considered for GWS application.

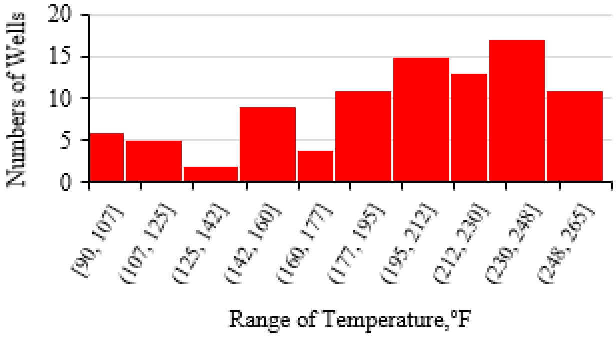

Figure 1. *General distribution of temperature for gathered wells.*

Further screening was carried out considering water cut to identify wells approaching abandonment, Figure 3 shows the distribution of water cut values for the gathered wells, ranging from 1% to 98%. Considering a water cut of 85% to mark wells approaching abandonment, about 33 wells were identified, as presented in Figure 4. Therefore, with a reservoir temperature above 176 ℉ and water cut above 85%, ten (10) wells were identified as immediate candidate for GWS application. These ten (10) wells (as summarized in Table 1) were considered in this study for modelling of the well performance of GWS in depleted oil reservoirs.

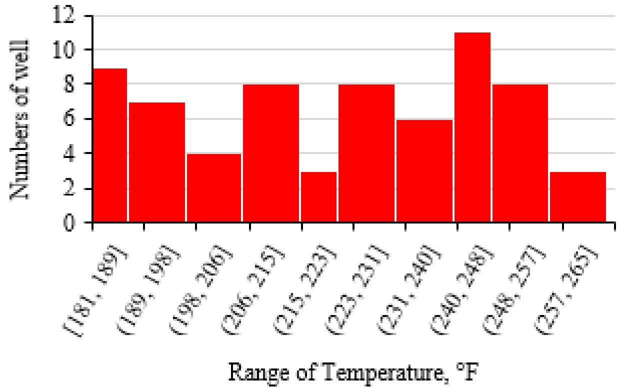

Figure 2. *Temperature distribution for the gathered well above 176 ℉.*

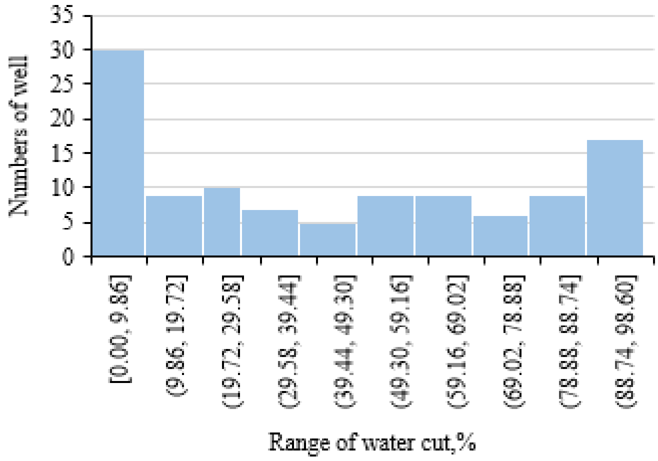

Figure 3. *Water cut distributions for the gathered wells.*

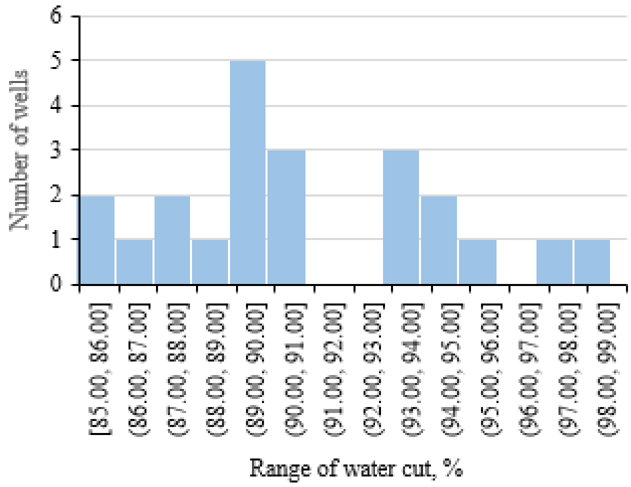

Figure 4. *Water cut distributions for the gathered wells, above 85%.*

Table 1. *Reservoir, fluid, and well parameters.*

Well Properties	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6	Well 7	Well 8	Well 9	Well 10
Fluid Type	oil	oil	Oil	oil	oil	Oil	oil	oil	oil	oil
Tubing Size (M)	2.875	2.375	2.375	2.875	2.875	2.875	31/5’’	2.875	2.375	2.375
Current GOR (scf/bbl)	418	1139	4258	1376	10938	1505	333	3500	2536	2142
API°	38.03	35.14	30.29	30.60	36.09	33.74	26.97	39.74	41.00	41.00
BSW (%)	85.00	57.00	87.00	19.00	40.00	20.00	16.60	91.00	81.00	37.00
THP (psig)	189	600	200	420	2000	725	305	290	232	1102
Current Reservoir Pressure (psia)	4058	3352	3230	3230	3281	3401	4030	3585	3564.7	3250
Porosity (%)	23	29	26	23	28	26	31	18	22	25
Permeability (md)	423	526	662	436	511	605	431	220	453	395
Water Saturation (%)	17	22	10	16	21	12	40	30	13	25
Thickness (ft)	80	59	90	110	42	30	120	35	61	32
Casing Depth (ft)	10510	7375	10908	7972	8820	8248	7,718	9507	9199	8566
Tubing Depth +0.5h (ft)	10456	7362	10875	7959	8751	8225	7,702	9493	9181	8520
Reservoir Temperature (℉)	218	162	221	182	168	152	150	194	190	182
Drainage Area (ft)	31	32	22	17	52	54	19	72	34	94

