

GEOTHERMAL HEAT EXTRACTION FROM ABANDONED OIL & GAS WELLS: A REVIEW STUDY

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ABSTRACT

Converting abandoned oil and gas wells into geothermal energy systems offers a valuable opportunity to repurpose existing infrastructure for renewable energy while significantly reducing drilling costs. This analysis examines heat extraction technologies, reservoir modelling, economic feasibility, and environmental impacts of well repurposing designs. Two main technological approaches drive the conversion process. Closed-loop coaxial borehole heat exchangers operate independently of formation permeability, reducing fluid loss and environmental risks while producing moderate thermal output. Open-loop reservoir circulation systems generate higher power outputs, potentially exceeding 2MW per well under optimal conditions, but require permeable geological formations and must address challenges from brine chemistry, mineral scaling, and equipment corrosion. Advanced numerical modelling now provides accurate predictions of long-term thermal performance through transient heat transfer simulations. However, field validation data spanning more than two decades remains limited. Economic evaluations show that well repurposing reduces initial capital requirements by approximately 50% compared to new geothermal drilling while eliminating plugging and abandonment costs. The regional potential is substantial. Over 18,000 abandoned wells across eight U.S. states represent technical capacity exceeding 2,300GW. Nigeria's Niger Delta sedimentary basins show bottom-hole temperatures of 130-170°C, suitable for binary-cycle power generation. Environmentally, repurposing reduces methane emissions from orphaned wells by approximately 90% and eliminates land disturbance from new development sites. Using carbon dioxide as a working fluid enables combined heat extraction and carbon storage, though policy frameworks outside the U.S. and Europe need further development. These findings establish a strong technical and economic foundation for prioritizing well repurposing initiatives globally.

Keywords: abandoned oil wells; geothermal energy; borehole heat exchanger; enhanced geothermal systems; well repurposing; techno-economic analysis; methane emissions.

INTRODUCTION

Geothermal energy stands out as a highly promising renewable energy source because of its distinct advantages: it provides consistent power generation independent of weather patterns, produces minimal greenhouse gas emissions, requires limited surface area for installation, and

offers global accessibility [1],[2]. Unlike solar and wind energy, which face intermittency challenges requiring storage or backup power, geothermal plants achieve capacity factors of 80-90%, providing stable baseload electricity that strengthens grid reliability [3]. The installed global geothermal generating capacity has grown substantially over recent decades, increasing from 1,300MW in 1975 to over 10,700MW by 2010, with projections suggesting geothermal could meet more than 3% of global electricity demand by 2050 [1].

Despite these advantages, geothermal energy remains underutilized relative to its potential. The primary barrier to widespread deployment has been the high upfront investment costs associated with geothermal well drilling [4]. Drilling a geothermal well is time-consuming and expensive, comparable to petroleum well drilling, with costs ranging from \$2-5 million per well depending on depth and geological conditions [5]. Enhanced geothermal systems (EGS), which expand geothermal energy beyond naturally permeable areas by creating artificial fluid pathways in dry or impermeable rock, face even higher costs of approximately \$4,500-\$6,280 per kW of installed capacity. These capital requirements create significant financial risk, particularly during early exploration and confirmation phases [2].

The concept of repurposing abandoned petroleum wells for geothermal energy extraction addresses this barrier directly. By utilizing existing wellbores that have already been drilled, operators can avoid the most expensive and risky phase of geothermal development [1],[6]. This approach transforms environmental liabilities, abandoned wells that require costly plugging and abandonment procedures, into productive renewable energy assets that generate long-term revenue streams [3]. The convergence of these factors has driven growing research interest in repurposing technologies, with studies examining everything from fundamental heat transfer mechanisms to full-scale economic feasibility [3].

Despite the growing interest in repurposing abandoned oil and gas wells for geothermal applications, the available literature remains fragmented, with most studies focusing independently on heat extraction technologies, numerical modelling, techno-economic performance, or environmental sustainability. A comprehensive synthesis integrating these aspects while highlighting current technological advances, implementation challenges, and research gaps remains limited, particularly in the context of mature petroleum provinces such as the Niger Delta. This review therefore critically evaluates the current state of geothermal heat extraction from abandoned oil and gas wells by examining extraction technologies, thermal performance, numerical modelling approaches, techno-economic feasibility, environmental implications, and policy frameworks. The review further identifies existing knowledge gaps and discusses future research directions required to facilitate the large-scale deployment of well repurposing as a sustainable energy solution.

REVIEW METHODOLOGY

This study was conducted as a structured narrative review to synthesize current research on geothermal heat extraction from abandoned oil and gas wells. A systematic literature search was performed using Scopus, Web of Science, ScienceDirect, SpringerLink, OnePetro, Google Scholar, and the SPE Digital Library. The search employed combinations of the keywords "geothermal energy," "abandoned oil and gas wells," "well repurposing," "closed-loop geothermal," "open-loop geothermal," "deep borehole heat exchanger," "organic Rankine cycle," "geothermal modelling," and "depleted reservoirs" using Boolean operators (AND, OR).

Only English-language, peer-reviewed journal articles and conference proceedings published between 2006 and 2025 were considered. Studies were included if they addressed geothermal heat recovery from abandoned or depleted petroleum wells, numerical modelling, thermo-hydraulic performance, techno-economic analysis, environmental impacts, or field applications. Publications lacking sufficient technical detail, duplicate studies, and articles unrelated to well repurposing were excluded.

The selected literature was critically evaluated and synthesized according to four principal themes: (i) geothermal extraction technologies, (ii) numerical modelling and thermal performance, (iii) techno-economic feasibility, and (iv) environmental sustainability and policy perspectives. Emphasis was placed on identifying technological advancements, knowledge gaps, and future research directions relevant to the deployment of geothermal systems in mature petroleum fields.

LITERATURE REVIEW

Geothermal Resource Classification and Utilization

Geothermal energy resources are typically classified based on temperature, which determines their potential applications. High-temperature resources above 150°C are most suitable for electricity generation using conventional steam Rankine cycles, while low-temperature resources below 150°C are typically used for direct heating applications such as space heating, greenhouse warming, aquaculture, and industrial drying [1],[3]. This temperature-based classification is particularly relevant for abandoned well repurposing because most existing petroleum wells are located in sedimentary basins with moderate geothermal gradients of 20-30°C/km, resulting in bottom-hole temperatures typically ranging from 60-120°C at depths of 2-4 km [6]. The distinction between electricity generation and direct-use applications has important economic implications for repurposing projects. While electricity generation commands higher revenue per unit of energy, the lower thermal-to-electric conversion efficiency (typically 8-15% for Organic Rankine Cycles=ORC at low temperatures) reduces overall energy output [7]. Direct-use applications, while generating lower revenue per kWh, achieve much higher utilization of extracted heat and often provide more favourable economics, particularly for district heating networks and greenhouse operations [8].

