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Review

A Review of North American Prospects for Power and Hot-Water Generation with Thermal Energy

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Abstract

This article outlines an innovative approach to explore thermal energy extraction for power generation or industrial hot water applications. Unlike traditional steady-state models, this approach embraces time-variant scenarios, explicitly incorporating a cyclical fluid circulation strategy to maintain a stable surface fluid temperature or power output. By introducing an increasing and decreasing stepwise rate sequence and an intermittent circulation strategy, the method aims to optimize efficiency in response to varying geothermal gradients. This approach also considers the effect of well configurations namely U-shaped heat exchangers, and conventional wellbore heat exchangers. The study emphasizes the importance of assessing the value proposition of this rate-sequencing approach in different North American basins, with the potential for replication in other regions. This approach recognizes the geographic dependency of thermal prospects, particularly at specific well depths. Notably, the article explores the possibility of retrofitting abandoned wells in oil fields and drilling new wells in geothermal-friendly areas for a comparative analysis of their relative value propositions. In essence, the proposed roadmap signifies a departure from traditional models, showcasing a dynamic and adaptable strategy for thermal energy extraction. This strategy aligns with the need for energy transition and changing energy mix for the future. The inclusion of retrofitting existing wells and drilling in strategic locations adds a practical dimension to the study, offering insights into the scalability and applicability of the proposed approach beyond its initial geographic focus.

Keywords
Thermal-energy; fluid circulation; designed wells; repurposed wells; power generation; hot-water generation

1. Introduction

The energy transition initiatives in most developed countries center on reducing carbon footprints, leading to increased focus on renewable sources like wind, solar, geothermal, and low-carbon alternatives such as biomass and hydrogen. While successful pilots have appeared, the critical concern now lies in these initiatives' scalability and economic viability. Notably, offshore wind and biomass projects are more costly and unstable than geothermal and natural gas alternatives.

In this context, geothermal energy is a promising avenue for achieving energy transition goals with minimal carbon impact. Numerous studies in North America, referenced from Nalla et al. [1], Davis and Michaelides [2], Lund [3, 4], Lund and Boyd [5], Gunawan et al. [6], and Lund and Toth [7], have explored the direct and indirect utilization of geothermal energy in various industries and power generation. Recent investigations by Westphal and Weijermars [8], and Weijermars et al. [9], have focused explicitly on fluid circulation in abandoned wells within deep shale plays. The configuration of horizontal wells enhances fluid residence time, ensuring efficient thermal energy extraction as supported by analytical models like the one presented by Sharma et al. [10].

However, these projects require a comprehensive review from engineering and economic perspectives. Repurposing hydrocarbon wells for geothermal use during an oilfield's late life has been explored in the UK [11] and Italian [12] contexts. While reusing abandoned wells [2, 13-23] appears attractive from a capital investment standpoint, challenges exist, including difficulties in controlling desired well depth and geothermal gradient in abandoned wells [10], and concerns related to mechanical integrity due to the well's age.

This study delves into using abandoned and designed wells in various North American prospects to establish the economic value proposition in both systems. The investigation focuses on the technical feasibility of harnessing geothermal energy using wellbore heat exchangers (WBHX). The designed wells meet all required metrics for power generation or direct use in industries. While presenting challenges, abandoned wells are deemed economically viable for generating fluid temperature for 'direct' service in various industrial sectors. This investigation suggests that the designed-well solution approach merits global exploration. Also, the study highlights the differences between U-shaped and conventional wellbore heat exchangers with various fluid circulation strategies, wherein a simplified analytical approach for a U-tube wellbore heat exchanger appears. In this context, this article offers a comprehensive overview of different approaches' technical and economic feasibility.

2. Methodology

Many authors, such as Nalla et al. [1] and Nian and Cheng [15], have investigated the continuous fluid-circulation strategy in a closed-loop WBHX system that started nearly two decades ago. However, given the steep decline in the near-wellbore formation temperature with time, a recent study by Al Saedi et al. [24] proposed a transient cyclical-circulation approach involving a circulation rate increase followed by a rate decrease. Besides preserving the near-wellbore temperature, this approach can deliver near-stable fluid temperature and power generation capability at the wellhead without well shut-in periods. More recently, the study of Benavides et al. [25] showed that juxtaposing the fluid circulation time with another energy source, such as solar or wind, over a day-and-night cycle preserves the near-wellbore thermal gradient, thereby outperforming previous continuous circulation methods.

This study uses some circulation methods, along with the U-shaped heat exchanger involving two vertical wells connected by a horizontal well segment, as depicted in Figure 1a. In contrast, Figure 1b displays the conventional WBHX. The performance outcome of this U-shaped approach is very encouraging; details of this study's model derivation appear in Appendix A. Multiple validation studies reaffirmed the U-shaped modeling approach, thereby enabling the next step toward exploring its economic value proposition, as discussed later. To that end, Figure 2 displays the history-matching effort of the overall temperature distribution with two horizontal sections during CO_2 circulation, as presented earlier by Sun et al. [26]. The improved heat-carrying capacity of CO_2 over water became an investigation item in various studies, such as those of Zhang et al. [27] and Hu et al. [28]. Furthermore, Figure 3 assures data validation of independent studies involving both model results [29] and that in a field setting [30] for water circulation.

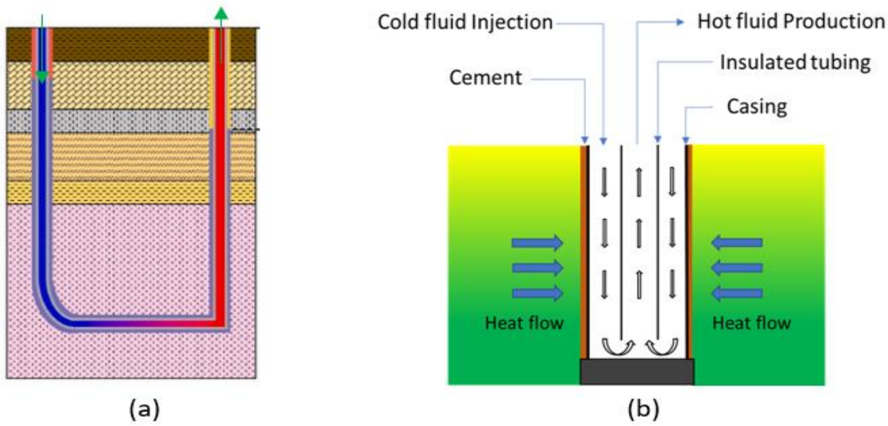


Figure 1 U-shaped heat exchanger (a), and conventional wellbore heat exchanger (b).

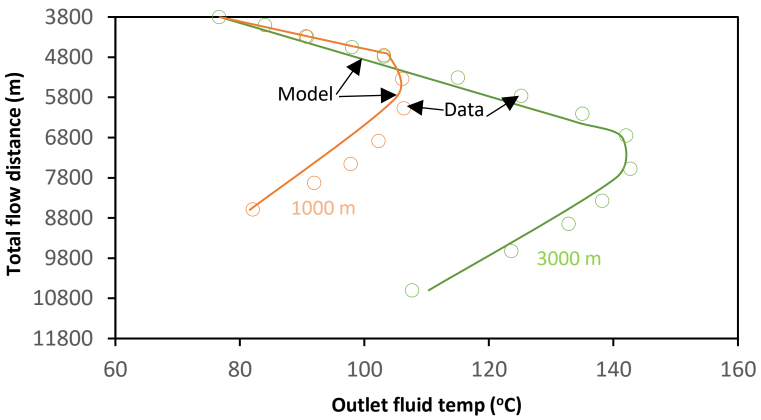


Figure 2 Matching wellbore fluid temperature distributions for two horizontal sections during CO_2 circulation (after Sun et al. [26]).