2.1.2. Well Performance Simulation

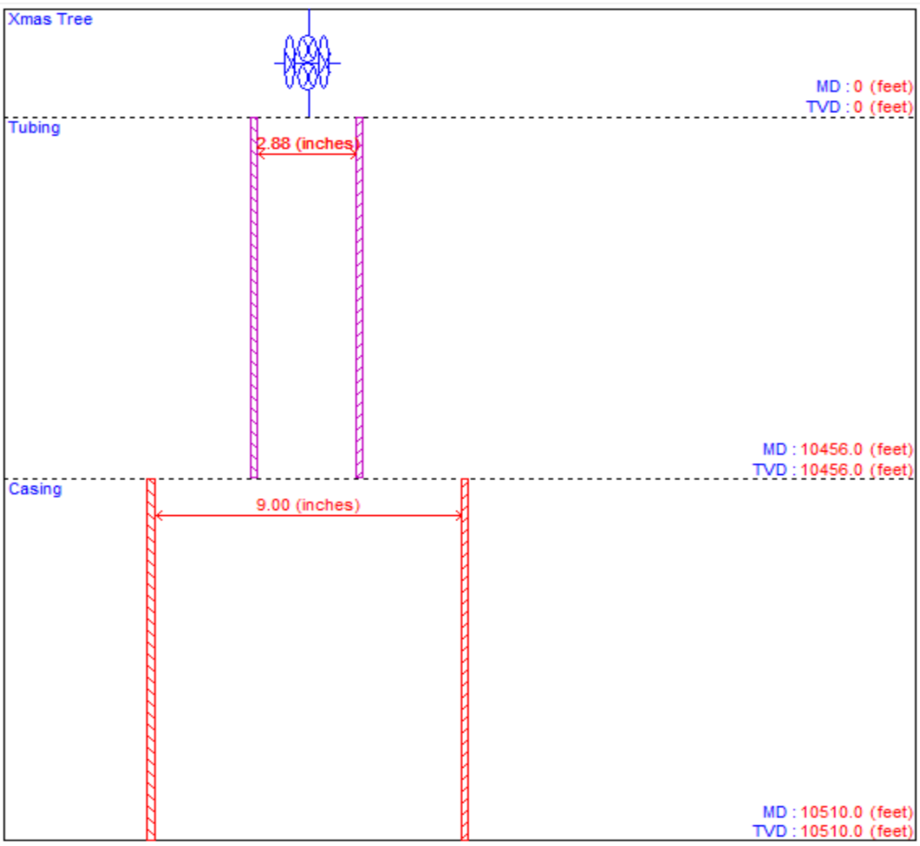

Figure 5. *Typical wellbore schematic of one the modeled wells.*

PROSPER® - a commercial software for well performance simulation was then employed to model and evaluate the temperature and pressure profiles, the IPR and VLP of the screened wells (see, Table 1 of the summary of the reservoir, fluid and well properties) to determine stable operating points or productivity of the wells; and sensitivity analyses were performed on critical variables such as tubing head pressures or reservoir pressure, tubing diameters, and water cut percentages. A typical modeled well is presented in the Figure 5.

2.1.3. Estimation of Overall Heat Recovered

The overall heat recovered was estimated using [23] Equations (1) and (2).

$$Q_{rev} = \left(C_{pw} + \rho_w \times q_w + C_{po} \times \rho_o \times q_o\right) \times (T_i - T_o) \quad (1)$$

$$Q = \left(C_p \times \rho \times q\right) \times (T_i - T_o) \quad (2)$$

where Q_{rev} is the recoverable thermal power, Q is the heat flow, C_p is the specific heat of the fluid, (W/kg K); ρ is the fluid density (kg/m^3), q is the fluid flow rate (m^3/s), T_i is the fluid temperature at wellhead (℃), T_o is the fluid temperature at the exit of electrical generator (℃), C_{pw} is the specific heat of water, equal to 4186 W/kg K, ρ_w is the water density (kg/m^3), q_w is the water flow rate (m^3/s), C_{po} is the specific heat of oil, equal to 2286 W/kg K, ρ_o is the oil density (kg/m^3), q_o is the oil flow rate (m^3/s).

2.2. Economic Analysis

A simplified economic evaluation was carried out to assess the investment in converting depleted oil wells to create geothermal wells, considering vertical coaxial GWS. The simplified capital cost economics of the geothermal well system (GWS) installation were estimated using Equation (3), taking into account the recommendations of Tester *et al*. [36].

$$C_{cap} = C_{gath} + C_{sim} + C_{plant} \quad (3)$$

where C_{cap}, capital expenditure (CAPEX), C_{gath}, field gathering system cost calculated based on a 750 m from each well to the power plant, at an assumed installation cost of $500 per meter for Niger Delta, C_{sim}, the reservoir simulation cost, the U.S. Department of Energy (DOE) provides a baseline estimate of $1.25 million per well for new wells in enhanced geothermal systems and C_{plant}, surface power plant cost, was estimated based on the plant type, capacity, and geofluid production temperature. According to NUPRC, the plant capital cost was estimated at $ 250 kWt/h.

Other economic indices: return on investment (ROI), net present value (NPV), and internal rate of return (IRR) were estimated as expressed in Equations (4) through (6).

$$PV = FV(1+i)^{-t} \quad (4)$$

$$NPV = \sum PV \quad (5)$$

$$IRR = C_o + \sum_{n=1}^{n} \frac{C_n}{(1+ROR)^n} = 0 \quad (6)$$

where PV = present value, FV = future value, t = time in years, i = discount rate and C_o = initial cost.

3. Results and Discussion

The screening of the gathered data for wells in depleted oil reservoirs for use for GWS showed only ten (10) wells out of the 110 wells investigated were potential candidates, considering Riney's [21] statement that electricity generation for GWS is technically and economically impractical at temperatures below 80 ℃ (176 ℉), and also considering water cut of 85% and more. Summary of the reservoir, fluid and well properties has been presented in Table 1.

3.1. Pressure and Temperature Gradients Estimation

Figure 6 presents typical pressure gradient curves for some five (5) selected wells, while Figure 7 depicts the temperature gradient curves for some five (5) selected wells. The pressure gradients for the selected wells range from 0.223 to 0.381 psig/ft, and the temperature gradient ranges from 0.02 to 0.023 ℉/ft. Figure 8 shows the regression analysis performed to identify the linear correlation between temperature and depth of the wells. An average temperature gradient of 0.011 °F/ft was obtained, with an approximate regression performance (R^2) value of 0.87.

