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Utilization of Oil and Gas Wells for Geothermal Applications

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ABSTRACT

Major hydrocarbon producers are in energy transition, directing new investments from fossil fuels to renewable energy sources. Geothermal energy is one of the fastest-growing sources in the renewable energy industry. It provides base-load energy with less impact on the environment. Thousands of wells abandoned in depleted oil and gas fields are now under investigation for geothermal applications. The geothermal gradient of hydrocarbon fields demonstrates potential for direct-use applications and even for electricity generation in some cases. Drilling activities constitute the major costs of geothermal projects. Geothermal projects using existing hydrocarbon wells could be economical viable since there will be no need for drilling and surface infrastructure such as pumps, pipelines, separators, and surface production systems. This study presents a comprehensive review of geothermal production from depleted oil and gas wells. Production techniques such as artificial lifting and wellbore heat exchangers are presented with a techno-economic analysis. It was found that most of the depleted wells are suitable for direct use applications such as district heating, drying food, and thermal swimming pools rather than electricity generation.

1. INTRODUCTION

Geothermal energy is utilized for various applications including direct use applications (district heating, food-drying, spa hotels, greenhouses, etc.) and electricity generation, depending on the available resource temperature. One of its unique advantages compared to other renewable resources is its ability to provide baseload power, meaning it can generate electricity continuously and reliably. Regions with high tectonic activity have high geothermal gradients, resulting in higher temperatures at shallower depths compared to areas with normal geothermal gradients (around 1.5°C per 100 meters). While high-temperature regions are ideal for electricity generation, their remote locations often pose significant development challenges. Therefore, the current focus is on utilizing sedimentary basins closer to potential user areas.

Abandoned oil and gas wells offer an environmentally friendly opportunity for geothermal energy extraction. Converting these wells eliminates the need for new drilling, thereby reducing the environmental impact associated with drilling footprints and carbon emissions. Drilling costs constitute a significant portion (over 50%) of geothermal project expenses. Repurposing existing wells eliminates these costs, making the project more economically viable. Estimates suggest a vast number of abandoned oil and gas wells worldwide, with 3.2 million in the U.S. alone (Raimi et al., 2021) and over 200,000 in China (Bu et al., 2012). Despite being uneconomical for hydrocarbon production due to high water cut, these wells retain significant heat, making them valuable geothermal resources. Oil reservoirs typically exhibit normal geothermal gradients and are encountered between 1000-3000 meters depths. Consequently, bottom-hole temperatures in repurposed wells generally range from 40-70°C. While some high-pressure/high-temperature (HPHT) regions exist, hydrocarbon reservoirs usually display lower temperatures (40-120°C) (Aydin & Merey, 2021).

Temperatures below 80°C are considered technically and economically infeasible for electricity generation. Typical large-scale geothermal power plants require reservoir temperatures exceeding 150°C (Riney, 1992). Pilot projects extracting from 150°C reservoirs exist, with an example being the 535-kW binary plant operating at 143°C (Riney, 1992). The first geothermal power plant utilizing oil wells at 99°C was reported by Wang et al. (2018b). For low-temperature resources, technologies like Organic Rankine Cycle (ORC) and thermoelectric modules are used for electricity generation. Thermoelectric modules exhibit efficiencies between 4-5%, while ORC units can achieve 8-12% depending on the geothermal fluid (Wang et al., 2018a).

This investigation delves into the methodologies for thermal energy extraction from abandoned hydrocarbon wells, evaluating both economic and technical considerations.

2. METHODS OF GEOTHERMAL PRODUCTION FROM HYDROCARBON WELLS

The geothermal heat could be recovered via hot water production or heat exchange in the wellbore.