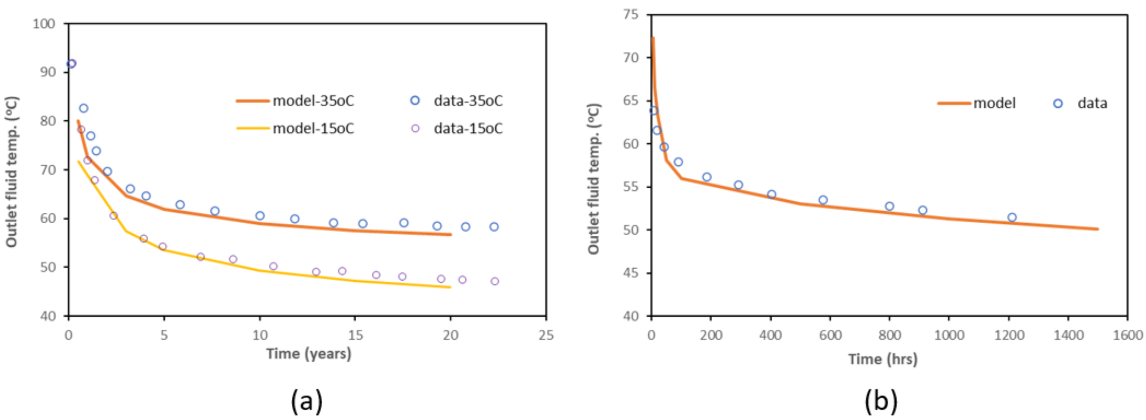


Figure 3 Matching outlet fluid temperature of Ma et al. [29] model (a), and in a field setting generated by Wei et al. [30] (b).

Although the U-shaped flow geometry retains a near-stable outlet fluid temperature for 20 years, the increase in circulation rate triggers a decreasing outlet temperature trend. Besides the fluid's circulation rate and inlet temperature, the horizontal well length, its degree of insulation, and the heat-carrying capacity of the fluid all contribute to the overall performance in power generation, as detailed in various studies [26-31], among others. Some investigators have explored nano-fluids [32], and multi-level, multi-branch systems [33, 34], to explore the U-shaped system's efficacy.

3. Evaluating Well Prospects

A recently developed transient analytical model employing a wellbore fluid-circulation approach [24] preserves the near-wellbore geothermal gradient. To that end, Appendix B presents the expressions and parameters of the various methods used in this study. This modeling technique, characterized by a stepwise increase and subsequent decrease in flow rates, ensures minimal alteration of the geothermal gradient, thereby significantly enhancing the efficiency of geothermal energy extraction. Water as the circulating fluid in this approach ensures a safe and sustainable utilization.

3.1 Power Generation Potential for Various System Variables with the Design of Experiments

As depicted in Figure 4, the Western part of the U.S. exhibits considerable thermal energy potential, forming the basis for this investigation. Specifically, a geothermal gradient of 0.11°C/m for a designed well becomes the primary focus for power generation. In contrast, an abandoned well in a Texas setting demonstrates a geothermal gradient of about 0.05°C/m in a 4,000 m well, making it potentially more suitable for direct use.

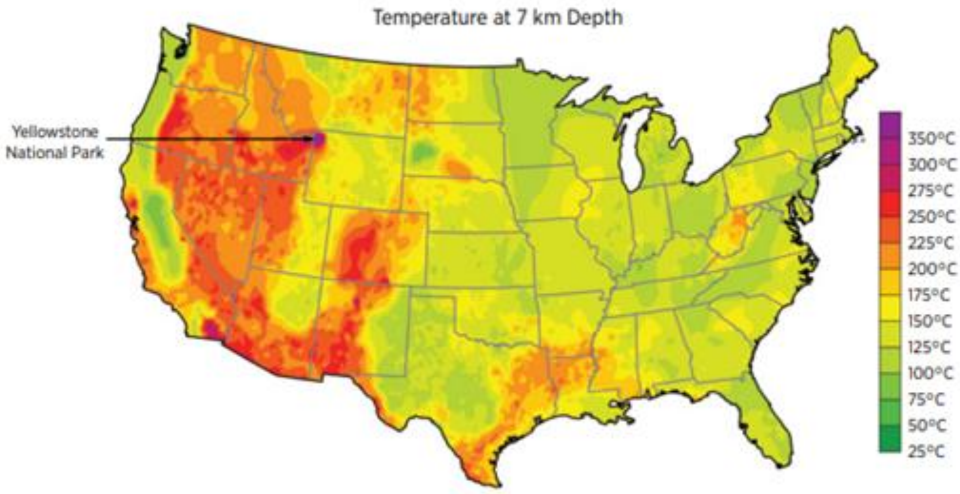


Figure 4 Favorable formation temperature at 7 km depth shows the potential for harnessing energy in the U.S. (after SMU Geothermal Laboratory).

Previous research by Sharma et al. [10] emphasized the significance of geothermal gradient and well depth as the two most influential variables in generating high-fluid temperature at the wellhead. This insight prompted an exploration of the efficacy of tubular internal diameters (I.D.), fluid injection temperature, and an operational variable, circulation rate. A range of independent variables assess the value-added proposition in the transient fluid-circulation strategy for a well depth of 4,500 m and a P-50 geothermal gradient of 0.11°C/m. Table 1 provides the relevant data used in the statistical design of experiments (DoE), wherein the outlet fluid temperature and power generation appear as the dependent variables of interest.

Table 1 Variables used in DoE runs.

DoE: independent variables	P10	P50	P90
Tubing ID, cm	5.240	7.201	8.890
Annulus ID, cm	16.828	20.363	26.888
Injection Temp (°C)	25	50	75
Circulation rate, min (m^3/h)	3.180	6.359	9.539
Circulation rate, max (m^3/h)	12.718	15.898	19.077

Figure 5a presents a Pareto chart illustrating the relative importance of independent variables affecting wellhead fluid temperature. Tubing I.D. stands out as a significant contributor, but casing I.D. and injection-fluid temperature also hold statistically significant value propositions in a relative sense. Figure 5b complements this by providing an overall perspective through a Cumulative Distribution Function (CDF) plot. The p-50 outcome suggests the feasibility of utilizing this fluid temperature for power generation in a binary plant.

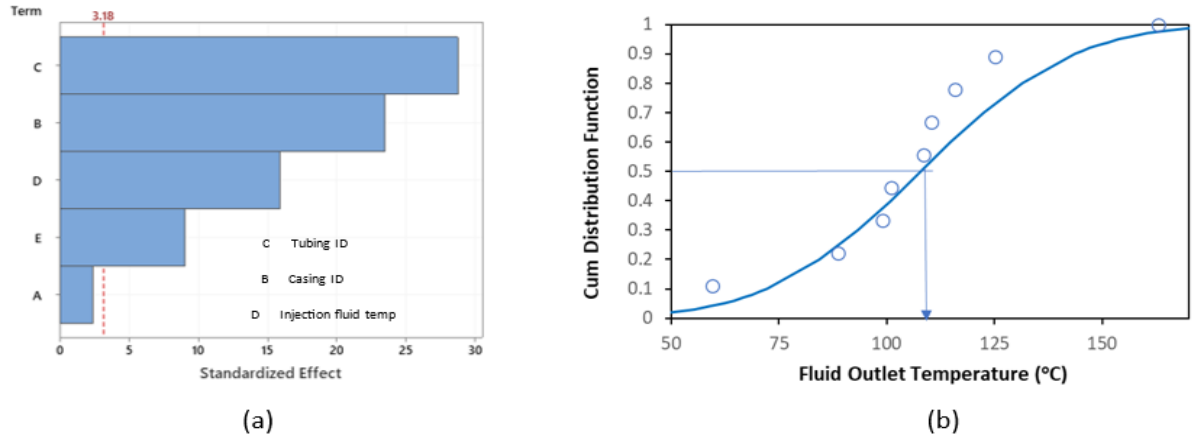


Figure 5 The Pareto chart for the wellhead-fluid temperature (a), and the CDF plot suggests a promising P-50 outcome for the wellhead-fluid temperature (b).

Moving from the focus on wellhead fluid temperature to considerations of power generation capability, the significance of handling larger fluid volumes through increased casing I.D. becomes apparent, as emphasized in Figure 6a's Pareto chart. The fluid injection temperature emerges as the second most important variable, followed by tubing I.D. Figure 6b, featuring the CDF plot for power generation, further illustrates these possibilities. The prominence of casing I.D. implies that managing a larger fluid volume during circulation translates to enhanced power generation capability. This discovery holds substantial value when optimizing a designed well's output potential.