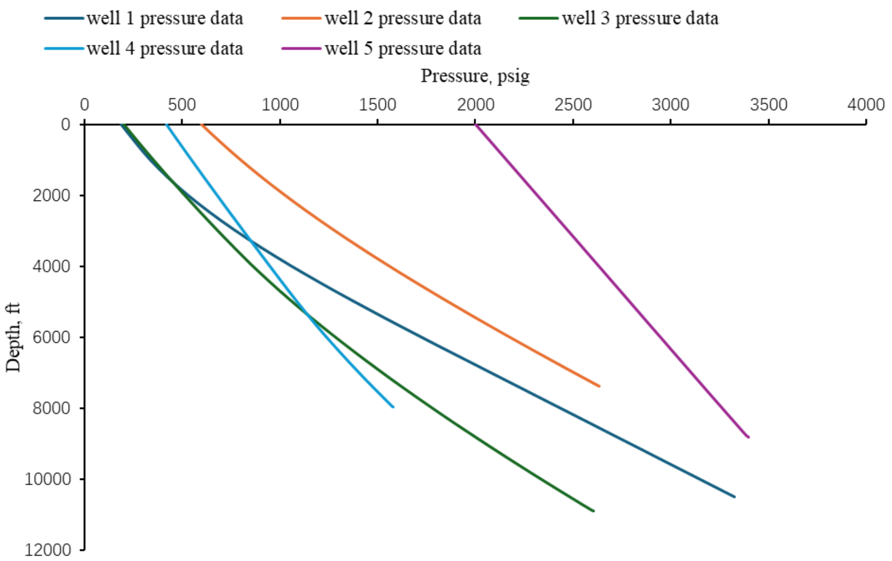

Figure 6. *Combine pressure gradient curves for some selected 5 wells.*

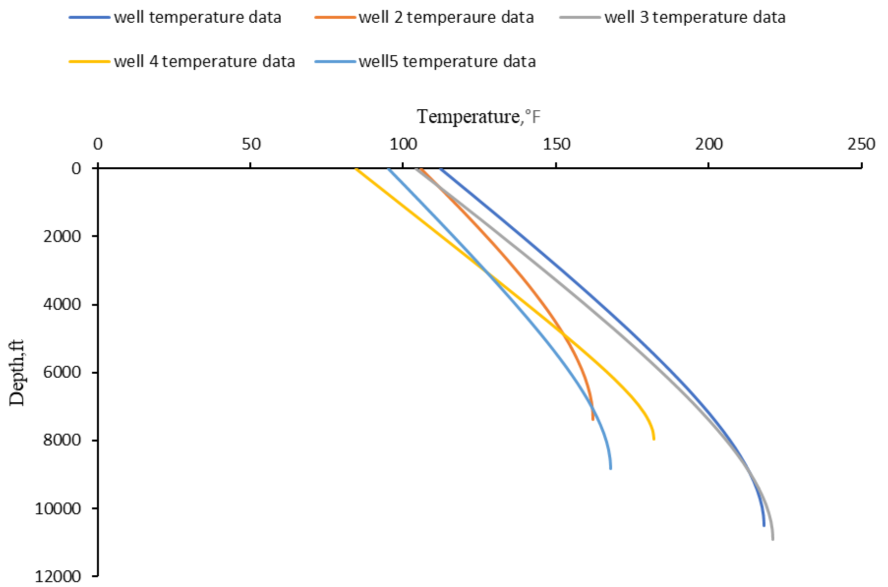

Figure 7. *Combine temperature gradient curves for some 5 wells.*

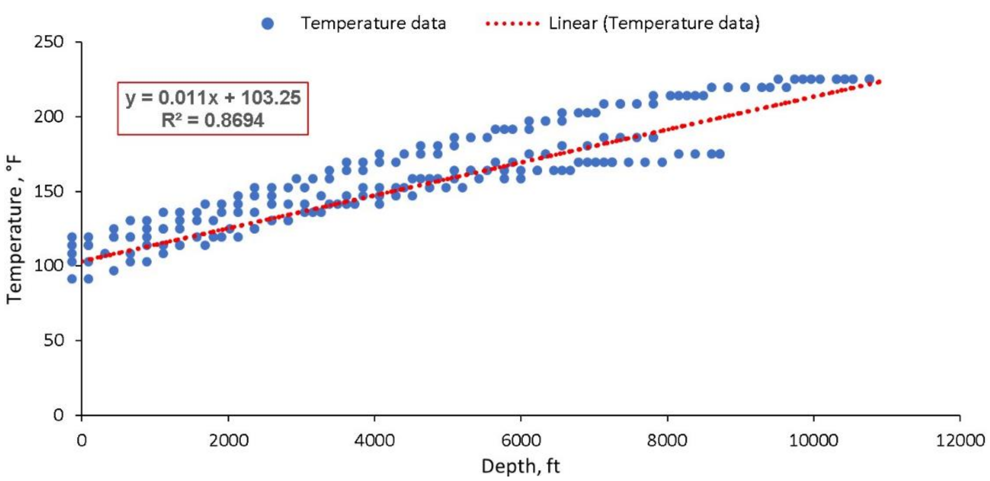

Figure 8. *Regression analysis of the temperature gradients for the wells studied.*

3.2. Inflow Performance Relationship (IPR) / Vertical Lift Performance (VLP)

The inflow performance relation (IPR) is a plot of pressure against the flow rate of the reservoir fluids. The absolute open flow potential (AOFP) for well 1 is 1547342 stb/day, as shown in Figure 9. Figure 9 also shows the AOFPs for four (4) other wells under study; these values range from 45444 to 154731stb/day. Figure 10 shows the IPR and VLP curves to generate the stable operating condition for a flowing well - well 1, as a case study, and Table 2 presents the summary of the IPR/VLP sensitivity results for well 1 for various tubing sizes, where stable operating point is possible.

