Optimizing Advanced Geothermal Systems: Insights from the FlexGeo Project

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ABSTRACT

Geothermal energy is a vital renewable energy source, offering consistent, low-carbon baseload power, unlike intermittent resources such as wind and solar. Its ability to operate largely independently of weather conditions positions it as a crucial component of the global transition to sustainable energy. However, conventional geothermal systems are often constrained by geographical limitations and subsurface characteristics, such as the need for high permeability, and may pose risks of water contamination. Additionally, hydraulic stimulation in low-permeability regions is associated with seismic and public acceptance risks. The Advanced Geothermal Systems (AGS), which utilizes a closed-loop network of wellbores, presents a promising alternative circumventing these issues. By isolating fluid circulation, AGS minimize environmental risks while tapping into geothermal resources across a wider range of geological settings. As part of the European research initiative FlexGeo, this study focuses on the techno-economic assessment of AGS and aims to address its two major challenges: high drilling costs and low energy extraction rates due to slow conductive heat transfer. To address these challenges, the research explores various scenarios to identify optimal operational parameters and system design features that minimize the levelized cost of electricity under specific geological conditions. The findings offer key insights into improving AGS efficiency, ultimately advancing the role of geothermal energy in the green energy transition. These results hold significant potential for scaling AGS deployment and contributing to a more resilient and sustainable energy future.

1. INTRODUCTION

Advanced Geothermal Systems (AGS) represent a revolutionary approach in the geothermal energy landscape, offering innovative solutions to longstanding challenges that have historically limited widespread geothermal deployment (Esmaeilpour et al., 2021). By fundamentally reimagining how heat is extracted from the Earth's subsurface, AGS technology bypasses traditional limitations such as geographic constraints, seismic risk, and resource depletion that have restricted conventional geothermal development. These systems access previously untapped thermal resources at greater depths, enabling geothermal energy production in regions previously considered unsuitable. As global energy systems undergo rapid transformation toward carbon neutrality, AGS technology stands poised to significantly elevate geothermal energy's contribution to the green energy transition, providing a reliable, dispatchable renewable resource that complements the variability of wind and solar power.

Despite its remarkable potential, AGS technology currently faces a significant economic hurdle in the form of high Levelized Cost of Electricity (LCOE). This elevated cost structure stems from several identifiable factors: the substantial capital expenditure required for deep drilling operations, specialized equipment needs for extreme temperature and pressure conditions, and the technical complexity of heat exchange systems at unprecedented depths. The identification of these specific cost drivers provides a clear roadmap for targeted research and development efforts. By focusing innovation on these particular aspects of AGS implementation, we can systematically reduce costs and improve economic viability, bringing this promising technology closer to widespread commercial deployment.

Several studies have advanced our understanding of Advanced Geothermal Systems' performance. (Beckers et al., 2022) analyze closed-loop geothermal systems under various design and operational scenarios using Slender-Body Theory (SBT) modeling, COMSOL, and GEOPHIRES. Their results show U-loop designs yield higher heat output than co-axial ones, though all configurations experience rapid thermal decline and relatively high levelized costs, especially for electricity generation. Esmaeilpour et al. (2022b) conducted pioneering research on deep closed-loop systems, demonstrating that thermosiphon-driven flow maintains stability throughout the system's lifespan. Their subsequent work (Esmaeilpour et al., 2023; Esmaeilpour et al., 2022a) revealed that multilateral AGS configurations substantially increase energy extraction per meter of drilled wellbores, offering a pathway to improved economic viability. Wu et al. (2024) provided a comparative analysis of multilateral butted closed-loop geothermal systems, documenting their performance advantages over conventional U-shaped configurations. Complementing the findings, Brown and Falcone (2025) established that groundwater flow significantly enhances performance in multi-lateral, U-Type advanced geothermal systems, broadening our understanding of external factors affecting AGS efficiency. Collectively, these investigations demonstrate promising technological advancements that could address the economic challenges currently limiting widespread AGS deployment.