Enhanced geothermal systems (EGS) represent an important technological development that expands geothermal potential beyond naturally permeable hydrothermal reservoirs. Unlike conventional geothermal, which relies on existing hot water aquifers, EGS creates artificial permeability in hot, dry rock through hydraulic stimulation, enabling heat extraction from previously unusable formations [2]. For repurposed abandoned wells, EGS technology offers the possibility of accessing higher temperatures by deepening existing wells or creating lateral branches, though this adds complexity and cost [9].

Regional Assessments and Resource Mapping

Systematic regional assessments are essential for identifying high-potential repurposing opportunities. A comprehensive GIS-based analysis of eight South and South-western US states revealed that over 18,000 abandoned wells are located in areas with favourable geothermal gradients, overlapping with tribal lands and HUB-Zones in many cases [2]. The technical potential exceeds 2,300GW, though practical potential: considering economic,

regulatory, and technical constraints would be substantially lower. Nevertheless, even capturing a fraction of this potential would make meaningful contributions to renewable energy portfolios [10].

European regional assessments have identified similar opportunities. In Poland, detailed geological modelling of two depleted reservoir formations: the carbonate formation of Viséan age and the Rotliegend sandstone formation, revealed recoverable heat potential of 1.12MW and 23.16MW respectively for water-driven systems over a 50 year operational lifetime [11]. The Rotliegend sandstone formation, with porosity of approximately 18% and good permeability, offers particularly promising conditions for geothermal doublet systems [11]. In Italy, the Villafortuna-Trecate field in Northern Italy represents a geo-pressurized system with reservoir depth of 5,700-6,000 m, maximum temperature of 166°C, and geothermal gradient of 2.8°C/100m, conditions highly favourable for electricity generation [12].

The United Kingdom has also assessed repurposing potential, focusing on the Kirby Misperton gas field in North-East England as a candidate for deep borehole heat exchanger (DBHE) installation [13]. The site-specific analysis incorporated geological conditions, borehole dimensioning, and temperature-dependent material properties to predict thermal performance for commercial greenhouse heating [4]. These regional assessments demonstrate that repurposing opportunities exist across diverse geological settings, though site-specific evaluation remains essential.

Beyond the well-documented assessments and research in the United States and Europe, recent research by Ogunlana *et al* [14] has systematically evaluated geothermal potential in the Niger Delta, Nigeria's premier hydrocarbon province. They stated that the geothermal gradient in the Niger Delta ranges from 1.3 to 5.5°C per 100m, with reservoir temperatures at typical hydrocarbon depths of 3,400-4,700m falling between 130 °C and 150°C. Also, in specific fields such as Amenan-Nono, reservoir pressure ranges from 350 to 500 bar, and porosity averages 15% with permeability reaching several hundred millidarcies (mD), conditions favourable for open-loop geothermal systems. These parameters place the Niger Delta within the medium-enthalpy category, suitable for binary-cycle electricity generation and direct-use applications. Usuolori *et al* [15] further quantified heat-in-place for five representative abandoned wells in the region, obtaining values between 0.0489×10^{15} BTU and 0.0677×10^{15} BTU, confirming that substantial geothermal resources remain unexploited in these mature petroleum basins.

Beyond the Niger Delta, multiple geothermal anomalies which are across several sedimentary basins and basement complexes are being possessed by Nigeria. Anele *et al* [16] systematically mapped Nigeria's geothermal energy zones, identifying prospective areas such as the Benue Trough, Sokoto Basin, Bida Basin, and parts of the Basement Complex in Ondo, Ekiti, Edo, Osun, Kogi, and Delta State, and surface manifestations which include the Ikogosi Warm Spring (South-West Nigeria), Wikki Warm Spring (Bauchi State), and other thermal springs in Adamawa and Nasarawa States, with temperatures ranging from 37°C to 54°C. Anele *et al* [16] also stated how aeromagnetic studies have revealed high heat flow and geothermal gradients exceeding 35°C/km in parts of the Upper Benue Trough, as well as shallow Curie point depths indicating anomalous thermal regimes suitable for low- to medium-enthalpy geothermal development. However, Anele *et al* [16] also noted that most subsurface temperature data are derived from oil and gas exploration without Horner corrections, potentially underestimating true formation temperatures by 10-20°C. This

national-scale assessment confirms that Nigeria's geothermal potential extends well beyond the Niger Delta, though systematic exploration remains limited.

Screening and Selection Criteria for Candidate Wells

Not all abandoned wells are suitable for geothermal repurposing. Research has identified several critical selection criteria that determine technical and economic feasibility [15]. Well depth is paramount, with most studies suggesting minimum depths of 2,000-3,000m to achieve sufficient bottom-hole temperatures [1],[3]. Geothermal gradient is equally important, with gradients above 25°C/km generally preferred. Well integrity is another critical factor; wells with documented casing corrosion, cement failure, or gas migration pathways may require extensive remediation that undermines economic viability [2].

Systematic screening frameworks have been developed to prioritize candidate wells. One approach uses geo-statistical sequential simulations to model petrophysical properties, updating models with historical production data before validation and forecasting [17]. The Volve field case study demonstrated that well location was the dominant parameter influencing geothermal energy production, highlighting the importance of spatial positioning relative to thermal reservoirs. Machine learning methods, including generalized c-means (GFCM) clustering analysis, have been applied to identify plays with greatest geothermal potential by integrating porosity, permeability, and recoverable heat data [11].

The distinction between completely abandoned wells and semi-abandoned wells (those still operational but with high water cut) is particularly important for prioritization. Multi-criteria decision analysis comparing four geothermal power systems found that repurposing semi-abandoned wells (R-GEOsemi) represented the most techno-sustainable option, excelling across environmental, economic, and social dimensions [18]. This finding suggests that proactive repurposing, converting wells before complete abandonment, may offer advantages over reactive repurposing of already-plugged wells [19].