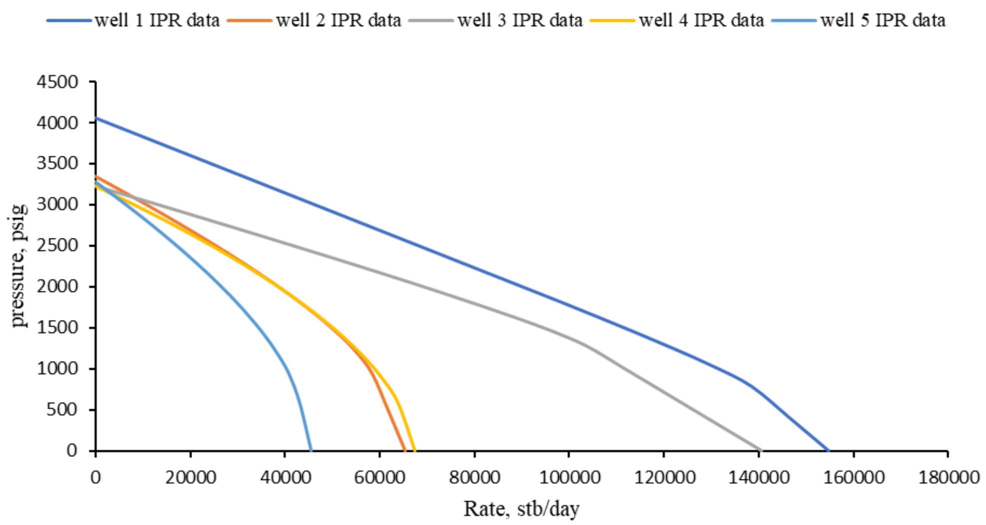

Figure 9. *IPR curves for some selected wells.*

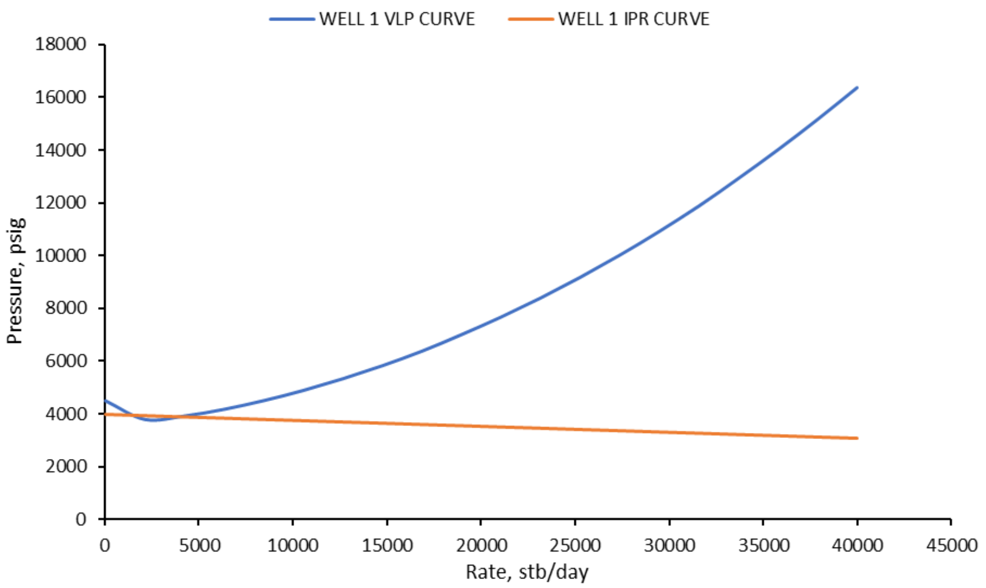

Figure 10. *IPR/VLP curve for well 1.*

Table 2. *Summary of IPR/VLP sensitivity results for well 1.*

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Oil rate (stb/day)	Water rate (stb/day)	Gas rate (MMscf/day)	Node pressure (psig)
60	4000	3	3922.4	1569	2353.5	0.65583	3910.7

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Oil rate (stb/day)	Water rate (stb/day)	Gas rate (MMscf/day)	Node pressure (psig)
60	4000	4	7368.3	2947.3	4421	1.232	3832.26
60	4000	5	10686.9	4274.7	6412.1	1.787	3756.71

3.3. Sensitivity Analyses of Some Parameters Affecting Well Performance

Sensitivity analyses on water cut, tubing size and reservoir pressure were performed to evaluate their effects on the wells' productivities under study. According to the sensitivity analyses carried out, it was observed that, at water cut of 60%, 70% and 80%, the results show a stable linear progressive operating solution condition. Also, as the reservoir pressure increases, the liquid rate increases alongside with different tubing sizes. However, for some of the tubing sizes, there were no stable operating solution details. Hence, it can be concluded that a higher flow rate depends on the tubing internal diameter size. Figures 11 through 13 present the sensitivity analysis for a case - well 3, at varying water cut, tubing sizes and reservoir pressure.

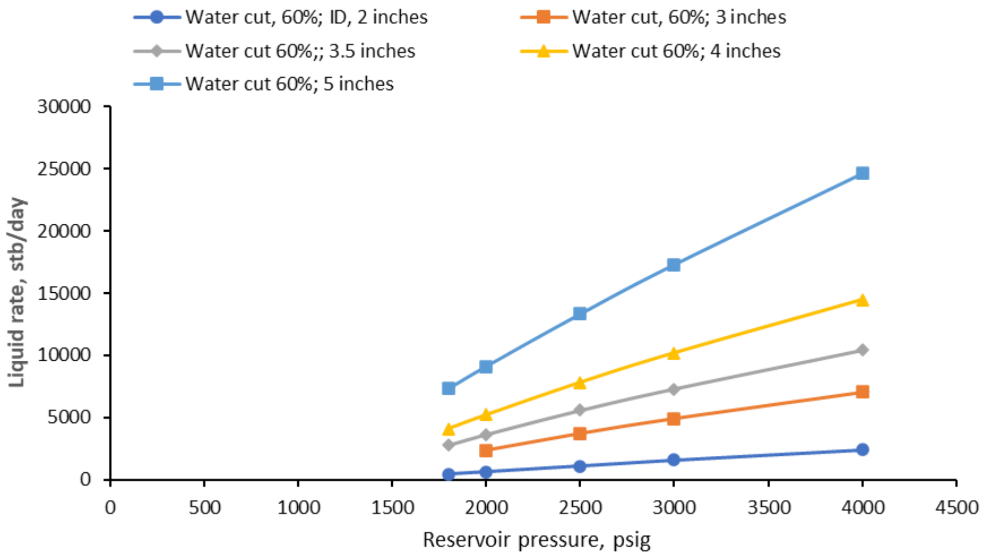

Figure 11. Sensitivity analysis for well 3 with 60% water cut.