2.1 Heat Extraction from Formation Water

Producing formation water provides high thermal recovery from the hydrocarbon reservoirs. This is because of having a vast heat transfer area in the porous medium and natural fractures in the reservoir. Re-injection of waste brine can boost thermal sweep efficiency in the reservoir. Thermal recovery of the reservoir is dependent on the formation permeability and porosity. Garg (2010) considered recovery factor between 5 % and 20 % in the fracture systems. Some studies reported recovery factor ranging from 5 % to 24 % (Muffler and Cataldi, 1978; Akin, 2017). The drawbacks of producing formation water are scaling problems and a need for re-injection well that is not far away from the production well. Hydraulic connection between re-injection and production well is essential to have a desired thermal recovery and sustainability of the production. Scaling and corrosion problems can be overcome using inhibitors damaging into the production wells. As abandoned hydrocarbon wells do not have sufficient pressure to produce by artesian flow, downhole pumps are needed to produce artificially. Volumetric method is used to estimate heat in place for particular hydrocarbon reservoirs. Heat is stored within the rock grain and water fills the porous medium. Equations 1,2,3 and 4 are used for heat in place calculations. Recoverable thermal power not only depends on heat in place, but also recovery rate, life, and load factor of the projects. Geological formations exhibit heterogeneous behavior in terms of reservoir properties such as permeability, porosity, and thickness. It is difficult to estimate the most likely value of each parameter to determine exact thermal power. Therefore, stochastic methods are employed to estimate thermal power with chance of occurrence. Aydin and Merey (2021) presented a schematic view of geothermal production from formation water in a depleted gas reservoir (Figure 1). Similarly, Merzoug and Okoroafor (2023) studied effect of rock properties on the power generation capacity from abandoned oil and gas wells.

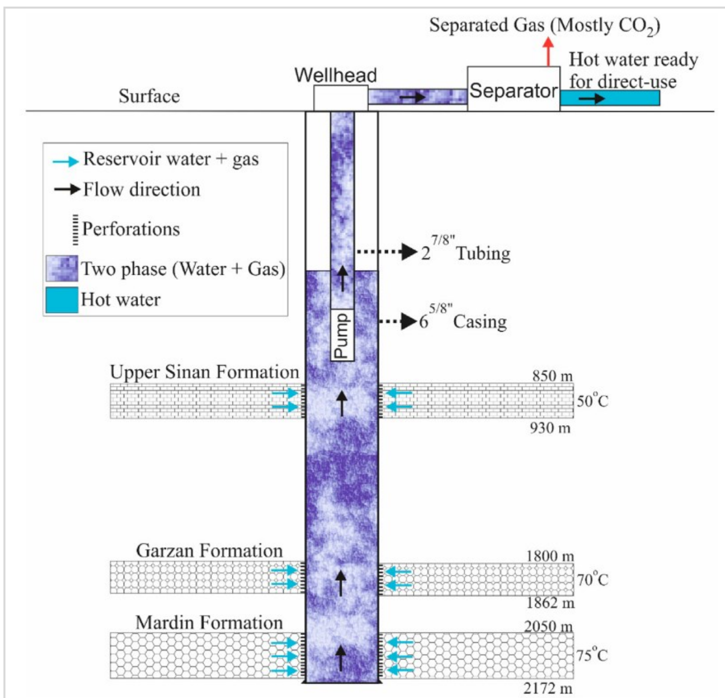

Figure 1: Wellbore scheme for geothermal energy extraction from the Dodan CO2 field production intervals (Aydin and Merey, 2021)

$$H_{Total} = H_R + H_F \tag{1}$$

$$\mathrm{H_R} = (1-\phi) \times \mathrm{c_R} \times \rho_\mathrm{R} \times \mathrm{A} \times \mathrm{h} \times (\mathrm{T_R} - \mathrm{T_U}) \tag{2}$$

$$\mathrm{H_F} = (\phi) \times \mathrm{S_F} \times \mathrm{c_F} \times \rho_\mathrm{F} \times \mathrm{A} \times \mathrm{h} \times (\mathrm{T_R} - \mathrm{T_U}) \tag{3}$$

Where, H_{Total} is total energy (kJ), H_R is energy stored in rock (kJ), H_F is energy stored in fluid (kJ), ϕ is porosity (fraction), c_R is specific heat capacity of rock (kJ/kg °C), c_F is specific heat capacity of fluid (kJ/kg °C), A is reservoir area (m^2), h is reservoir thickness (m), T_R is reservoir temperature, T_U is utilization temperature, ρ_F is fluid density (kg/m3), ρF is rock density (kg/m3), SF is fluid saturation (fraction).

$$\mathrm{MWt} = \frac{\mathrm{H_{Total}} \times \mathrm{RF} \times \mathrm{HE_E}}{\mathrm{LF} \times \mathrm{PL}} \quad (4)$$

where, MWt, RF, HE_E, LF, PL are thermal megawatt, recovery factor (fraction), the efficiency of heat exchanger found on the surface (fraction), load factor (fraction) and project life (years) respectively.