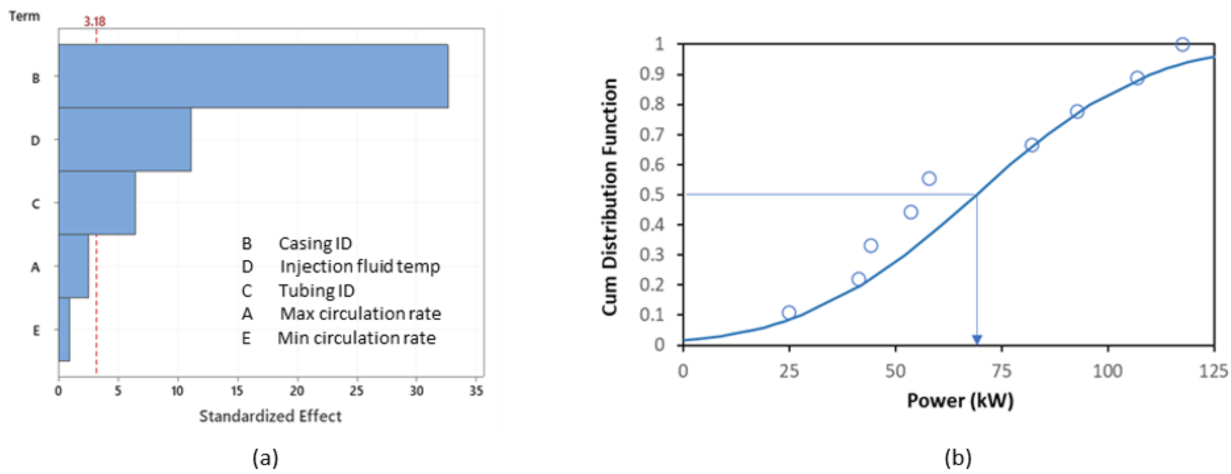


Figure 6 The dominance of casing I.D. and injection fluid temperature in a designed-well setting (a), the corresponding power-generation capability with CDF (b).

3.2 Understanding the Efficacy of Circulation Strategy on Fluid Temperature Output

The value proposition of the cyclical fluid circulation strategy compared to its continuous circulation counterpart becomes relevant. Figure 7a presents the two solutions concerning the output fluid temperature. Adjusting the range of circulation rates in the stepwise solution ensured that this comparison was fair. For further clarity, Figure 7b directly compares the value proposition by including a second well. The second well starts with a mirror opposite or high-to-low strategy to offset the temperature cycle for the circulation steps in the first well. This holistic approach delivers the desired outcome of a stable overall solution.

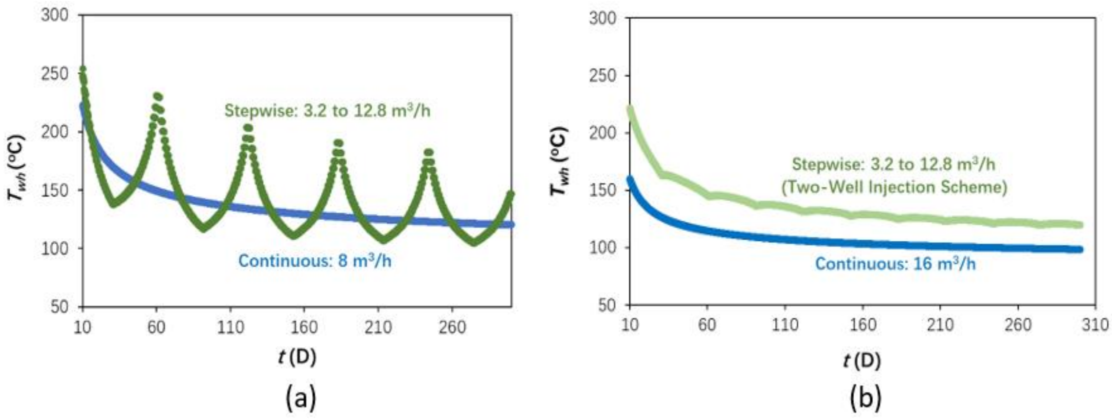


Figure 7 Performance comparison of stepwise and continuous fluid circulations for the wellhead-fluid temperature (a), including the second well in stepwise circulation, generates a relatively smooth signature (b).

A recent study [25] showed that the day/night cycle of fluid circulation in a single well by including another green energy source, such as solar, provides a very realistic economic outcome due to the preservation of the near-wellbore geothermal gradient. This circulation approach is termed an intermittent circulation strategy. When the performance of a U-shaped system is compared with the intermittent fluid circulation strategy, the outlet fluid temperature outcomes get close, as Figure 8 demonstrates.

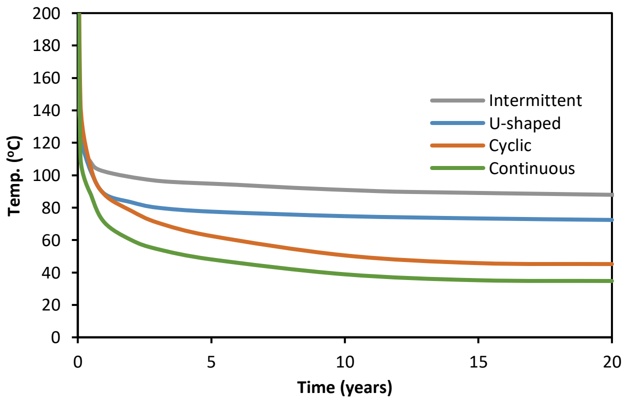


Figure 8 Comparison of different circulation strategies and wellbore configuration. Continuous: Single well continuous circulation; Cyclic: Two wells, offsetting circulation; intermittent: Single well combined with another green energy source; and U-shaped: Single well in U-shaped wellbore continuous circulation. The intermittent fluid-circulation strategy outperforms others.

As expected, the continuous circulation strategy performs the worst. The cyclic circulation strategy provides an improvement with a relatively higher outlet temperature. Intermittent and U-shaped outlets stand out in terms of long-term sustained outlet temperatures. However, any realistic comparison between these strategies will require consideration of economics. The economic analysis section will highlight the most suitable system for a realistic project.

4. Prospect Evaluation in North America

To explore the energy generation prospects in the U.S., let us consider the geothermal gradient as a starting point in the lower 48 states, as indicated in Figure 4. This landscape with diverse geothermal gradients provides an overall perspective at a given depth. Specifically, the western states, marked in red, have the highest potential for generating power with the circulated fluid, followed by the states colored in yellow. That leaves 30+ green states suitable for generating hot water for various industrial needs. The range of water temperature output for three colored prospects appears in Figure 9. Besides the red and yellow states, the green window in Figure 9 suggests that the organic Rankine cycle (ORC) can convert water temperature from 75 to 145°C to power. In the yellow states, this reality implies that the indirect use of hot water for power generation becomes feasible via ORC and for direct use in various industries. As Watson et al. [11] showed, one can offset the geothermal gradient by drilling a deeper well in any setting.

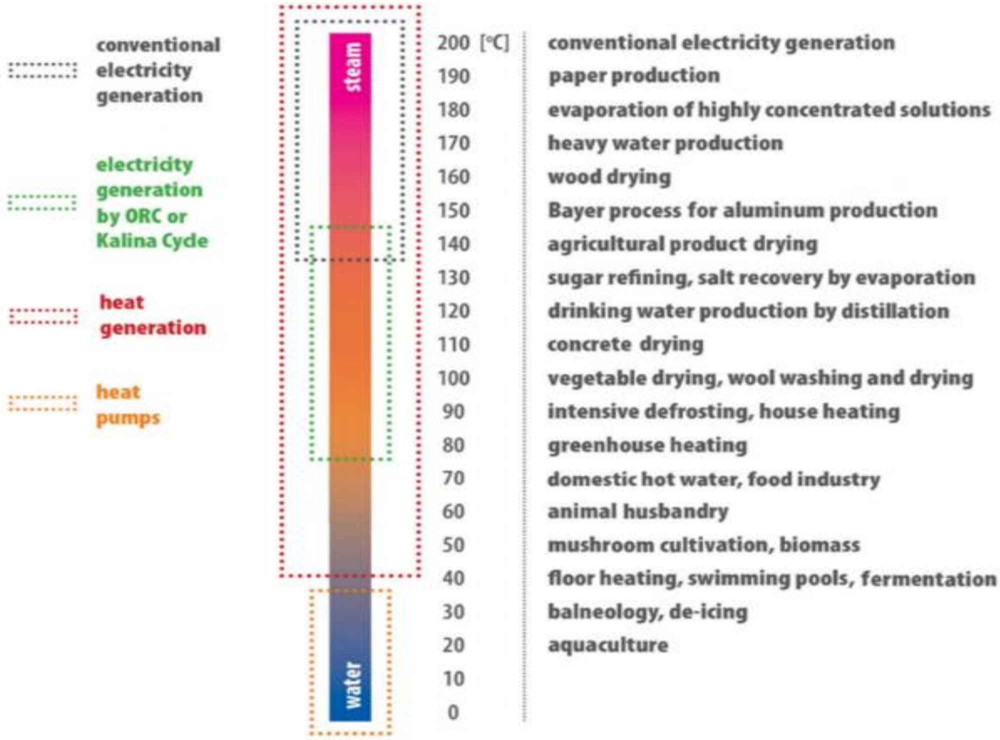


Figure 9 Potential applications of geothermal fluids in various industries (after [11]).