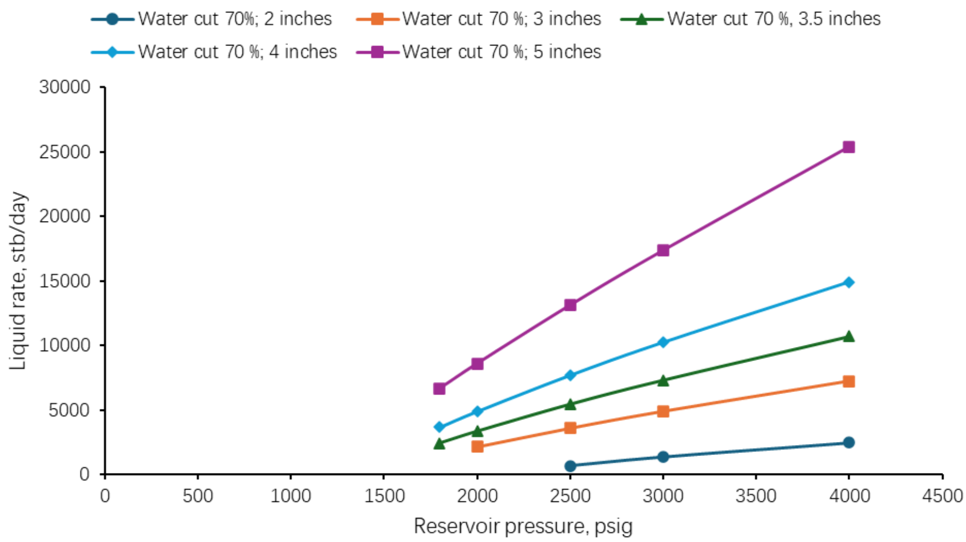

Figure 12. Sensitivity analysis for well 3 with 70% water cut.

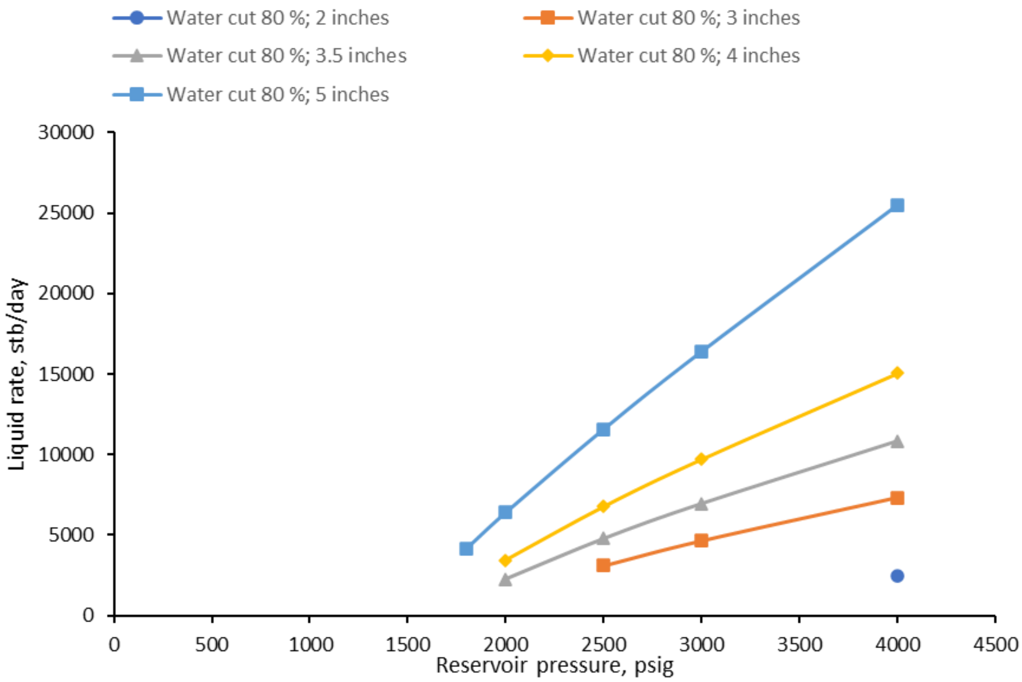

Figure 13. *Sensitivity analysis for well 3 with 80% water cut.*

3.4. Estimated Heat Generation from Well

The estimated overall heat recovered for the proposed GWS in this study was evaluated. It was observed that, as the liquid flow rate increases alongside different tubing sizes, there is a high rate of recoverable heat generated that is sufficient for the production of geothermal well system for electricity production. The estimated overall heat capacity for well 3 at varying internal tubing diameter and water cut is shown in Figure 14.

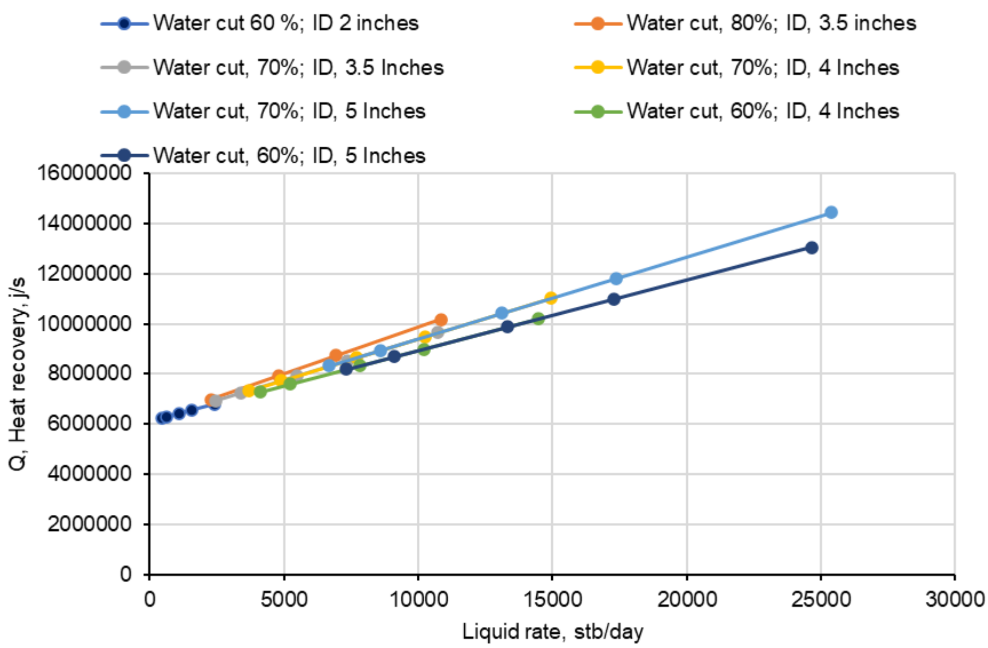

Figure 14. *Thermal heat power for vertical coaxial system for well 3.*

Table 3 presents the summary of the estimated average heat recovery (along with its standard deviation) for the wells under study. Tables 6 through 10 present the estimated heat recovery for some of the wells under study at various operating conditions.