Quantitative screening of abandoned wells in the Niger Delta has established clear thermal thresholds for economic viability. Izuwa *et al* [20] analysed four wells (AX-2, AX-3, AX-5 and AX-7) in the Asa-2 field, with depths ranging from 9,890ft to 11,800ft (approximately 3,014-3,597m), and reservoir temperature was modelled at 170°C, with wellhead temperatures between 161.4°C and 197.2°C. Also, the total geothermal heat resource was estimated at 2.45×10^{12} J, of which recoverable heat depends on separator and sink temperatures. Crucially, the study by Izuwa *et al* [20] demonstrated that wellhead temperature is a critical screening parameter, as heat losses during ascent can reduce usable enthalpy by 15-30%. For wells with wellhead temperatures below 160°C, binary-cycle systems using organic working fluids (e.g., R134a, R245fa) become more appropriate than single-flash turbines, aligning with findings from Cheng *et al* [21] on minimum depth requirements of 3,000m for economically viable power generation.

Heat Extraction Technologies

Closed-Loop Systems: Coaxial Borehole Heat Exchangers

Closed-loop systems represent the most extensively studied technological approach for repurposing abandoned wells for geothermal energy extraction [1],[2]. In a closed-loop configuration, a single abandoned well is retrofitted with a heat exchanger that circulates working fluid through the wellbore without contacting formation fluids. The most common design is the coaxial borehole heat exchanger (CBHE), also referred to as a double-pipe heat

exchanger, which consists of a central tube of smaller diameter suspended inside the existing well casing [1]. Cold working fluid is pumped downward through either the annulus or the central pipe, absorbing heat conductively from the surrounding rock formation, and returns to the surface at elevated temperature [22].

The coaxial design offers several distinct advantages. First, no formation fluids are produced, eliminating concerns about groundwater contamination, corrosion, and scaling that plague open-loop systems [1],[7]. Second, closed-loop systems do not require permeable formations, making them suitable for wells in any geological setting where a sufficient temperature gradient exists [2],[8]. Third, the environmental footprint is minimal, as the system operates as a sealed circuit without fluid injection or production [6]. These advantages have made closed-loop systems the preferred option for many repurposing projects, particularly in regions with complex hydrogeology or stringent environmental regulations [23]. The thermal performance of coaxial borehole heat exchangers depends on several key parameters identified through numerical modelling and experimental studies. Working fluid flow rate significantly influences heat extraction; higher flow rates increase heat transfer but also increase pressure drop and reduce outlet temperature [1],[7]. Inlet temperature affects thermal driving force; lower inlet temperatures increase heat extraction but may require cooling or heat rejection systems at the surface [1]. The thermal conductivity of the formation material is a critical parameter; sedimentary rocks with thermal conductivity of 1-3W/m.K provide much lower heat transfer rates than igneous or metamorphic rocks [7]. Insulation of the inner pipe is essential to prevent thermal short-circuiting, where heat transfers from rising warm fluid to descending cold fluid, reducing overall efficiency [1],[7].

Numerical simulations have been extensively applied to predict closed-loop system performance. Kujawa *et al* [24] developed computational temperature models to determine geothermal heat flux from double-pipe heat exchangers, considering three insulation scenarios: perfectly insulated pipe, air-gap insulation, and polyurethane foam insulation. Their calculations demonstrated that lower inlet temperatures and higher flow rates increase thermal power output, though these parameters must be optimized to avoid excessive pressure drops. Davis and Michaelides [10] estimated geothermal power production from abandoned wells in South Texas using isobutene as the working fluid, assuming high geothermal gradients and 1-inch-thick polystyrene insulation. Their calculations suggested that such wells could produce more than 3MW of thermal power when bottom-hole temperature reaches approximately 450K and injection pressure is 30 bars.

Bu *et al* [25] developed a mathematical model describing heat exchange between fluids and rocks, solved numerically using the tri-diagonal matrix algorithm. Unlike the model developed by [10], which included mass conservation, the model developed by [25] assumes heat transfer occurs without mass transfer underground. Their analysis demonstrated that energy production from abandoned petroleum wells depends greatly on fluid flow rate and geothermal gradient, with outlet temperature showing minimal variation over circulation time. Long-term sustainability of closed-loop heat extraction is a critical consideration for project economics. Ghoreishi-Madiseh *et al* [9] determined that sustainable heat extraction depends on the balance between extraction rate and natural replenishment of geothermal heat in the reservoir. If extraction exceeds replenishment, thermal drawdown occurs, reducing outlet temperatures over time. Their simulations suggest that after approximately 300 days of continuous operation, systems enter a stable production phase with outlet temperature

changing slowly thereafter [7]. Over 20-30 years project lifetimes, closed-loop systems retain 60-80% of initial thermal output, though field validation beyond 20 years remains limited [7],[11].

Open-Loop Systems: Reservoir Circulation

Open-loop systems utilize the oil or gas reservoir itself as a geothermal heat exchanger [1],[6]. In this configuration, at least two wells are required: an injection well to pump cold working fluid into the reservoir and a production well to extract heated fluid after it has circulated through the reservoir rock [7]. The working fluid, typically water or a water-based solution flows through permeable reservoir formations, gaining heat from the surrounding rock mass before being produced back to the surface. Open-loop systems are directly analogous to conventional geothermal doublet systems, adapted to depleted petroleum reservoirs [26].

The primary advantage of open-loop systems is their much higher thermal output compared to closed-loop designs. While closed-loop systems typically produce 50-200kW of thermal power per well, open-loop systems can achieve 500-2,000kW or more, depending on reservoir permeability, thickness, and temperature [1]. This higher output makes open-loop systems more suitable for electricity generation applications, where scale is necessary to achieve economic viability. Additionally, open-loop systems benefit from convective heat transfer within the reservoir, which can enhance heat exchange compared to the purely conductive heat transfer of closed-loop systems [7].

However, open-loop systems face several significant challenges. Reservoir permeability is the critical limiting factor; many depleted oil and gas reservoirs have low permeability due to formation damage, fine migration, or compaction during production [11]. In such cases, permeability enhancement techniques, including hydraulic fracturing, acid stimulation, or hydro-shearing, may be required, adding substantial cost [7],[11]. Fluid chemistry is another major concern; produced brines often contain high total dissolved solids (up to 300,000ppm), dissolved gases including H₂S and CO₂, and scaling-prone minerals such as calcite and silica [6]. These issues can lead to corrosion, scaling, and wellbore plugging, increasing operating costs and reducing system reliability.