For economic prospect evaluations, vis-à-vis the well cost, one can start searching for DUCs (drilled but uncompleted wells). Figure 10 shows the DUCs' prospects in various unconventional reservoir basins. These deep basins ensure a desirable well depth. Besides the well's young age, choosing tubing I.D. and providing tubular insulation make these wells far more attractive than abandoned wells. Nonetheless, one can explore the prospect evaluation with some of the 4.7 million abandoned wells, wherein several practical issues may surface. These issues stem from tubular integrity, tubular I.D.'s and lack of insulation, well-depth, and the desired geothermal gradient. Despite adversity, DUCs do make a good value proposition for field trials.

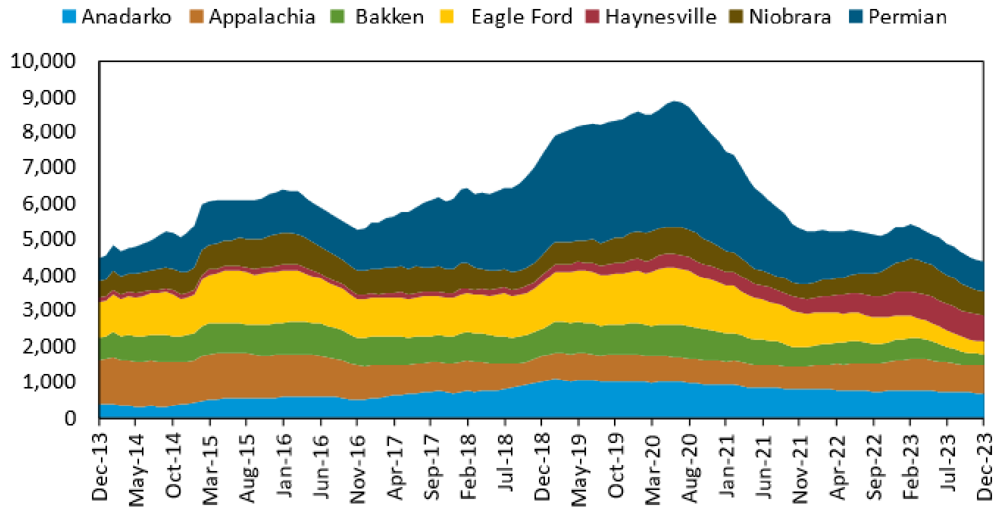


Figure 10 Availability of a number of DUCs over ten years in unconventional plays of USA.

The offshore prospect evaluation [35] in the Gulf of Mexico also appears attractive, given that recently abandoned wells and platforms may provide an economic advantage, as Figure 11 illuminates.

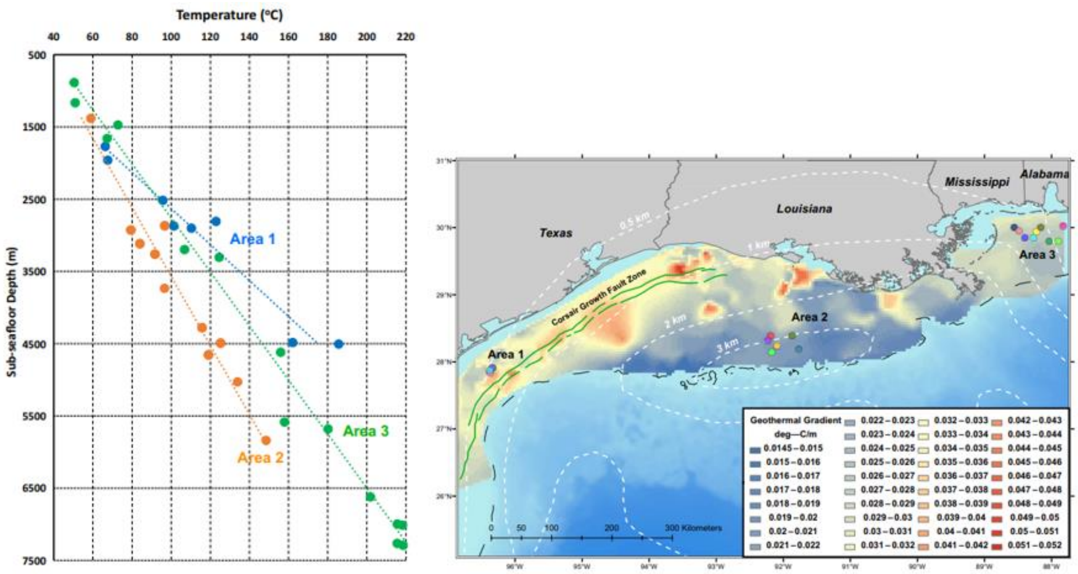


Figure 11 The Gulf of Mexico prospects near the U.S. coastline appear attractive (after Christie and Nagihara [35]).

As expected, Mexico offers a large spectrum of high geothermal gradient potential above 0.11°C/m, as Figure 12 illustrates. The Prol-Ledesma et al. [36] study provided the platform for this prosperous prospect. Therefore, the enormous potential for electricity generation exists in Mexico, given the favorable geothermal gradient and the consequent shallower well depth opportunity;

Figure 13 reaffirms this point. The conductive 2D thermal modeling of Espinoza-Ojeda et al. [37] amplifies the potential for prospect evaluation for geothermal exploration. They found that thermal logs from two exploration wells can provide reliable temperature distribution to facilitate modeling large geographic areas.

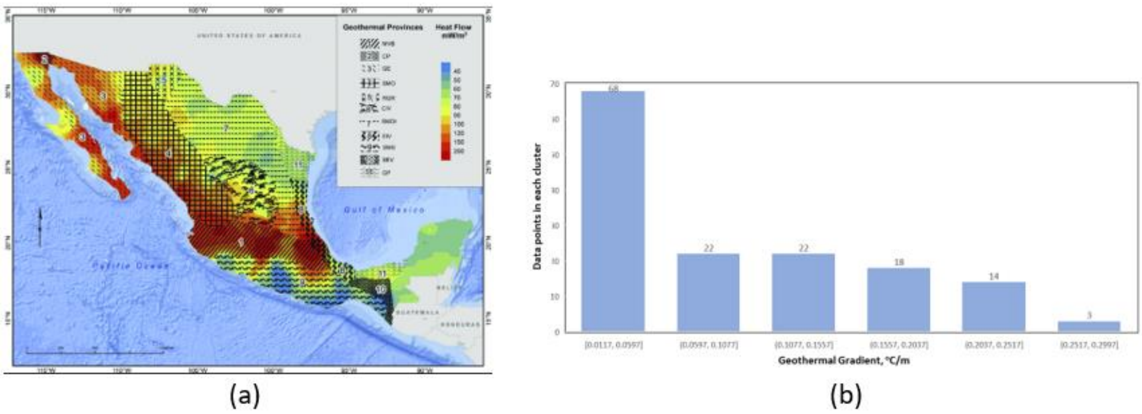


Figure 12 The heat-flow map of Mexico provides clarity of the immense potential for thermal energy extraction (a), and high geothermal gradient prospects (b) (after [36, 37]).