2.2 Downhole Heat Exchanger

While direct formation water production offers higher energy efficiency and heat recovery due to its larger extraction area within the reservoir, it necessitates downhole pumps and complex reservoir management strategies. Conversely, WBHEs operate as closed systems within the wellbore, eliminating the need for artificial production and reservoir management. However, their heat exchange surface area is inherently limited by the well diameter, leading to potentially lower recovery rates. Figure 2 depicts a closed-loop wellbore heat exchanger (WBHE) system for extracting geothermal energy.

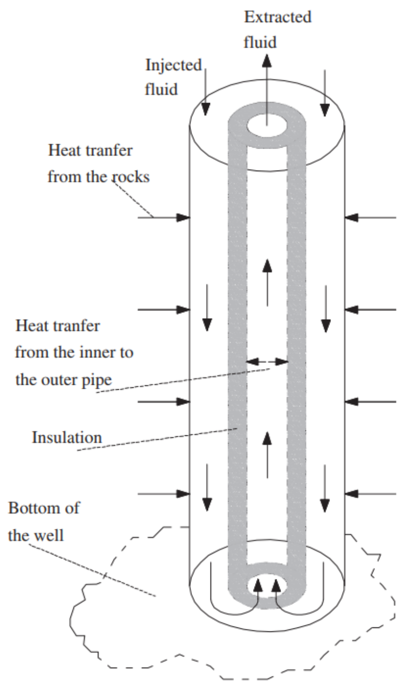

Figure 2: Schematic representation of heat exchange in the single well (Bu et al., 2012)

Mathematical modeling plays a crucial role in estimating the production capacity of WBHE systems. The heat transient from the formation to the heat exchanger is expressed with Ramey's radial heat flow equation (Cheng et al. 2013). Equations 5 and 6 specifically calculate the rate of heat extracted from the surrounding rock formations into the circulating fluid. Notably, WBHE systems often employ intermittent production cycles to optimize heat transfer efficiency. Comprehensive sensitivity analyses are conducted to evaluate the impact of various operating parameters on overall heat recovery. These analyses allow for the identification of critical factors influencing system performance and inform strategies for maximizing energy yields.

$$\mathrm{Q} = \mathrm{m} \times (\mathrm{H_2} - \mathrm{H_1}) \quad (5)$$

$$\mathrm{Q} = \mathrm{m} \times C_\mathrm{p} \times (\mathrm{T}_{out} - T_{in}) \times (h_1^{"} - h_2) \times (1 - X) \times n_z/(2r_w) \quad (6)$$

Where, T_{in} is inlet temperature of fluid at wellhead, T_{out} is outlet temperature of fluid at wellhead, m is mass flow rate of fluid, Q is heat obtained from rocks, H_1 is enthalpy of injected fluid, and H_2 is enthalpy of extracted fluid, C_p is specific heat of fluid, h''_1 is inlet enthalpy of turbine, h_2 is outlet enthalpy of turbine, X is proportion of electricity used by electric power plant, n_z is the unit efficiency, and r_w is the latent heat of vaporization.

Various fluid types can be used as working fluids in wellbore heat exchangers. Fresh water is employed for direct-use applications such as district heating and spa hotels. Organic fluids could be used for electricity generation due to their lower boiling temperatures compared to fresh water. Cheng et al. (2014) studied R134a, R143a, R290, R600, and R600a as working fluids to produce electricity from abandoned oil wells. They demonstrated that oil wells with depths less than 3000 meters are not viable for electricity generation. R134a exhibited the highest production performance when compared to other organic fluids (Figure 3).

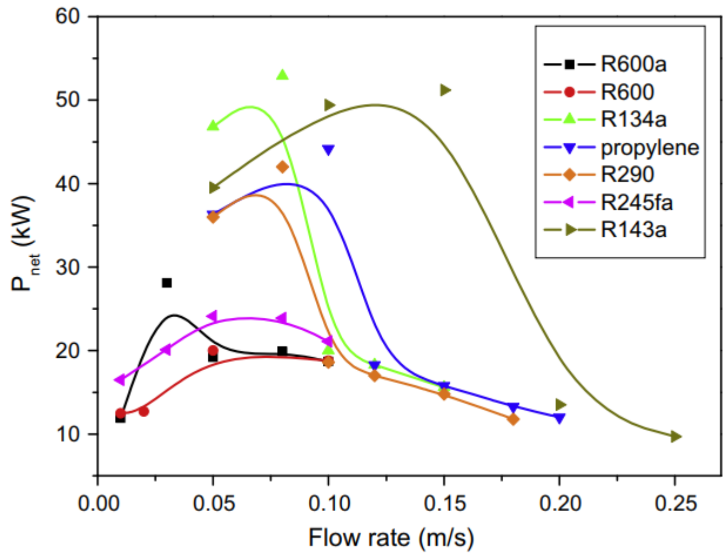

Figure 3: Net power produced with different organic fluids (Chen et al. 2014)