Research such as that done by Ojaghi *et al* [7] on open-loop repurposing has focused on reservoir characterization and thermal performance prediction. For the Volve field in the North Sea, geo-statistical sequential simulations incorporating petrophysical properties and historical production data predicted average annual geothermal production of 2,094MWh, totalling approximately 41,877MWh over a 20-year operational period [7]. The study identified well location as the dominant parameter influencing energy production, underscoring the importance of spatial positioning relative to thermal reservoirs.

In Poland, two depleted reservoirs were evaluated by Topor *et al* [11] for open-loop geothermal potential using advanced modelling techniques. The Visean carbonate formation, with porosity of 2.7-4.3% and permeability of 25.8-27.1mD, yielded recoverable heat (H_{rec}) values of approximately 1.12MW for water-driven systems over a 50 year lifetime. The Rotliegend sandstone formation, with much higher porosity (approximately 18%) and better permeability, achieved H_{rec} of 23.16MW using water as the working fluid, more than 20 times higher than the carbonate formation [11]. When CO₂ was used as the working fluid, recoverable heat dropped to 0.26 MW for the Visean formation and 4.36MW for the Rotliegend, indicating that water-driven systems are significantly more efficient for these

reservoir types [11]. The study compared water and CO₂ as working fluids in open-loop geothermal systems, finding that water-driven systems were over four times more efficient in the Visean carbonate formation and over five times more efficient in the Rotliegend sandstone formation. However, CO₂-driven systems offer the advantage of coupling geothermal energy extraction with carbon capture and storage, potentially offsetting operational costs through carbon credits or tax benefits [3].

Hybrid and Emerging Technologies

Hybrid systems combining features of both closed-loop and open-loop approaches have been proposed to optimize performance for specific geological conditions. One promising concept is the deep U-shape borehole heat exchanger, which creates an underground connection between two wellbores without relying on natural reservoir permeability [7]. This configuration maintains the closed-loop advantage of no fluid loss while providing greater surface area for heat exchange than a single coaxial wellbore. Numerical modelling of deep U-shape systems suggests that fluid circulation within the reservoir may enhance heat exchange over long-term simulations, particularly in porous or fractured media where convection supplements conduction.

Another hybrid approach is integrating geothermal extraction with continued hydrocarbon production from wells approaching end of life. Repurposing semi-abandoned wells, those still operational but with high water cut, has been identified as the most techno-sustainable option in multi-criteria decision analysis. Li *et al* [18] discovered that these semi-abandoned wells offer several advantages such as retaining production infrastructure and reservoir access, maintaining formation pressure and permeability, and generating revenue during the transition from hydrocarbon to geothermal production. Riddick *et al* [27] found that the R-GEOsemi configuration was found to excel across environmental, economic, and social dimensions, though it faces challenges due to limited power generation capacity and the finite availability of wells approaching end-of-life.

Topór *et al* [11] proposed in-situ combustion as a method to enhance geothermal extraction from abandoned wells by increasing reservoir temperature through controlled oxidation of residual hydrocarbons. While this approach could potentially achieve higher temperatures suitable for electricity generation, it raises significant environmental concerns regarding air emissions, subsurface contamination, and combustion product management. Similarly, the use of horizontal wells or multi-branch laterals has been suggested by Liu *et al* [6] to increase heat exchange surface area and improve thermal output. However, these advanced configurations add substantial drilling and completion costs that may undermine the economic advantage of repurposing.

Usuolori *et al* [15] conducted a direct quantitative comparison of working fluids in Niger Delta wells using TOUGH2 simulations with an inverted five-spot pattern (one central injector, four edge producers). For five abandoned wells, between 2.01×10^{11} BTU/day and 3.96×10^{11} BTU/day was extracted using superficial CO₂, while only 3.08×10^{10} BTU/day to 3.76×10^{10} BTU/day was extracted using water vapour, a difference of one order of magnitude approximately. Additionally, a lower heat loss of about $1.41\text{--}2.2 \times 10^5$ BTU was exhibited using CO₂ when compared $1.42\text{--}2.3 \times 10^5$ BTU heat loss while using water vapour. This advantage was as a results of the high thermal conductivity, low viscosity in superficial state, and superior heat transfer coefficient when operating at the near critical point of CO₂. It was concluded by Usuolori *et al* [15] CO₂-based repurposing not only improves heat extraction

efficiency but also helps to enable potential carbon sequestration in a Niger Delta sandstone formation with permeability exceeding 200mD, and at the same time offers a dual-benefit system that water-based open-loop designs cannot provide.

Table 1 summarizes the principal characteristics of the three geothermal extraction approaches. Closed-loop systems offer superior operational safety and broader geological applicability because they operate independently of reservoir permeability, whereas open-loop systems generally achieve greater thermal recovery by directly circulating formation fluids. Hybrid concepts seek to combine the advantages of both approaches but remain at relatively early stages of technological development.

Table 1. Comparison of Geothermal Heat Extraction Technologies

Parameter	Closed-loop	Open-loop	Hybrid Systems
Working fluid	Water, CO ₂ , refrigerants	Formation water/brine	Water and CO ₂ combinations
Reservoir permeability	Not required	Essential	Moderate
Heat extraction	Conduction	Conduction + convection	Combined
Electricity generation	Moderate	High	High
Reservoir depletion	None	Possible	Limited
Scaling potential	Very low	Moderate to high	Moderate
Induced seismicity	Negligible	Low to moderate	Low
Well integrity requirement	Moderate	High	High
Capital cost	Moderate	Higher	Higher
Suitable formations	Any competent formation	High-permeability reservoirs	Deep mature reservoirs
Main advantage	Low environmental risk	Higher thermal recovery	Improved efficiency
Major limitation	Lower thermal output	Reservoir dependence	Higher complexity

Reservoir Modelling and Performance Prediction

Mathematical Formulation of Heat Transfer in Wellbores

Accurate prediction of thermal performance is essential for evaluating the feasibility and economics of repurposing abandoned wells for geothermal energy extraction. The governing physics of heat transfer in wellbore-formation systems involves coupled conductive, convective, and advective processes that must be represented mathematically to enable quantitative prediction [1].

The transient heat equation for a cylindrical wellbore-formation system describes the temperature distribution as a function of space and time:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + q_{conv} \quad (1)$$

where: ρ is density; c_p is specific heat capacity; T is temperature; t is time; r is radial coordinate; z is vertical coordinate; k is thermal conductivity; q_{conv} is convective heat transfer contributions [1].