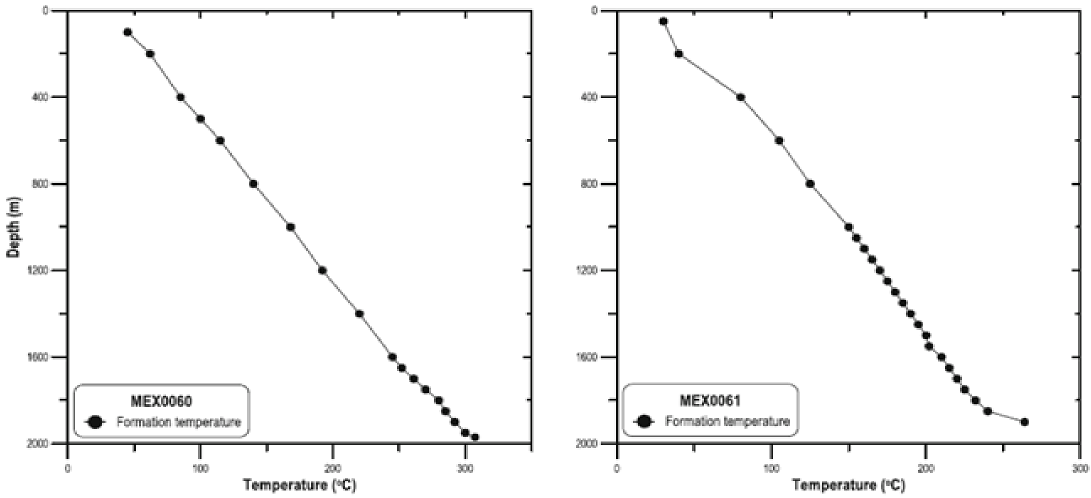


Figure 13 Formation temperature plots of two wells in Acolculco, Mexico (after [36]).

Canada also offers potential power generation prospects in the Western Canada Sedimentary Basin (WCSB), as displayed in Figure 14. Figure 14a presents a geothermal gradient map with 68,377 gradient values from 26,592 wells, as Weides and Majorowicz [38] showed. Figure 14b displays a geothermal gradient with limited field data from an old study by Jones et al. [39]. The Northwest Territories in Figure 14a indicate binary cycle options for generating power.

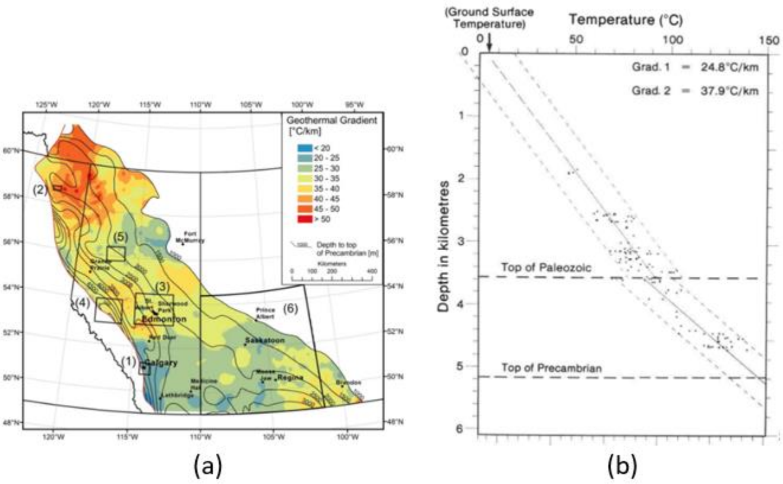


Figure 14 (a) Geothermal gradient map in Western Canada Sedimentary Basin (WCSB) (after [38]), (b) geothermal gradients (after [39]).

5. Economic Evaluation

This section explores the economic value proposition of installing binary geothermal plants for power generation in North America. Figure 15 presents a roadmap for power generation with a binary geothermal plant using a fluid-circulation strategy and the subsequent economic analysis by comparing it with the gas-fired power generation plant. The underlying idea is to infuse objectivity in the value proposition by directly comparing the two scenarios. Contextually, two metrics, the net present value or NPV and the Levelized Cost of Energy or LCOE, provided the required platform. So, the first approach provides an overall understanding of the economic value proposition of a binary plant. In contrast, the second approach compares systems involving various circulation strategies, including the U-shaped wellbore system.

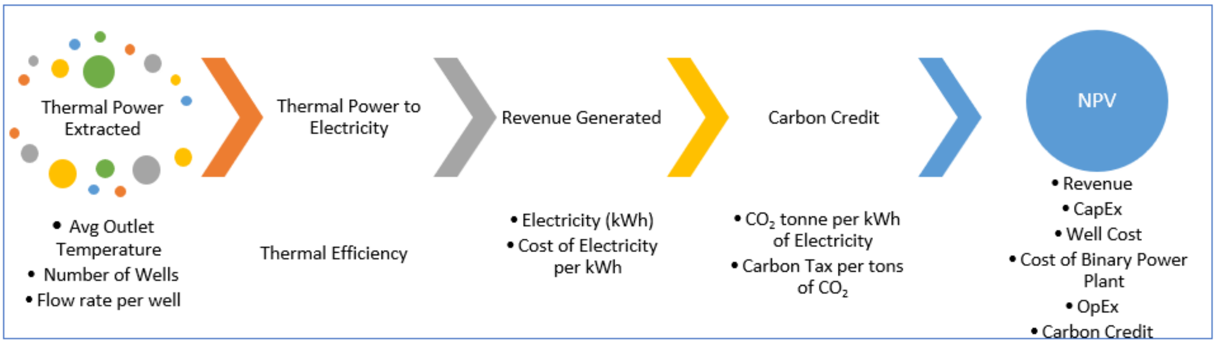


Figure 15 Stepwise approach for binary-power generation.

5.1 Binary Plant Evaluation

An objective evaluation of well prospects can be assessed by the statistical design of experiments or DoE. Specifically, DoE helped gauge the importance of six variables for generating about 130°C water temperatures, leading to power generation. Table 2 contains the range of variables used, and Figure 16 presents the relevant Pareto chart. The chart shows that the two economic parameters, discount rate and electricity price, outperform all others for a water-circulation rate of 28.6 m^3/h for an injection temperature of 50°C.

Table 2 Range of six independent variables for exploring the value proposition.

Variable	Min	Mode	Max
Binary Power Plant Cost ($ per kW)	2,000	2,500	3,000
Binary Power Plant Opex ($ per kWh)	0.01	0.02	0.03
Carbon Tax ($ per ton of CO_2)	**20**	**25**	**35**
Electricity Price ($ per kWh)	0.15	0.2	0.3
Discount Rate (annual)	5%	10%	20%
Cost per ft of Well	250	350	400

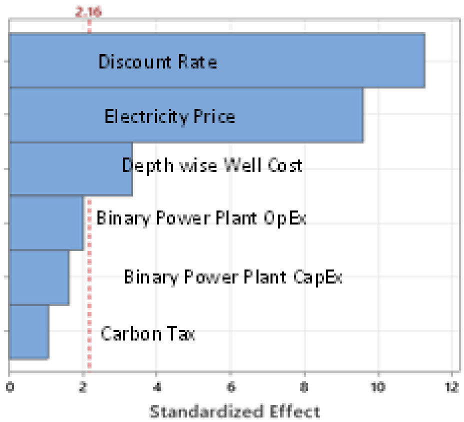


Figure 16 Both discount rate and electricity price dominate the NPV outcome.

Once the desired surface-water temperature of 130°C is assured, exploring the impact of the other independent variables by setting aside the discount rate can follow. For the five input variables in Table 3, the corresponding Pareto chart in Figure 17 shows that besides the electricity price, the well cost influences the net present value, NPV.

Table 3 Range of five independent variables for NPV estimation.