The above-mentioned studies provide valuable insights into AGS performance but exhibit important limitations, particularly in comprehensive economic evaluation. None fully accounts for critical cost factors such as permitting, exploration, surface plant infrastructure, and surface gathering systems for calculating electricity costs. In this study, we address this gap by developing an integrated AGS model coupled with a surface plant within the TANGO framework—a sophisticated tool for techno-economic analysis of geo-energy operations. This approach enables us to compute the complete cost of energy with unprecedented accuracy and comprehensiveness. Furthermore, we identify key parameters that significantly influence economic outcomes and optimize these variables to systematically reduce energy costs, providing a practical pathway toward enhancing AGS’ commercial viability.

2. SYSTEM DESCRIPTION

Advanced geothermal systems (AGS) typically comprise two deep vertical wellbores interconnected by one or more horizontal wellbores, forming a closed-loop configuration. Unlike open geothermal systems, AGSs do not involve mass exchange between the wellbores and the surrounding reservoir. This closed-loop design enables stable and safe operation, minimizing pressure losses and eliminating risks associated with fluid contamination and induced seismicity. The relatively low-pressure loss in AGSs allows for natural thermosiphon-driven circulation, where fluid motion is sustained by the density difference between the injection and production wellbores. This thermosiphon effect can significantly reduce or even eliminate the need for external pumping, thereby lowering internal energy consumption and improving system efficiency. However, it is important to note that in AGS, heat extraction is limited to the lateral area surrounding the wellbores. Consequently, to achieve meaningful energy output, the system requires deep and extended wellbore configurations, which inherently involve high drilling costs and increased operational risk.

A schematic representation of the advanced geothermal system is provided in Figure 1, Figure 2, and Figure 3, with detailed thermo-physical and geometrical parameters listed in Table 1 and Table 2. Two distinct power plant configurations are designed to accommodate water- and CO_2-based AGS. It is noteworthy that the wellbore systems shown in Figure 3 are cased and cemented in the vertical section, while the horizontal section is left uncased and is directly exposed to the hot formation. The horizontal section has a diameter of 0.4 meters, and the casing program for the vertical section is detailed in Table 2.

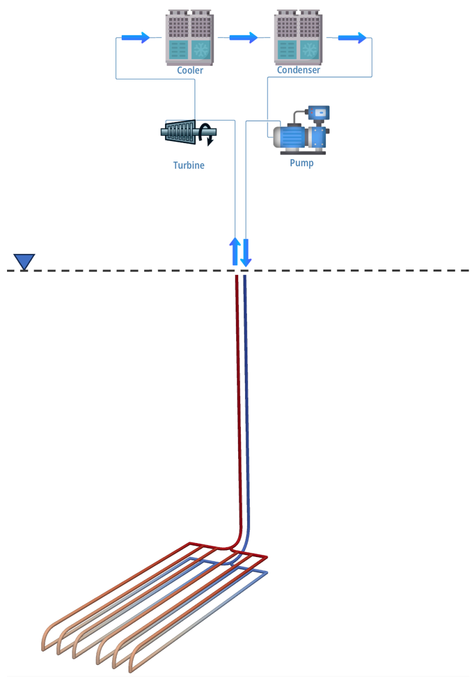

Figure 1: Schematic of the coupled AGS–surface plant system using CO_2 as the working fluid.

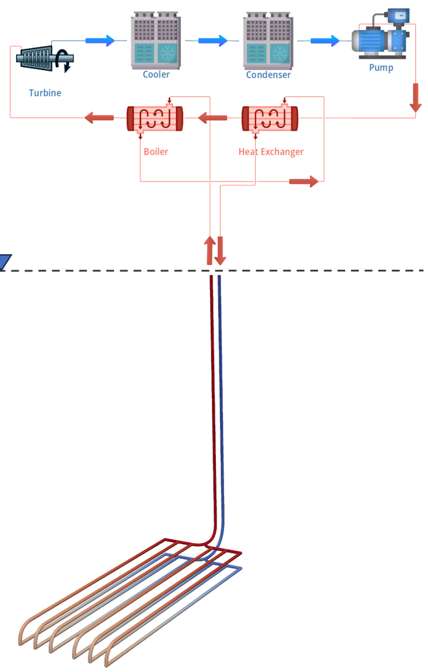

Figure 2: Schematic of the coupled AGS–surface plant system using water as the working fluid.