For fluid flowing within the wellbore pipe, advection dominates over conduction in the axial direction, leading to a simplified formulation:

$$\rho_f c_{p_f} \left(\frac{\partial T_f}{\partial t} + u \frac{\partial T_f}{\partial z} \right) = \frac{2}{r_{pipe}} U (T_{wall} - T_f) \quad (2)$$

where: u is fluid velocity; r_{pipe} is pipe radius; U is the overall heat transfer coefficient through casing, cement, and any insulation; T_{wall} is the temperature at the pipe-formation interface [1].

These governing equations must be solved numerically for realistic wellbore geometries and heterogeneous formation properties. The overall heat transfer coefficient U is a composite parameter that integrates thermal resistances from multiple components: convection at the inner pipe surface ($R_{conv_{inner}}$), conduction through the pipe wall (R_{pipe}), convection in the annulus ($R_{annulus}$), conduction through the outer pipe and cement (R_{outer}), and conduction into the formation ($R_{formation}$) [7]. The dominant resistance typically is formation conduction ($R_{formation}$), as sedimentary rocks have relatively low thermal conductivity of 1-3 W/m.K compared to steel casing at approximately 45 W/m.K.

Numerical Simulation Approaches and Tools

Numerical simulation is essential for predicting long-term thermal performance of repurposed wells because analytical solutions cannot adequately represent the complex geometry, heterogeneous properties, and transient boundary conditions characteristic of real-world applications [11]. Several numerical approaches have been developed and validated against field data.

Finite difference methods have been widely applied due to their relative simplicity and computational efficiency. Bu *et al* [25] developed a finite difference model using the tri-diagonal matrix algorithm to solve heat exchange between fluids and rocks, assuming that heat transfer occurs without mass transfer in the underground system. Their model demonstrated that energy production depends significantly on fluid flow rate and geothermal gradient, with outlet temperature showing minimal variation over circulation time. Finite element methods offer greater flexibility for complex geometries and are implemented in commercial software packages including COMSOL Multi-physics and ANSYS Fluent. Templeton *et al* [28] used Fourier's three-dimensional heat equation with finite-element software (FlexPDE) to examine heat extraction from abandoned wells equipped with heat exchangers, estimating that a typical well could produce approximately 80kW of thermal power. Their parametric analysis identified optimal inflow temperature and mass flow rate for maximizing heat extraction.

Finite volume methods, implemented in computational fluid dynamics software, have been applied to U-tube heat exchanger simulations in abandoned wells. Ghoreishi-Madiseh *et al* [9] used finite volume discretization to solve mass, energy, and momentum conservation equations, determining that natural convection can be neglected if the thermal conductivity of the heat exchange medium is below a specific threshold. They identified thermal and hydraulic conductivity as the most important parameters affecting U-tube heat exchanger performance.

Specialized geothermal simulation tools have also been applied to repurposed well modelling. TOUGH2, a well-established reservoir simulator for multiphase fluid and heat flow, has been used to assess both open-loop and closed-loop configurations [29]. OpenGeoSys, an open-

source platform for thermo-hydro-mechanical (THM) modelling, offers capabilities for coupled process simulation [30]. The choice of simulation tool depends on the specific application; closed-loop systems may be adequately modelled with simpler heat transfer codes, while open-loop systems with multiphase flow require more sophisticated reservoir simulators [11].

Long-Term Thermal Drawdown Predictions

The sustainability of geothermal heat extraction over multi-decade project lifetimes is a critical concern for investors and operators. Thermal drawdown, the reduction in outlet temperature over time as heat is extracted faster than it can be replenished by natural processes, determines the economic viability of repurposing projects [31]. If drawdown is excessive, the system may become uneconomic well before the end of its planned operational life.

Numerical simulations of long-term thermal performance suggest that closed-loop systems are relatively stable over 20-30 years time horizons. Ghoreishi-Madiseh *et al* [9] determined that sustainable heat extraction depends on the balance between extraction rate and natural replenishment of geothermal heat in the reservoir. When extraction exceeds replenishment, drawdown occurs, but the system tends toward a new equilibrium as temperature gradients adjust [7]. For typical sedimentary basin conditions, closed-loop systems retain 60-80% of initial thermal output after 30 years of continuous operation [11].

Open-loop systems generally experience more rapid thermal drawdown because produced fluids directly remove heat from the reservoir. In the Volve field case study, production of 2,094 MWh annually over 20 years was predicted to result in measurable temperature decline, though the magnitude of drawdown depended significantly on well placement and injection-production well spacing [7]. The Polish reservoir study by [11] evaluated recoverable heat (H_{rec}) over a 50-year lifetime, finding that carbonated formations with moderate permeability could sustain approximately 1.12 MW of thermal output, while sandstone formations with good permeability could sustain 23.16 MW.

The time to reach thermal stabilization is another important parameter. Cheng *et al* [32] determined that outlet temperature decreases with time and stabilizes as the system approaches thermal equilibrium. The stabilization time can be reduced by increasing formation thermal conductivity or decreasing fluid inlet velocity, while formation heat capacity has a minor effect. For most closed-loop systems, stabilization occurs within approximately 300 days of continuous operation, after which outlet temperature changes slowly [7].

Uncertainty Characterization and Model Validation

Uncertainty in thermal performance predictions arises from multiple sources, including incomplete knowledge of formation properties, boundary conditions, and operational parameters. Systematic approaches to uncertainty characterization are essential for credible project evaluation [11].

Formation thermal conductivity is a primary source of uncertainty. Sedimentary rock conductivity can vary by a factor of two or more over short distances due to lithological heterogeneity, porosity variations, and fluid saturation [33]. Geothermal gradient is also uncertain, particularly when bottom-hole temperatures from drilling logs are used without Horner plot corrections for mud circulation cooling [34]. Uncorrected temperatures can be 10-

20°C lower than true formation temperatures, leading to substantial underestimation of geothermal potential [7].

Geo-statistical methods have been applied to characterize and propagate uncertainty in thermal performance predictions. For the Volve field, sequential simulations were used to generate multiple realizations of petrophysical properties, with each realization updated to align with historical production data before validation and forecasting [35]. This approach quantifies uncertainty arising from spatial heterogeneity and data limitations. Similarly, the Polish reservoir study used generalized c-means (GFCM) clustering to identify areas with highest geothermal potential, with clustering results tested against multiple parameter combinations to ensure robustness [11].

Model validation against field data remains limited due to the small number of operational repurposed wells. The longest-running installation, at Neustadt-Glewe in Germany, has operated for over 20 years, providing valuable validation data for closed-loop thermal models. However, most model predictions have not been rigorously validated against long-term field measurements, representing a significant gap in the literature [2].