Variable	Min	Mode	Max
Binary Power Plant Cost ($ per kW)	2,000	2,500	3,000
Binary Power Plant Opex ($ per kWh)	0.01	0.02	0.03
Carbon Tax ($ per ton of CO_2)	20	40	60
Electricity Price ($ per kWh)	0.15	0.2	0.25
Cost per ft of Well	250	350	400

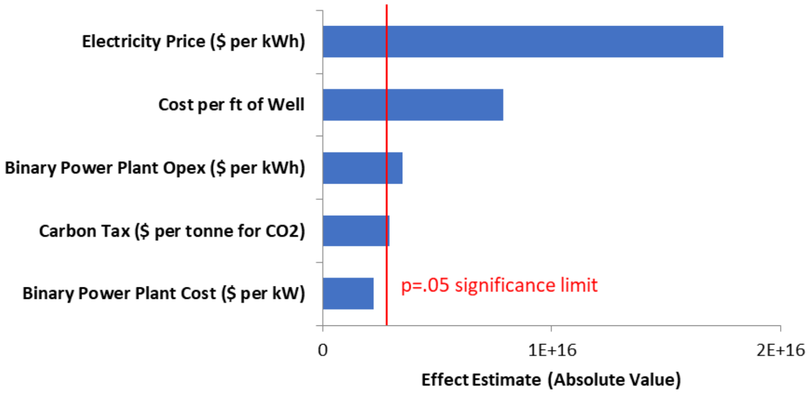
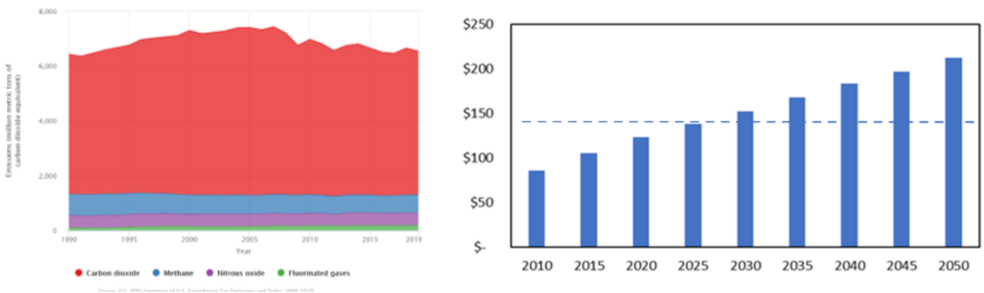


Figure 17 Both electricity price and well cost dominate the NPV outcome.

Given the low impact of the carbon tax credit from the previous Pareto charts, exploring a carbon tax's current and future potential in the U.S. followed. Figure 18a shows the carbon emissions significantly higher than other components, such as methane. However, the U.S. carbon tax has healthy future potential, as Figure 18b exhibits. In Canada, the carbon tax in 2022 was $50 per ton of CO_2, growing to $170 in 2030. The current CO_2 tax credit appears in Europe in Figure 19, wherein Sweden, Switzerland, and Liechtenstein lead the way.



(www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks)
(a) (b)

Figure 18 Dominance of CO_2 in the U.S. greenhouse gas emissions (a), and projection of U.S. Social Cost of CO_2 based on the report from interagency Working Group on Social Cost of Greenhouse Gases, U.S. Government (b).

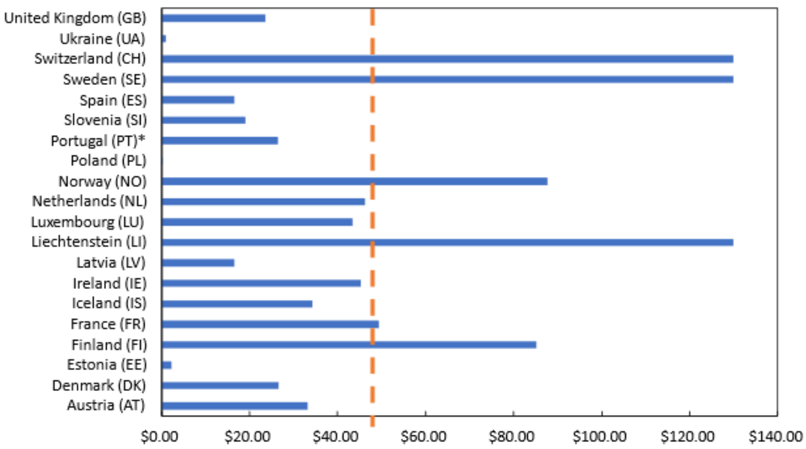


Figure 19 Variable carbon tax credit in Europe (Source: taxfoundation.org).

For the CO_2 tax credit profiles, as shown in Figure 18b, comparing the NPV of a binary geothermal plant with that of a natural gas power plant followed. Figure 20 presents two profiles with the carbon tax credit and the discount rate. As Figure 20a suggests, the carbon tax credit must be about $150 per ton of CO_2 for the binary geothermal plant to be financially attractive. To gain further insights, exploring the value proposition regarding capital investment became a logical step, as Figure 21a displays. The lower investment in the plant appears attractive for a conventional gas plant. A similar trend appears in Figure 21b based on the Levelized Cost of Energy or LCOE for the current $25 carbon tax credit scenario. However, Figure 22 shows that when the CO_2 tax credit gets boosted to around $145 per ton of CO_2, then the economic feasibility of the carbon-neutral power generation strategy becomes attractive.

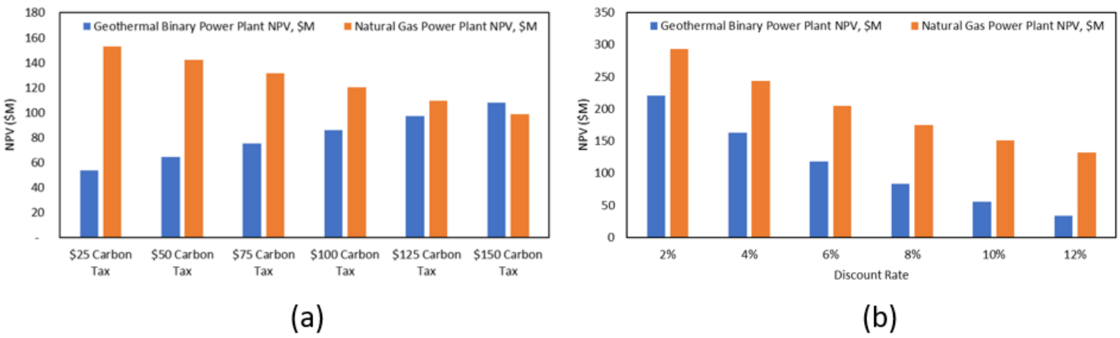


Figure 20 NPV comparison of binary geothermal and natural gas power plants with a carbon tax (a), discount rates (b).

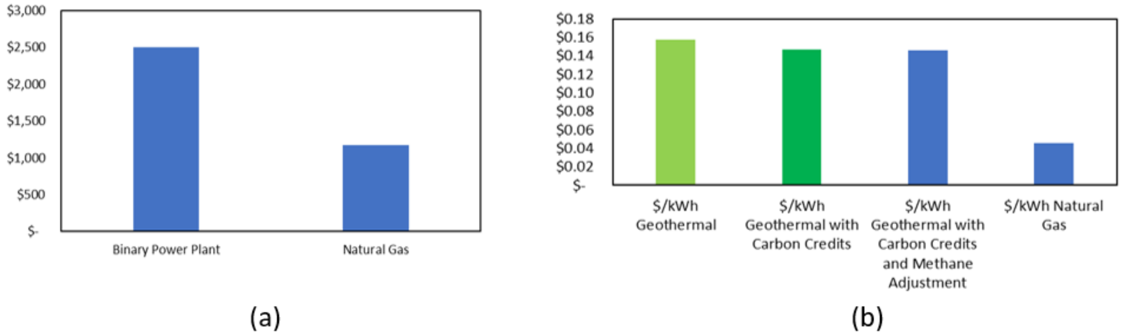


Figure 21 Comparison of two power plants: Capex $/kW (a), LCOE with $25 carbon tax for various carbon credit scenarios (b).

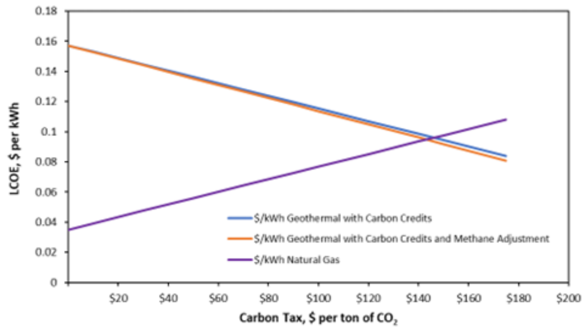


Figure 22 The Levelized Cost of Energy (LCOE) suggests a carbon tax of about $145/ton: CO_2 brings equality between the two power plants.