3. RESULTS AND DISCUSSIONS

Extracting hot water from depleted hydrocarbon wells offers higher thermal recovery compared to wellbore heat exchangers (WBHEs) but necessitates additional investments. Downhole pumps become essential due to insufficient reservoir pressure, leading to increased initial capital expenditure. Moreover, the chemical composition of formation water necessitates continuous chemical injection to mitigate corrosion and scaling, contributing to ongoing operational expenses (OPEX).

Waste brine disposal presents a further challenge with hot water production. Reinjection into the reservoir for disposal and maintaining material balance becomes crucial. This requires a dedicated re-injection well with proper hydraulic connection to the production well, ensuring sustainable production.

Sensitivity analysis of volumetric heat-in-place calculations identifies recovery factor and utilization temperature as the critical parameters influencing recoverable heat. However, a significant portion of the energy resides in the rock grains, limiting extraction efficiency compared to WBHEs.

While geothermal power plants typically experience OPEX around 5% of annual turnover, with chemical dosing constituting over 70% of that expense, hot water production incurs additional costs. Re-injection pumps alone consume nearly 10% of electricity production. Consequently, the OPEX of hot water production from hydrocarbon reservoirs is likely to be higher than for WBHE systems, despite offering potentially higher recoverable thermal power. For example, Aydin and Merey (2021) estimated a recoverable thermal power of 3.27 MWt from the depleted Dodan gas field, significantly higher than the 50 kW reported by Bu et al. (2012) for a single WBHE well. However, the economic feasibility of each approach requires a comprehensive cost-benefit analysis considering both recovered thermal power and associated expenses.

WBHEs leverage heat transfer between injected and extracted fluids within the wellbore, interacting with both surrounding rock formations and previously injected fluids. However, the limited heat exchange area within the wellbore inherently restricts the recoverable thermal power compared to other methods. Despite this limitation, WBHEs offer distinct advantages. Their closed-loop nature eliminates direct interaction between circulating fluids and formation water, effectively mitigating corrosion and scaling concerns. Consequently, operational expenses (OPEX) associated with chemical dosing and infrastructure maintenance are typically lower compared to hot water production systems. The rate of reinjected fluid significantly influences the outlet temperature of the extracted fluid. While higher injection rates enhance circulation, they can also limit heat extraction if conductive heat transfer from the surrounding rock is insufficient to compensate for the temperature drop in the extracted fluid. In this context, the performance of insulation materials plays a crucial role in minimizing heat loss during extraction. Several studies have investigated optimization parameters for WBHE systems. Sharma et al. (2020) utilized an analytical model to identify vertical well depth, geothermal gradient, and insulation strength as the most influential factors impacting heat recovery. Similarly, Davis and Michaelides (2009) highlighted the importance of bottom-hole temperature and injection pressure for electricity generation from abandoned oil wells in the South Texas region. Furthermore, Cheng et al. (2013) demonstrated the significant role of formation heat transfer in geothermal power generation through a double-pipe WBHE system, observing a gradual decrease in extracted isobutane temperature until reaching a steady state.

4. CONCLUSION

Geothermal energy is one of the clean and renewable energy resources abundant in the earth. Millions of abandoned hydrocarbon wells can be repurposed for geothermal production, offering a cost-efficient method due to the elimination of drilling costs. Relatively shallow wells often suit direct-use applications like district heating, greenhouse heating, and thermal hotels. Conversely, wells with HPHT may possess sufficient heat for electricity generation. Depleted hydrocarbon wells can be utilized by either directly producing hot water from the reservoir or through wellbore heat exchangers. While geothermal brine production offers higher thermal energy recovery, it incurs higher capital and maintenance costs. Parameter analysis demonstrates that recovery rate and utilized temperature are critical factors for optimal thermal recovery. Effective reservoir management also plays a crucial role in such systems. Wellbore heat exchange systems operate as closed loops, minimizing fluid-rock interactions and requiring lower investment and maintenance costs compared to hot brine production. Parameter analysis studies reveal that formation heat transfer, bottom-hole temperature, and well depth significantly influence geothermal production from abandoned oil wells.

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