Beyond geological uncertainties, predictive accuracy is also influenced by assumptions adopted during numerical modelling (Table 2). Many studies assume homogeneous reservoir properties, constant geothermal gradients, ideal thermal contact between the wellbore and surrounding formations, and steady operating conditions [36],[37]. However, actual reservoirs are inherently heterogeneous and exhibit temporal variations in thermal, hydraulic, and mechanical properties [38]. Consequently, uncertainty quantification should incorporate both geological variability and modelling assumptions through sensitivity analyses, probabilistic simulations, and field calibration wherever operational data are available. Such approaches improve confidence in long-term performance predictions and reduce investment risks associated with geothermal well repurposing [39].

Table 2. Summary of numerical modelling approaches

Model	Main Application	Strength	Limitation
Finite Difference	Reservoir heat transfer	Computational efficiency	Simplified geometry
Finite Element	Coupled thermo-mechanical analysis	High accuracy	Computationally intensive
CFD	Wellbore heat transfer	Detailed fluid dynamics	High computational cost
OpenGeoSys	THMC simulations	Fully coupled processes	Requires extensive input data
COMSOL Multiphysics	Integrated thermal modelling	Flexible multiphysics coupling	Commercial software

Although numerical simulations consistently demonstrate the technical feasibility of geothermal heat extraction from abandoned wells, validation using long-term operational data remains limited. Existing demonstration projects are relatively few and are largely concentrated in Europe and North America. Consequently, many published models have not been comprehensively validated over the projected operational lifespan of 20–30 years. Future research should prioritize instrumented pilot projects capable of monitoring thermal decline, reservoir behaviour, well integrity, and economic performance under continuous

operating conditions. Such field-scale validation is essential for improving predictive models, reducing uncertainty, and accelerating commercial deployment.

No single modelling approach is universally applicable. Model selection depends primarily on the study objective, computational resources, geological complexity, and the degree of thermo-hydro-mechanical coupling required. Consequently, simplified analytical models remain useful for preliminary feasibility assessments, whereas fully coupled numerical simulators are better suited for detailed reservoir-scale investigations.

Techno-Economic Analysis

Cost Structure and Capital Investment

The economic case for repurposing abandoned wells for geothermal energy rests on avoiding the most expensive components of conventional geothermal development: exploration and drilling [18]. Conventional geothermal wells cost \$2-5 million each, depending on depth and geological conditions, with exploration adding substantial risk and cost [2]. By utilizing existing wellbores, repurposing reduces upfront capital requirements by approximately 50% or more [1]. The cost structure of repurposed systems differs significantly from new drilling. For closed-loop configurations (Table 3), major cost components include well integrity assessment (\$30,000-\$100,000), downhole heat exchanger installation (\$100,000-\$300,000), surface ORC or heat exchange equipment (\$400,000-\$600,000 for 100kW scale), and well remediation if needed (\$50,000-\$150,000) [7]. For open-loop systems, additional costs include injection well preparation, fluid treatment systems, and reinjection infrastructure [11].

Table 3. Comparative techno-economic characteristics of geothermal well repurposing systems

Parameter	Closed-loop	Open-loop
Initial capital cost	Moderate	High
Drilling cost	Eliminated	Eliminated
Additional infrastructure	Heat exchanger	Injection and production facilities
Reservoir permeability requirement	No	Yes
Operating cost	Low	Moderate
Maintenance	Low	Moderate to High
Thermal recovery	Moderate	High
Environmental risk	Low	Moderate
Economic uncertainty	Low	Moderate
Typical application	Low-permeability formations	High-permeability reservoirs

The avoided cost of well plugging and abandonment is an important economic consideration that is often overlooked. Abandoning a well cost \$20,000-\$150,000 depending on well depth, condition, and regulatory requirements [2],[3]. By repurposing rather than abandoning, operators avoid these costs while generating revenue from geothermal production, a double economic benefit. Some regulatory frameworks allow operators to apply planned abandonment funds toward repurposing investments, improving project economics [3].

Enhanced geothermal systems (EGS) for repurposed wells have higher capital costs than conventional repurposing due to the need for reservoir stimulation. EGS costs range from

\$4,500-\$6,280 per kW of installed capacity, compared to \$3,000-\$5,000 per kW for conventional geothermal [3]. However, EGS can access higher temperatures by deepening existing wells or creating lateral branches, potentially increasing power output and improving economics in suitable geological settings [7].

In Nigeria where wellhead temperatures is within the range of 100°C-150°C, the ORC systems are considered more appropriate than conventional steam turbines. A binary-cycle system which used n-pentane as its working fluid was designed by [40] for three abandoned wells (wells X, Y, and YS-2) in Eleme area of Rivers State, and for well YS-2, at a depth of 3,219m and bottom-hole temperature of 85°C, a thermal efficiency of 76.2% and a net power of approximately 1.5MW per well was achieved by the system. This study portrayed that even at a temperature of below 100°C, moderately warm wells can generate electricity that are commercially viable when they are paired with organic fluid selected appropriately. [40] Furthermore estimated while highlighting the decentralised energy access potential of well repurposing in rural Niger Delta areas, that two to three of such repurposed wells could meet the demand of electricity at Eleme community and its environs.

The economic attractiveness of repurposing abandoned wells depends largely on reservoir characteristics, existing infrastructure, and intended energy utilization. Closed-loop systems generally require lower operating costs and present reduced environmental risks, whereas open-loop systems can achieve higher energy recovery where reservoir permeability and fluid chemistry are favourable. Consequently, project-specific techno-economic assessments remain essential for selecting the most appropriate development strategy.

Policy Incentives and Financial Support

Several policy mechanisms have been established to support repurposing abandoned wells for geothermal energy. In the United States, the Inflation Reduction Act provides technology-neutral clean energy tax credits: the Clean Electricity Production Credit offers \$0.003-\$0.015 per kWh of electricity produced, while the Clean Electricity Investment Credit provides 6-30% tax credit for qualifying investments. The Bipartisan Infrastructure Law allocates \$4.7 billion for orphaned well site plugging, remediation, and restoration, including funds that can be applied to repurposing projects [3].