5.2 Economics of Fluid Circulation Strategies

Interestingly, although the U-shaped system provides a comparable fluid-temperature outcome to the intermittent day/night cycle system, as shown earlier in Figure 8, it runs into economic hurdles when operated independently, as Figure 23 depicts. However, the NPV landscape improves when the hybrid approach involving another independent power source, such as solar, wind, or grid, is commingled, as Figure 24a implies. The corresponding LCOE in Figure 24b presents the value proposition of the intermittent approach. The key takeaway is that besides the low investment requirements, the intermittent operation with a green energy source preserves the near-wellbore geothermal gradient more efficiently than the other methods explored in this study.

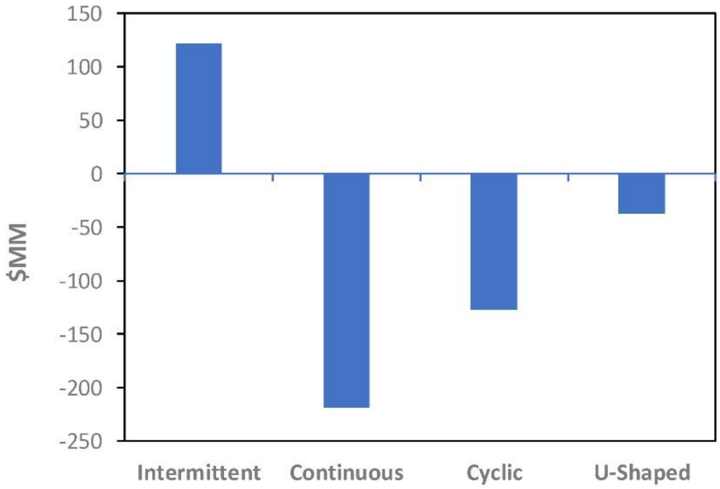


Figure 23 The NPV outcome favors the intermittent circulation strategy.

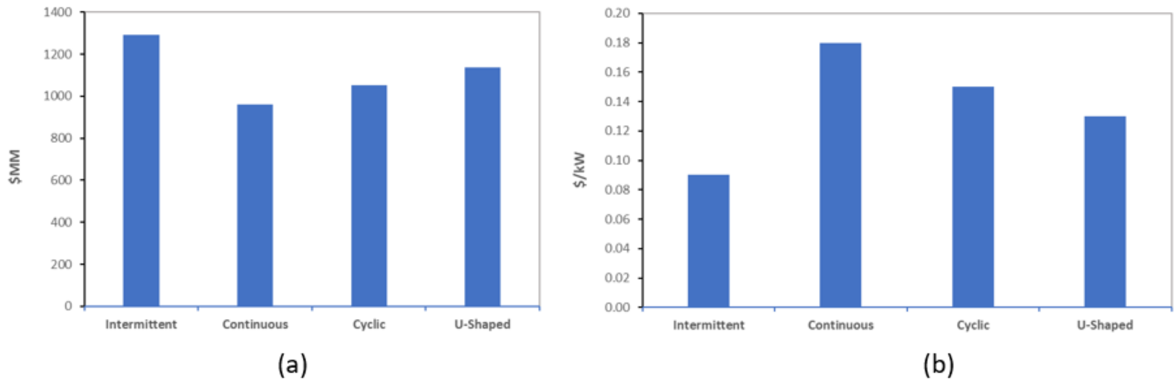


Figure 24 The NPV (a) and LCOE (b) favor the intermittent circulation strategy in a hybrid approach.

6. Discussion

This study primarily focused on designed wells, recognizing the challenges associated with abandoned wells. Existing wells will likely face limitations in meeting geothermal gradient, well-depth requirements, and tubular diameters, resulting in lower probabilities of power generation. Consequently, the logical solution for these wells is the direct usage of hot water in industries, particularly those near the well sites, an aspect to be addressed in a future article. Meanwhile, the insights gained from this study can serve as valuable guidance for global adoption, emphasizing fundamental considerations such as geothermal gradient, well depth, tubular diameters, circulation rates, and economic factors in project execution.

Here are some of the other lessons learned with designed wells. Although not shown in an explicit form, the high geothermal-gradient (g_T > 0.1°C/m) wells markedly outperform those in low-g_T environments; this advantage exists even in adverse fluid-circulation timestep situations. Hence, if this type of energy-harnessing measure leads to power generation, the abundance of prospects in the Western states in the U.S. and Mexico provide industrial-scale field development opportunities in North America. Of course, the development of conventional geothermal reservoirs for power generation provides the necessary assurance in these settings. Despite many options for harnessing thermal energy with multi-level and multi-branch designs in a closed-loop system, field verifications need exploring for commercialization. Such a project in Germany will start producing power in 2024, with a total capacity in 2026.

Project economics of designed wells suggested that the current carbon tax in North America cannot compete with the low-power-generation cost associated with natural gas. However, when the carbon tax reaches about $140 per metric ton of CO_2 by 2025, exploring this green energy's excellent value proposition toward carbon emission minimization becomes realistic. This timeline appears holistic because the industrial-scale project initiation and execution take time. Finally, given that most countries are poised to meet the Paris Climate Accord goals, a hybrid intermittent approach, as explored here, merits serious attention.

In summary, the overall lessons learned from designed wells include the following:

- **Geothermal gradient influence:** High geothermal-gradient wells (g_T > 0.1°C/m) outperform those in low-gradient environments, even in adverse fluid-circulation timestep situations. This advantage opens industrial-scale field development opportunities, especially in the Western states of the U.S. and Mexico.
- **Commercialization challenges:** Despite various options for harnessing thermal energy with complex closed-loop system designs, field verifications are essential for successful commercialization. A project in Germany set to produce power in 2024 highlights the potential for such endeavors.
- **Project economics and carbon tax:** Project economics for designed wells indicate that, currently, the carbon tax in North America cannot compete with the low power-generation cost associated with natural gas. However, a realistic green energy value proposition exploration becomes feasible when the carbon tax reaches approximately $140 per metric ton of CO_2 by 2025.
- **Hybrid intermittent approach:** With many countries aligning with the Paris Climate Accord goals, the hybrid intermittent approach explored in this study deserves serious consideration. Combining intermittent power generation methods can contribute to sustainable energy practices.

7. Conclusions

This review article synthesizes significant findings from both engineering and economic analyses related to generating thermal power through fluid circulation in wellbores. Key conclusions include:

a) **Impact of variables:** Statistical design of experiments highlights the substantial influence of casing I.D. and inlet-fluid temperature on the fluid's output wellhead temperature and power generation capability within a given well depth and geothermal gradient system.
b) **Power generation factors:** Higher fluid injection temperatures increase fluid temperature output and power generation. Larger casing I.D., allowing for the handling of larger fluid volumes in designed wells, enhances power output. Geothermal gradients exceeding 0.05°C/m facilitate power generation with the cyclical fluid-circulation strategy, meeting the minimum output fluid temperature requirement for organic Rankine cycle (ORC) power generation.
   Overall, this study provides required insights into the nuanced factors influencing wellbore thermal power generation, offering a foundation for informed decision-making in pursuing sustainable and efficient geothermal energy extraction.
c) **Utilizing intermittent fluid circulation in low-geothermal gradient settings:** In regions with low geothermal gradients (<0.05°C), the intermittent fluid circulation strategy emerges as a viable solution to meet diverse industrial hot water needs throughout North America. However, the feasibility of such projects requires thorough validation through engineering and economic analyses to ensure practicality and sustainability.
d) **Economic viability with carbon tax incentives:** Economic analyses indicate that a carbon tax credit of approximately $145 per metric ton can significantly enhance the viability of the wellbore thermal energy extraction approach for power generation. This financial incentive, particularly in a hybrid approach, positions the method as an economically competitive and environmentally beneficial option for sustainable energy practices.
e) **Nature of energy transition**: The technical and economic feasibility of the Intermittent strategy highlights the need for an energy mix to achieve a realistic energy transition. No energy resource will be sufficient for all energy needs, so a mixed strategy will ensure economic viability and deliver energy reliability.