Table 3. *Summary of the estimated average heat recovery (along with its standard deviation) for the wells under study.*

WELL	Average Estimated Heat Recovery, from the stable operating conditions J/s	Standard deviation of the estimated Heat Recovery, from the stable operating conditions, J/s
1	2137106.706	926383.6
2	3828415.673	1113605
3	8809371.794	2113289
4	5750277.777	1652454
5	85364.39235	11484.27
6	2625683.539	605983.2
7	2396355.487	269760.5
8	8073533.634	1487695
9	5604048.093	1522610
10	3537336.387	8200.522

3.5. Economic Analyses

Table 4 present the summary of the economic analyses for the ten (10) wells evaluated for GWS development proposed in this study. Figure 15 presents the NPV of some of the potential candidate wells for GWS development for the study. According to guidelines for the preparation of feasibility studies and economic viability oil business [30], typical IRR thresholds for viability project is roughly 12- 15% on investment. Nine out of the ten (10) wells evaluated met this criterion. Well 5 did not meet the IRR threshold of 12 - 15%, as the well produces more of gas. The gas-oil ratio of well 5 is quite high.

Table 4. *Summary of wells economic analysis for GWS development.*

Well	Total Cost ($)	Total Revenue ($)	Average Qrev (j/s)	NPV at 10%, ($)	NPV at 20%, ($)	NPV at 30% ($)	IRR (%)	Remarks
Well 1	10729873	1797221.503	2137106.706	2110496.63	-1397850.516	-3376470.233	18	Possible viable for Geothermal well system is greater than 12- 15% IRR
well 2	16649455	3219544.444	3828415.673	6352796.333	67939.65556	-3476561.737	20	Possible viable for Geothermal well system is greater than 12- 15% IRR
Well 3	34200553	7408329.304	8809371.794	18728752.85	4266990.111	-3889081.031	25	Possible viable for Geothermal well system is greater than 12- 15% IRR
Well 4	23375972	4835753.599	5750277.777	6777254.461	-2296251.089	-7310105.602	20	Possible viable for Geothermal well system is greater than 12- 15% IRR
Well 5	3548775.4	71787.70944	85364.39235	-3035883.293	-3176019.723	-3255053.151	0.5	not economic viable for geothermal well system
Well 6	12439892	2208094.829	2625683.539	3335989.681	-974421.2384	-3405384.79	19	Possible viable for Geothermal well system is greater than 12- 15% IRR
Well 7	11637244	2015239.11	2396355.487	2760767.058	-1173171.174	-3391813.58	19	Possible viable for Geothermal well system is greater

Well	Total Cost ($)	Total Revenue ($)	Average Qrev (j/s)	NPV at 10%, ($)	NPV at 20%, ($)	NPV at 30% ($)	IRR (%)	Remarks
								than 12- 15% IRR
Well 8	23567921	6789518.845	8073533.634	24940252	11686466.08	4211663.533	40	Possible viable for Geothermal well system is greater than 12- 15% IRR
Well 9	22864168.33	4712780.284	5604048.093	10806606.67	1606811.742	-3581641.647	25	Possible viable for Geothermal well system is greater than 12- 15% IRR
Well 10	15630677.36	2974758.408	3537336.387	5622683.709	-184327.3651	-3459335.834	20	Possible viable for Geothermal well system is greater than 12- 15% IRR

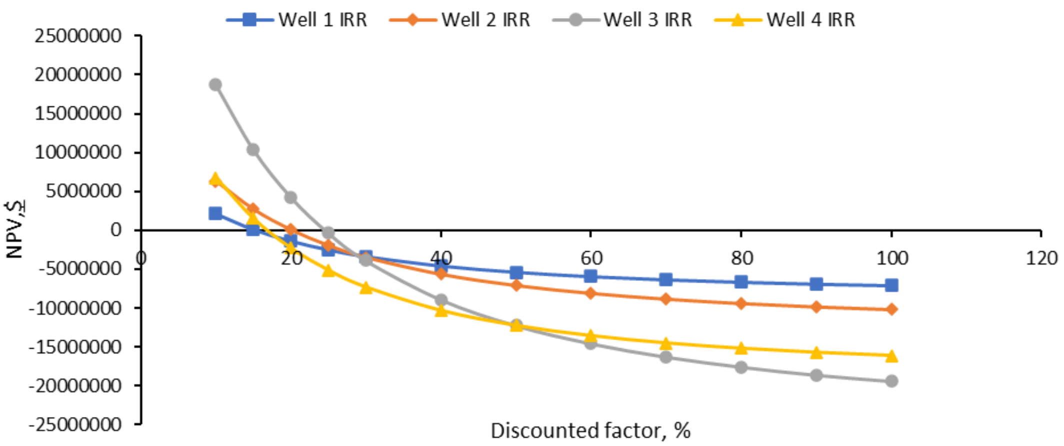

Figure 15. *Combined NPV curve plot for selected wells.*

3.6. Comparing This Study with Some Related Existing Studies

The technical and economic findings of this research are consistent with published studies on geothermal repurposing of depleted oil reservoirs. For example, Bu *et al.* [5] and Wang *et al*. [33] reported similar ranges of recoverable heat and economic feasibility when evaluating abandoned oilfield assets in China and elsewhere. The recoverable heat and power generation estimates derived in this study for the Niger Delta wells fall within the expected range for low- to medium-enthalpy geothermal systems. These comparative results strengthen confidence in the methodology and confirm that repurposing depleted hydrocarbon wells in the Niger Delta is in line with global trends and technical best practices. Key differences observed relate to local geological and operational characteristics, suggesting the need for site-specific screening and adaptation of international models when applied to the regional context. As summarized in Table 5, the present study compares favourably with other existing studies. The results are in tandem with typical thermal heat output of geothermal wells for high-temperature geothermal wells development.