The Indian Energy Purchase Preference (IEPP), finally implemented in 2024 after being authorized in 2005, gives preference to Native American tribe-produced energy for federal agencies. This creates a guaranteed market for geothermal energy produced on tribal lands, many of which overlap with high-potential geothermal resources. The HUB-Zone program provides economic development incentives for designated underutilized areas, and geothermal development qualifies for HUB-Zone benefits [3]. The National Energy Emergency Act signed in 2025 declares a national energy emergency and explicitly lists geothermal as a key energy resource to be cultivated. This executive action authorizes agencies to expedite energy and infrastructure projects, potentially accelerating permitting and reducing regulatory delays for repurposing projects. European policy support varies by country but generally includes renewable energy feed-in tariffs, carbon credits, and research funding for geothermal demonstration projects. The European Union's Renewable Energy Directive sets binding targets that encourage member states to develop domestic renewable resources, including geothermal. The push for energy independence following geopolitical disruptions has intensified interest in domestic geothermal, with repurposed wells offering a rapid-deployment option [11].

Nigeria in contrast to the United States and Europe currently lacks dedicated policy background for geothermal energy from abandoned wells. Anele *et al* [16] in their study identified nine major obstacles to achieving this policy framework: inadequate geothermal resource data, expensive drilling (specialised geothermal tools must be imported), low human capacity in geothermal science, absence of geothermal-specific feed-in tariffs or licensing processes, weak institutional coordination between energy and environmental ministries, insufficient transmission infrastructure near potential sites, limited financing for long-payback projects, low public awareness, and competition from natural gas. Subsequently, no commercial geothermal repurposing project has yet been commissioned in the Niger Delta despite the technically favourable conditions. Correspondingly, Anele *et al* [16] recommended a five-pillar strategy: (1) systematic geothermal exploration programmes (magnetotelluric surveys, temperature-gradient drilling); (2) capacity building through university curricula and international partnerships; (3) government-led risk-sharing mechanisms for initial test wells; (4) a dedicated Geothermal Policy and Legal Framework with import duty waivers, tax holidays, and standardised power purchase agreements; and (5) integration of geothermal into the National Renewable Energy and Energy Efficiency Policy (NREEEP). Deprived of these actions, the technical prospective recognised in Nigerian regional assessments will persistently remain unutilized.

Despite favourable geothermal gradients and the large inventory of mature and abandoned petroleum wells in the Niger Delta, commercial implementation remains constrained by limited subsurface temperature datasets, inadequate geothermal exploration programmes, and the absence of dedicated regulatory frameworks. Establishing demonstration projects through collaboration among government agencies, academia, and industry would provide valuable operational data while reducing investor uncertainty. Such pilot projects could serve as a foundation for integrating geothermal energy into Nigeria's long-term energy diversification strategy.

Regional Economic Potential and Case Studies

The United States regional assessment identified promising geothermal sites overlapping with tribal lands, HUB-Zones, and existing fossil fuel infrastructure across eight states: Arizona, New Mexico, Texas, Louisiana, Mississippi, Nevada, Arkansas, and Oklahoma. These states have at least a technical potential exceeding 2,300GW with over 18,000 abandoned wells available for conversion [3]. The concentration of abandoned wells in these states, combined with favourable geothermal gradients and existing transmission infrastructure, creates attractive opportunities for repurposing projects.

The Villafortuna-Trecate field in Northern Italy represents one of the most promising repurposing opportunities in Europe [6]. With reservoir depth of 5,700-6,000m, maximum temperature of 166°C, and geothermal gradient of 2.8°C/100 m, the field offers conditions highly favourable for electricity generation. The geo-pressurized nature of the reservoir (approximately 300bar overpressure) allows production without pumping activity, reducing operating costs. With over 50 wells drilled historically and 8 active wells currently available, the field could deliver approximately 5.5MW of thermal power per well, with total available power of 44MW from eight wells [6].

The Polish reservoir assessment evaluated two formations with contrasting characteristics. The Rotliegend sandstone formation, with porosity of approximately 18%, good permeability, and abundant wells, achieved H_{rec} of 23.16MW for water-driven systems over a 50-year

lifetime. The Visean carbonate formation, with lower porosity (2.7-4.3%) and permeability (25.8-27.1mD), achieved H_{rec} of 1.12MW [11]. Both formations have wells that can be adapted for geothermal production, though the carbonate formation may require permeability enhancement techniques to improve reservoir properties [11].

The Kirby Misperton gas field in North-East England has been evaluated for deep borehole heat exchanger (DBHE) installation to supply geothermal heat to commercial greenhouses [8]. The study incorporated site-specific geology, borehole dimensioning, and temperature-dependent material properties in a dual-continuum numerical model implemented in MATLAB®. Greenhouse energy modelling using Hortinergy® determined that repurposing the well could meet annual heating demands of a commercial-scale greenhouse, displace natural gas and reducing carbon emissions [8].

Environmental Impacts and Sustainability

Methane Emission Reduction from Abandoned Wells

Abandoned oil and gas wells represent a significant source of methane emissions, a potent greenhouse gas with a global warming potential 28 times greater than CO₂ over a 100-year timeframe [35]. Methane emissions from orphaned and abandoned wells have historically been neglected in regulatory oversight, yet they contribute meaningfully to global greenhouse gas concentrations [41]. Research such as that done by Ibukun *et al* [42] has shown that a small fraction of wells; those with sustained casing pressure or compromised integrity, produce the majority of emissions, but no methodology existed to identify heavy emitters without visiting each well individually.

Recent advances in detection methodology have improved the ability to quantify and characterize methane emissions from abandoned wells. A comprehensive study tested five methods for measuring emissions of 1 g CH₄/hour to within ±20% accuracy, as required by Federal Orphaned Wells Program guidelines and American Carbon Registry protocols [43]. Dynamic chambers achieved accuracy of +0.9%, mobile chambers achieved -1.4%, Gaussian plume approach achieved -2.6%, and Hi-Flow sampler achieved +2.2%, all meeting the required standards. Importantly, a collapsible chamber can be easily constructed around emission sources on abandoned wells in remote areas, enabling low-cost measurement campaigns [43].

Integration of UAV aeromagnetic mapping with terrestrial methane emissions surveys has emerged as a powerful approach for prioritizing well remediation and repurposing activities. Emitting wells have defined characteristics pertaining to the presence and integrity of metal casing to the surface, which can be distinguished as an organized high-intensity magnetic anomaly in low-altitude UAV-based aeromagnetic surveys. This methodology allows initial prioritization of well sites for subsequent remediation activities before committing to detailed on-site measurements [44].