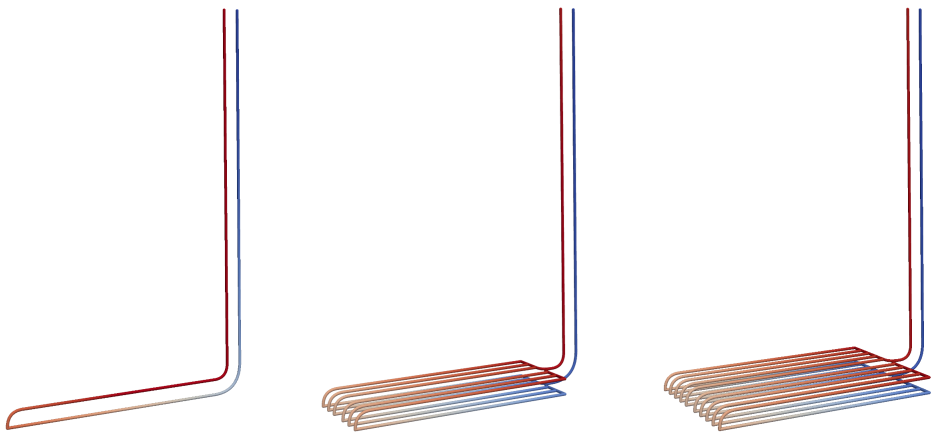

Figure 3: Various configurations of advanced geothermal systems (AGS): a) single-loop, b) six-loop, and c) twelve-loop setups

Table 1: Thermo-physical properties of formation, casing, and cement layer.

Formation density	Formation heat capacity	Formation thermal conductivity
2500 $kg.m^{-3}$	1000 $J.kg^{-1}.K^{-1}$	2.5 $W.m^{-1}$
Casing Thermal conductivity	Cement thermal conductivity	Roughness
43.75 $W.m^{-1}$	0.7 $W.m^{-1}$	0.0001 m
Subsurface temperature gradient	Surface temperature	
0.03 $C.m^{-1}$	15 C	

Table 2: Geometrical specifications used in the modeling.

Depth	Horizontal extension	Distance between parallel wellbores
5 km	2×3.3 km	200 m
Casing inner diameter	Casing thickness	Cement thickness
0.3 m	0.015 m	0.035 m

3. NUMERICAL MODELING

For the simulations presented in this study, we utilized TANGO, a Python-based tool for the Techno-economic ANalysis of Geo-energy Operations. TANGO models the entire geo-energy system—encompassing both surface and subsurface components—as a directional graph, where each node represents a physical component and directional edges carry fluid state and mass flow information from the outlet of one node to the inlet of the next. This graph-based structure enables a high degree of modeling flexibility, allowing users to design complex surface plants composed of multiple interconnected units or to simplify systems by encapsulating several nodes into a single entity. Additionally, TANGO supports coupling with external simulation tools (such as MOOSE-based applications (Permann et al., 2020; Gaston et al., 2009)) and enables the implementation of custom cost models, making it a powerful platform for integrated techno-economic analysis. For high-fidelity modeling of the Advanced Geothermal Systems, we employed the MOOSE-based wellbore simulator MOSKITO. The resulting subsurface models were then coupled to two different surface power plant configurations: an Organic Rankine Cycle (ORC) plant for water-based systems, and a specialized plant designed for CO_2 as the working fluid. For further details on the governing equations used in the wellbore modeling, readers are referred to (Esmaeilpour et al., 2022b; Esmaeilpour et al., 2024).