Table 5. *Analysis of the study with some related existing studies.*

Author (s)	Depth (ft)	Temp. ℃	Pressure (psia)	Fluid flow rate	Type of fluid used	Type of GWS	Heat generated
Steward [31]	6561.68	72	Not stated	Not stated	CO_2	Deep geothermal single well	1,800000 kWh
Usuolori *et al.* [32]	2438.4	96	3992	Not stated	CO_2 and Water vapour	Not stated	59.39×10^{18} J

Author (s)	Depth (ft)	Temp. ℃	Pressure (psia)	Fluid flow rate	Type of fluid used	Type of GWS	Heat generated
Sennaoui *et al.* [22]	2500	178.26	Not stated	1-57Kg/s	Cool fluid	Coaxial close-loop (vertical & L-shape)	1361.95 KW
This study	10211	90	3585	2890.3 stb/day	Oil and water	Vertical Coaxial open loop	8073.53 KW (Well 8)

4. Conclusion

A comprehensive evaluation was conducted on a dataset of 110 wells, with screening based on reservoir temperature and water cut to identify suitable candidates for geothermal conversion. Reservoir temperatures ranged from 90 ℉ to 265 ℉, and applying a minimum threshold of 176 ℉ for electricity generation narrowed the candidate pool to over 50 wells. Subsequent screening using a water cut of ≥85% identified 10 wells as immediate candidates for the geothermal well system (GWS) application.

Well performance was assessed using a production system simulator, involving more than 1,000 simulation runs to examine the influence of tubing size, reservoir pressure, temperature, and water cut. The results revealed pressure gradients of 0.223 - 0.381 psig/ft and temperature gradients of 0.020 - 0.023 ℉/ft. Inflow performance and vertical lift analyses confirmed stable operating conditions, with liquid production rates strongly influenced by tubing internal diameter and reservoir pressure. The estimated recoverable heat ranged from 0.1 MW to 8 MW.

Economic analysis, using net present value (NPV) and internal rate of return (IRR) criteria, demonstrated that several wells are economically viable. The thermal power output achieved approximately 8 MW, with IRR values meeting the 12-15% viability threshold. Based on these findings, the following conclusions were drawn:

1) The findings of this study confirm that vertical coaxial open-loop depleted oil configuration reservoirs can be technically and economically viable for direct reuse for geothermal applications.
2) Flow rate is a primary control on thermal output for GWS development that is heavily dependent on well geometry.
3) Pressure and temperature gradients, water cut, and overall heat recovered are key reservoir and operational parameters considered for GWS.
4) Sensitivity analyses indicate that a higher flow rate depends on the tubing internal diameter size, considering water cut, tubing size, and reservoir pressure.
5) The recoverable heat and power generation estimates derived in this study for the Niger Delta wells fall within the expected range for low- to medium-enthalpy geothermal; therefore, the technical assessment and economic analysis presented in this work demonstrate that depleted oil reservoirs, particularly those with high water cut and adequate reservoir temperature, can be successfully repurposed as geothermal well systems. The results provide compelling evidence that geothermal conversion is not only feasible but also offers a practical pathway for extending the productive life of mature oilfields. This recovery of interest in geothermal applications, especially in regions like the Niger Delta, opens up new opportunities for sustainable energy generation by leveraging existing oilfield infrastructure. The findings encourage further exploration and investment in geothermal well systems as a means to diversify energy portfolios and promote cleaner energy sources.

5. Recommendation and Suggestion for Further Studies

Based on the conclusions drawn, the following recommendations are proposed:

Conduct comprehensive field evaluations to validate the technical and economic findings of this study. Power plant operators and energy generation companies should collaborate on pilot-scale field analyses to confirm model predictions and refine system design.

Foster partnerships between the oil and gas and geothermal sectors to leverage shared expertise and infrastructure, enhancing project feasibility and reducing costs.

Support further research on advanced well configurations, working fluids, and heat extraction technologies to maximize geothermal output from depleted reservoirs in the Niger Delta.

Future studies should investigate the application of closed-loop horizontal well configurations and hybrid system designs for geothermal energy production from depleted oil reservoirs. Such research could provide deeper insights into optimizing heat recovery, enhancing system efficiency, and expanding the range of viable reservoir candidates in the Niger Delta.

Abbreviations

AOFP	Absolute Open Flow Potential
API	American Petroleum Institute

BSW	Basic Sediment & Water
CAPEX	Capital Expenditure
DL	Deep Learning
FV	Future Value
GOR	Gas-Oil Ratio
GSHP	Ground Source Heat Pump
GWS	Geothermal Well Systems
HIP	Heat In Place
HSA	Hot Sedimentary Aquifer
HT	High Temperature
IPR	Inflow Performance Relationship
IRR	Internal Rate of Return
MT	Medium Temperature
NN	Neural Network
NPV	Net Present Value
ORC	Organic Rankine Cycle
NUPRC	Nigerian Upstream Petroleum Regulatory Commission
PROSPER™	Production System Performance Software
PV	Present Value
ROI	Return On Investment
RNN	Recurrent Neural Network
THP	Tubing Head Pressure
VLP	Vertical Lift Performance

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Isaac Ouets: Writing – review & editing

Data Availability Statement

The full datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Table 6. Estimated Heat Recovery, J/s, for Well 1, where there are stable operating conditions.

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Qrev, J/s; W
60	4000	3	3922.4	1204965.301
60	4000	4	7368.3	2148731.654
60	4000	5	10686.9	3057623.162

Table 7. Estimated Heat Recovery, J/s, for Well 2, where there are stable operating conditions.

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Q, Heat Recovery, J/s.W
60	3000	3	4409.4	2681158.18
60	3000	3.5	6035.9	2909024.631
60	3000	4	7613.3	3129980.379
60	3000	5	10266	3501570.793
60	4000	2	3622.5	2570937.123
60	4000	3	9859.8	3444674.221
60	4000	3.5	13900.9	4010768.263
60	4000	4	18293.3	4626054.375
60	4000	5	27122.7	5862883.59
70	3000	3	2483.8	2469424.487

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Q, Heat Recovery, J/s.W
70	3000	3.5	3184.1	2583871.346
70	3000	4	3912.4	2702894.211
70	3000	5	4541.9	2805760.972
70	4000	2	3476.8	2631685.945
70	4000	3	9454.3	3608593.315
70	4000	3.5	13260.8	4230696.743
70	4000	4	17311.2	4892630.107
70	4000	5	25177.3	6178184.453
80	4000	2	3241.6	2668947.713
80	4000	3	8784.2	3704152.473
80	4000	3.5	12152.8	4333353.381
80	4000	4	15634.4	4983613.259
80	4000	5	21959.3	6164946.719
90	4000	2	2788.5	2649429.644
90	4000	3	7356.3	3609223.683
90	4000	3.5	9972.2	4158881.456
90	4000	4	12488.7	4687667.036
90	4000	5	16443.1	5518562.439
95	4000	2	2443.7	2605490.642
95	4000	3	6206.4	3440051.52
95	4000	3.5	8181.8	3878180.806
95	4000	4	9951.6	4270713.454
95	4000	5	12444.8	4823709.844