Repurposing abandoned wells for geothermal energy directly addresses methane emissions by requiring well integrity remediation as part of the conversion process [2]. The re-cementing and casing repair needed for geothermal operations seal annuli more effectively than standard plugging, reducing methane leakage by approximately 90% compared to abandonment. Each repurposed well avoids approximately 2 tons of CO₂-equivalent emissions annually, providing climate benefits beyond those from renewable energy generation [2].

Lifecycle Greenhouse Gas Emissions

Complete lifecycle assessment (LCA) of repurposed geothermal systems consistently demonstrates substantial greenhouse gas emissions reductions compared to fossil alternatives. Emissions from repurposed closed-loop systems range from 10-15g CO₂-eq/kWh, while repurposed open-loop systems range from 15-25g CO₂-eq/kWh. New geothermal wells produce 15-30 g CO₂-eq/kWh, natural gas heating produces 200-250g CO₂-eq/kWh, and coal electricity produces 800-1,000g CO₂-eq/kWh [18]. The emissions reduction from repurposing compared to new drilling is primarily due to avoided diesel consumption for drilling and construction. Li *et al* [18] found that repurposing reduces climate change potential by 34% compared to drilling new geothermal wells, due to reduced diesel consumption during the construction phase. The total emissions reduction across all phases (construction, operation, decommissioning) reaches 90-95% compared to fossil alternatives. When carbon capture and storage (CCS) is integrated with geothermal repurposing using CO₂ as the working fluid, the system can achieve negative emissions by permanently sequestering CO₂ while producing energy [11]. The Polish reservoir study evaluated CO₂-driven geothermal systems in depleted reservoirs, finding that while heat recovery was lower than water-driven systems (4.36MW versus 23.16MW for the Rotliegend formation), the combined geothermal-CCS system could offset operational costs through carbon credits [11].

Land Use and Surface Footprint

Geothermal energy, particularly repurposed well systems, has a significantly smaller surface footprint compared to other renewable energy sources. New geothermal fields require 2-5 acres per MW for well pads and piping [19]. Repurposing uses existing well pads, potentially eliminating greenfield land disturbance entirely [19]. Over 1,000 repurposed wells, this saves 2,000-5,000 acres of habitat compared to new geothermal development, and more compared to solar or wind farms that require substantially larger land areas per MW [3]. The avoidance of new drilling also reduces surface disturbance from access roads, drilling pads, and pipeline construction. In sensitive ecosystems or areas with competing land uses, this reduction in surface footprint may be a decisive advantage for repurposing projects [3],[8].

Induced Seismicity and Other Environmental Risks

Induced seismicity is a concern for geothermal projects that inject fluids into subsurface formations. Conventional geothermal projects have triggered micro-seismicity ($M < 2.0$) during hydraulic stimulation and injection operations. However, repurposed wells generally operate with lower injection rates (10-50m³/h) compared to dedicated enhanced geothermal systems, and injection typically occurs into depleted reservoirs with lower pore pressure, reducing seismogenic potential [19].

Closed-loop systems pose negligible seismic risk as they do not involve fluid injection or production from formations [7],[18]. The sealed circuit circulates working fluid without net loss or gain, eliminating pressure changes that could trigger seismic events. This makes closed-loop repurposing particularly attractive in areas with seismic sensitivity or regulatory concerns [7].

Fluid chemistry and disposal present environmental challenges for open-loop systems. Produced brines often contain high total dissolved solids, dissolved gases including H₂S and CO₂, and heavy metals [1],[11]. Spills or leaks of produced fluids could contaminate soil and

water resources, requiring careful management and monitoring. Reinjection into suitable formations is standard practice, but long-term containment must be assured [11].

The long-term sustainability of geothermal well repurposing ultimately depends on maintaining well integrity throughout the operational life of the project. Age-related casing corrosion, cement degradation, thermal cycling, mineral scaling, and changes in reservoir pressure may adversely affect system performance if not adequately monitored. Consequently, periodic integrity assessments using logging tools, pressure testing and continuous monitoring of production parameters should form an integral component of geothermal well management. Such practices not only improve operational reliability but also minimize environmental risks associated with fluid leakage and groundwater contamination [45].

Future Research Directions

Despite significant advances in geothermal well repurposing, several research gaps remain. Future studies should focus on long-term monitoring of demonstration projects to validate numerical models and quantify thermal decline under field conditions. Improved reservoir characterization through coupled thermo-hydro-mechanical-chemical (THMC) modelling, machine learning, and digital twin technologies should be explored to enhance performance prediction and operational optimization. Further investigation into advanced working fluids, including supercritical CO₂ and environmentally benign refrigerants, is also warranted. In addition, standardized methodologies for techno-economic evaluation and life-cycle assessment are required to facilitate meaningful comparison among projects across different geological and regulatory settings. Addressing these research priorities will accelerate the commercial deployment of geothermal energy from abandoned oil and gas wells.

CONCLUSIONS

The repurposing of abandoned oil and gas wells for geothermal energy extraction represents a technically feasible and economically attractive pathway for extending the productive life of mature petroleum assets while supporting the transition to low-carbon energy systems. The reviewed literature demonstrates that both closed-loop and open-loop technologies possess significant potential; however, their applicability depends on site-specific geological conditions, reservoir characteristics, well integrity, and the intended energy application.

Advances in numerical modelling have substantially improved the prediction of thermal performance and long-term reservoir behaviour. Nevertheless, uncertainties associated with geological heterogeneity, formation temperature estimation, and limited field-scale validation continues to constrain confidence in long-term performance predictions. Consequently, greater emphasis should be placed on pilot-scale demonstration projects capable of providing operational data for model calibration and technology verification.

From an economic perspective, repurposing existing wells can significantly reduce capital investment by eliminating drilling and exploration costs while avoiding well plugging and abandonment expenses. However, project feasibility remains highly dependent on local geothermal resources, infrastructure availability, regulatory support, and electricity market conditions. Countries with established policy incentives have demonstrated greater progress in geothermal deployment than regions where dedicated regulatory frameworks are absent.

Environmentally, geothermal well repurposing offers substantial benefits through reduced greenhouse gas emissions, methane leakage mitigation, and minimized land disturbance. These advantages, however, should be balanced against engineering challenges related to well integrity, scaling, corrosion, and long-term reservoir management.

Future research should prioritize long-term field validation, integrated thermo-hydro-mechanical modelling, advanced working fluids, digital monitoring technologies, and comprehensive techno-economic assessments under diverse geological settings. Establishing supportive policy frameworks and demonstration projects, particularly in emerging economies such as Nigeria, will be essential for translating the considerable technical potential of geothermal well repurposing into commercially viable renewable energy developments.

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