Appendix A Model for the U-Shaped Heat Exchanger

Based on the Al Saedi et al. [40] study, the second-order differential equation representing the heat transfer for forward circulation in a vertical wellbore is

$$AB\frac{d^2T_t}{dz^2} - \frac{BdT_t}{dz} - T_t + T_f = 0 \quad (\mathrm{A}-1)$$

$$T_f = T_{es} + zg_G \quad (\mathrm{A}-2)$$

Only the tube section is pertinent for the U-shaped heat exchanger, given that this system does not require the annular section. So, for the horizontal section the same equation can be used but with one modification of the formation temperature, as follows:

$$T_f = T_{es} + Lg_G + z_H g_{GH} \quad (\mathrm{A}-3)$$

$$T_f = T_H + z_H g_{GH} \quad (\mathrm{A}-4)$$

where L is the length of the vertical section and g_{GH} is geothermal gradient for the horizontal section, which will be zero for a perfect horizontal section. So, the differential equations for the two vertical sections and one horizontal section appear as

$$AB\frac{d^2T_{tV1}}{dz_{V1}^2}-\frac{BdT_{tV1}}{dz_{V1}}-T_{tV1}+T_{es}+z_{V1}g_G=0 \qquad (\mathrm{A}-5)$$

$$AB\frac{d^2T_{tH}}{dz_H^2}-\frac{BdT_{tH}}{dz_H}-T_{tH}+T_H+z_Hg_{GH}=0 \qquad (\mathrm{A}-6)$$

$$AB\frac{d^2T_{tV2}}{dz_{V2}^2}-\frac{BdT_{tV2}}{dz_{V2}}-T_{tV2}+T_{es}+z_{V2}g_G=0 \qquad (\mathrm{A}-7)$$

Here are the associated boundary conditions and the solutions:

$$T_{tV1}|_{z_V=0}= T_{ti} \qquad (\mathrm{A}-8)$$

$$\alpha_1+\beta_1=T_{ti}-T_{es}+Bg_G \qquad (\mathrm{A}-9)$$

$$T_{tV1}|_{z_{V1}=L}= T_{tH}|_{z_H=0} \qquad (\mathrm{A}-10)$$

$$\alpha_1e^{\lambda_1L}+\beta_1e^{\lambda_2L}-\alpha_2-\beta_2 = B(g_G-g_{GH}) \qquad (\mathrm{A}-11)$$

$$T_{tV2}|_{z_{V2}=L}= T_{tH}|_{z_H=H} \qquad (\mathrm{A}-12)$$

$$\alpha_3e^{\lambda_1L}+\beta_3e^{\lambda_2L}-\alpha_2e^{\lambda_1H}-\beta_2e^{\lambda_2H}= g_{GH}H-B(g_{GH}-g_G) \qquad (\mathrm{A}-13)$$

$$\frac{dT_{tV1}}{dz}|_{z_{V1}=L}=\frac{dT_{tH}}{dz}|_{z_{v1}=0} \qquad (\mathrm{A}-14)$$

$$\frac{dT_{tV2}}{dz}|_{z_{V2}=L}=\frac{dT_{tH}}{dz}|_{z_{v1}=H} \qquad (\mathrm{A}-15)$$

$$\alpha_1\lambda_1e^{\lambda_1z}+\beta_1\lambda_2e^{\lambda_2z}+g_G=0 \qquad (\mathrm{A}-16)$$

$$\alpha_1\lambda_1e^{\lambda_1L}+\beta_1\lambda_2e^{\lambda_2L}+g_G=0 \qquad (\mathrm{A}-17)$$

$$\alpha_1\lambda_1e^{\lambda_1L}+\beta_1\lambda_2e^{\lambda_2L}=-g_G \qquad (\mathrm{A}-18)$$

Appendix B Models for Heat Exchanger

This appendix introduces the various methods used in prior studies to generate solutions for different fluids, specifically water, pentane, isobutane, and R134a. In this context, Python became the chosen coding platform. Different well configurations, including two-well, intermittent fluid circulation, stepwise, and continuous circulation, appear in this study. Temperature calculations within the tubing and the annulus are performed to ensure the accurate evaluation of fluid PVT (Pressure, Volume, Temperature) properties over time.

Eqs. (B-1) and (B-2) present the analytical solutions of Al Saedi et al. [24] for temperature in the annulus and the tubing, respectively. Eq. (B-3) represents the line-source solution of the temperature-diffusivity equation, as shown earlier [24]. Notably, Eq. (B-3) aided estimation of the new geothermal gradient at each timestep.

$$T_a = (1 - \lambda_1 B)\alpha_1 e^{\lambda_1 Z} + (1 - \lambda_2 B)\beta_1 e^{\lambda_2 Z} + g_G Z + T_{es} \qquad (\mathrm{B} - 1)$$

$$T_t = \alpha_1 e^{\lambda_1 Z} + \beta_1 e^{\lambda_2 Z} + g_G Z + T_{es} + B g_G \qquad (\mathrm{B} - 2)$$

$$T_{bh} = T_s + 0.68 \left(\frac{Q_r}{hk_e}\right) E_i \left(\frac{-r_w{}^2}{4\alpha_e t}\right) \qquad (\mathrm{B} - 3)$$

where T_a represents the annulus fluid temperature at a given depth, T_t is the tubing-fluid temperature, and T_{bh} is the formation temperature at the same depth. Definitions of all other independent variables appear in the Nomenclature.

In this study, the design of the hybrid plant (geothermal, solar, wind, and grid) is based on the total power output of 50 MW in 20 years. The number of wells varied depending on the method used (refer to Table B1). However, the number of solar panels and wind turbines remains constant to ensure no variation in the power output. The number of solar panels used in this study is 33,000 regular panels and 2,163 SF or Smart-Flower panels. The number of wind turbines is 26. The energy distribution among the different energy sources appears in Table B2.

Table B1 Number of wells and well cost required to deliver same power at variuous heat extraction methods.

Method	Number of Wells	Price per well ($M)
U-tube	200	3.5
Continuous	482	1.5
Intermittent	150	1.5

Table B2 Energy distribution among the different energy sources.

	Energy Source			
	Geothermal	Solar	Wind	Grid
Percentage	30%	10%	35%	25%

The financial reports of the U.S. Energy Information Administration or EIA provided the required economic data. The specific economic parameters used in this study are like those of Benavides et al. [25], as shown in Table B3. Tables B4 and B5 present the economic data of solar and wind energy sources, respectively.

Table B3 Economic data for a binary plant.

Binary Plant		
Parameters	Value	Units
Binary power plant cost	2,000	$/kW
Binary power plant OpEx	0.01	$/kW
Cabon tax	150	$ton of CO_2

Electricity price	0.3	$/kWh
Discount rate (annual)	3.6	%
Years of operation	20	years

Table B4 Economic data for solar energy.

Solar Energy		
Parameters	Value	Units
Panel power	0.7	kW per panel
Panel efficiency	22	%
Solar plant CapEx	5,000	$/kW
Solar plant Opex	0.004	$/kWh
Cost of SF panels	27,000	$ per panel

Table B5 Economic data for wind energy.

Solar Energy		
Parameters	Value	Units
Turbine power	2.1	MW
Turbine efficiency	32	%
Turbine plant CapEx	1265	$/kW
Turbine plant Opex	0.003	$/kWh
Turbine cost	20,000	$

Nomenclature

T_a temperature of annulus fluid, °C
T_{es} surface temperature of earth, °C
T_t temperature of tubing fluid, °C
T_f formation temperature, °C
T_{wb} temperature at wellbore/formation interface, °C
T_{ti} injection fluid temperature, °C
T_H temperature at horizontal section, °C
T_{v1} temperature at injection section, °C
T_{v2} temperature at production section, °C
g_G geothermal gradient, °C/m
g_{GH} geothermal gradient for horizontal section, °C/m
k_e conductivity of the formation, J/s-m-°C
r_w wellbore radius, m
α_1 differential equation solution constant, °C
λ_1 parameter defined by Eq. A-3, m^{-1}
λ_2 parameter defined by Eq. A-4, m^{-1}
h perforation interval length, m
β differential equation solution constant, °C
A parameter defined by Eq. A-1, m

B	parameter defined by Eq. A-2, m
Q	heat flow rate, W
z	any depth of vertical section of well, m
z_H	any depth of horizontal section of well, m
α	heat diffusivity of formation (=$k_e/c_e\rho_e$), m^2/sec
L	total depth, m

Author Contributions

Conceptualization: S.K.; Formal analysis: J.B., P.S., S.K.; Investigation: J.B., P.S., S.K.; Methodology: J.B., P.S., A.S., S.K.; Project administration: P.S., S.K.; Resources: J.B., P.S.; Software: J.B., P.S.; Validation: J.B., P.S., S.K.; Writing, review, & editing: P.S., S.K.

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