Table 8. *Estimated Heat Recovery, J/s, for Well 3, where there are stable operating conditions.*

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Qrev, J/s.W
60	1800	2	442	6252486.496
60	1800	3.5	2787.6	6911672.938
60	1800	4	4117.1	7285293.106
60	1800	5	7318.7	8184988.457
60	2000	2	630.6	6305506.181
60	2000	3	2362.9	6792331.809
60	2000	3.5	3645	7152603.381
60	2000	4	5220.9	7595448.898
60	2000	5	9105.1	8687036.167
60	2500	2	1103.5	6438383.255
60	2500	3	3719	7173399.088

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Qrev, J/s.W
60	2500	3.5	5580.3	7696476.691
60	2500	4	7827.6	8328029.198
60	2500	5	13329.2	9874077.604
60	3000	2	1578	6571728.701
60	3000	3	4916.4	7509877.374
60	3000	3.5	7304.5	8181007.297
60	3000	4	10194.3	8993117.125
60	3000	5	17307.7	10992127.88
60	4000	2	2427	6810317.285
60	4000	3	7038.6	8106301.998
60	4000	3.5	10407.8	9053115.55
60	4000	4	14468.7	10194303.39
60	4000	5	24645.9	13054321.98
70	1800	3.5	2461.4	6935278.876
70	1800	4	3674.9	7333113.865
70	1800	5	6684.4	8319832.692
70	2000	3	2187.4	6845445.168
70	2000	3.5	3378.9	7236067.232
70	2000	4	4893.9	7732775.504
70	2000	5	8603.9	8949137.015
70	2500	2	695.2	6356184.008
70	2500	3	3628.9	7318079.131
70	2500	3.5	5477.6	7924152.213
70	2500	4	7699.6	8652657.678
70	2500	5	13131.2	10433500.86
70	3000	2	1382.9	6581658.182
70	3000	3	4933.7	7745843.077
70	3000	3.5	7342.2	8535471.059
70	3000	4	10252.1	9489544.373
70	3000	5	17368.3	11822644.72
70	4000	2	2494.9	6946238.775
70	4000	3	7266.1	8510553.681
70	4000	3.5	10741.8	9650055.382
70	4000	4	14927.6	11022431.53
70	4000	5	25399.8	14455830.86
80	1800	5	4184.7	7696242.505
80	2000	3.5	2269.3	6978556.428
80	2000	4	3431.7	7414142.183
80	2000	5	6417.7	8532941.852

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Qrev, J/s.W
80	2500	3	3099.1	7289508.452
80	2500	3.5	4778.5	7918765.938
80	2500	4	6764	8662727.672
80	2500	5	11589.9	10470970.6
80	3000	3	4645.7	7868978.017
80	3000	3.5	6947.3	8731437.812
80	3000	4	9697	9761715.214
80	3000	5	16407.5	12276122.27
80	4000	2	2502.2	7065814.09
80	4000	3	7323.7	8872464.554
80	4000	3.5	10835.4	10188261.39
80	4000	4	15051.7	11768126.24
80	4000	5	25496.1	15681606.64
90	3000	3	2716	7273162.277
90	3000	3.5	4344.6	7959654.794
90	3000	4	6160.5	8725161.63
90	3000	5	10551.9	10576260.58
90	4000	2	2233.1	7069607.902
90	4000	3	6632.1	8923938.613
90	4000	3.5	9808.9	10263060.37
90	4000	4	13649.7	11882127.93
90	4000	5	22900.7	15781744.53
95	4000	3	4638.7	8192295.057
95	4000	3.5	6941.9	9217092.509
95	4000	4	9617.8	10407740.41
95	4000	5	15717	13121580.17

Table 9*. Estimated Heat Recovery, J/s, for Well 4, where there are stable operating conditions.*

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Qrev, J/s.W
60	2500	3	3217.2	3867962.563
60	2500	3.5	4757.1	4157141.315
60	2500	4	6371.1	4460215.67
60	2500	5	9377.8	5024802.758
60	3000	3	5691.7	4332620.24
60	3000	3.5	8197.5	4803161.641
60	3000	4	10979.4	5325561.179
60	3000	5	16733.3	6406006.857

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Qrev, J/s.W
60	4000	2	3525.5	3925860.906
60	4000	3	9863.3	5115969.176
60	4000	3.5	14235.3	5936936.387
60	4000	4	19182.4	6865907.481
60	4000	5	30238.1	8941922.995
70	3000	3	4890.7	4335280.434
70	3000	3.5	7009.4	4799437.369
70	3000	4	9291.8	5299428.683
70	3000	5	13714.7	6268396.578
70	4000	2	3448	4019218.073
70	4000	3	9642.7	5376323.942
70	4000	3.5	13831.6	6293997.035
70	4000	4	18570.4	7332161.274
70	4000	5	29009.8	9619145.833
80	3000	3	2703.9	3940820.586
80	3000	3.5	3804.4	4216354.108
80	3000	4	4851.6	4478555.362
80	3000	5	6386.8	4862906.472
80	4000	2	3261.7	4080465.131
80	4000	3	9142.2	5552773.056
80	4000	3.5	13040.6	6528845.234
80	4000	4	17361.6	7610699.25
80	4000	5	26437.2	9882974.499
90	4000	2	2864.6	4070700.654
90	4000	3	7952.3	5503762.89
90	4000	3.5	11139	6401343.693
90	4000	4	14505.9	7349687.259
90	4000	5	20888.4	9147446.465
95	4000	2	2453.3	3993273.356
95	4000	3	6578.8	5219841.934
95	4000	3.5	8980	5933744.154
95	4000	4	11372.1	6644954.884
95	4000	5	15374	7834781.486

Table 10. *Estimated Heat Recovery, J/s, for Well 5, where there are stable operating conditions.*

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Qrev, J/s.W
60	4000	2	86.2	66255.0972

Water cut (%)	Reservoir pressure (psig)	Tubing size (inches)	Liquid rate (stb/day)	Qrev, J/s.W
60	4000	3	2672.4	77367.8264
60	4000	3.5	3990.1	83029.82531
60	4000	4	5418.2	89166.64148
60	4000	5	8621.3	102930.6128
70	4000	3	2611.7	78977.76487
70	4000	3.5	3843.2	85151.10545
70	4000	4	5175.6	91830.77454
70	4000	5	7910	105538.885
80	4000	4	2345.3	79321.52398
80	4000	5	2365.6	79438.25884

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