4. RESULTS

In this section, we model multi-lateral Advanced Geothermal Systems (AGS) employing two different working fluids: water and carbon dioxide (CO_2). While the use of CO_2 as a working fluid in AGS configurations may offer certain thermodynamic and operational advantages, its effectiveness remains uncertain and requires thorough evaluation through numerical modeling. Notably, CO_2 exhibits a strong sensitivity in density to variations in pressure and temperature, potentially enhancing the thermosiphon effect compared to water-based systems. This enhanced natural circulation could lead to improved system performance, but the exact impact on electric power generation, particularly in comparison with Organic Rankine Cycle (ORC) systems, must be quantified. Furthermore, using CO_2 may influence the capital and operational costs of the power plant relative to ORC setups. In our study, we explore AGS configurations with varying numbers of laterals, optimizing the flow rate in each case to minimize the Levelized Cost of Electricity (LCOE). These results are then compared against the LCOE values obtained for water-based systems, offering insights into the economic and technical viability of CO_2 as an alternative working fluid in AGS applications.

4.1. CO_2 as working fluid

In this section, we investigate AGS configurations utilizing CO_2 as the working fluid, focusing on systems with a single horizontal loop and multiple-loop arrangements. For single-loop systems (Figure 3a), flow rates between 25 kg/s and 70 kg/s were analyzed. The results (Figure 4 and Figure 5) indicate an optimal flow rate of approximately 55 kg/s, which agrees with findings by (Malek et al., 2022). Increasing the flow rate beyond this point has minimal to negative impacts on power generation, making further increases economically unjustifiable (Figure 6). In contrast, systems with 6 or 10 horizontal loops allow for higher flow rates and enhanced power generation. Nonetheless, care must be taken to ensure that the increased capital costs from additional loops are justified by proportional gains in electric power output. For example, at lower flow rates such as 55 kg/s, the 10-loop system exhibits a higher LCOE than the single-loop case, underscoring the importance of operating at sufficiently high flow rates to boost power generation and justify multi-loop investments.

Despite the theoretical advantages of using more loops, practical limitations constrain the achievable flow rates. Although increasing the flow rate to values even above 200 kg/s could further reduce the LCOE, this study is restricted to a maximum of 100 kg/s due to wellbore integrity concerns. Specifically, our model assumes a single vertical injection and production wellbore, which cannot accommodate such high flow rates without compromising structural stability. Exceeding this threshold would require multiple vertical wellbores, which falls outside the scope of this analysis. Consequently, while the 10-loop configuration is promising in concept, it becomes less economically attractive than the 6-loop alternative due to underutilization of its capacity and higher infrastructure costs. The lowest observed LCOE in this study is approximately \$1.2/kWh, achieved with a 6-loop system operating at 100 kg/s. While this cost remains relatively high, it demonstrates the potential of CO_2-based AGS, particularly as advancements in drilling technology and reductions in associated costs could significantly improve their economic viability.

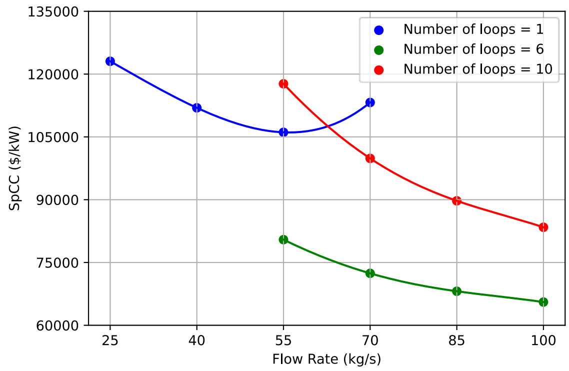

Figure 4: Variation of specific capital cost with flow rate for AGS using CO_2 as the working fluid.

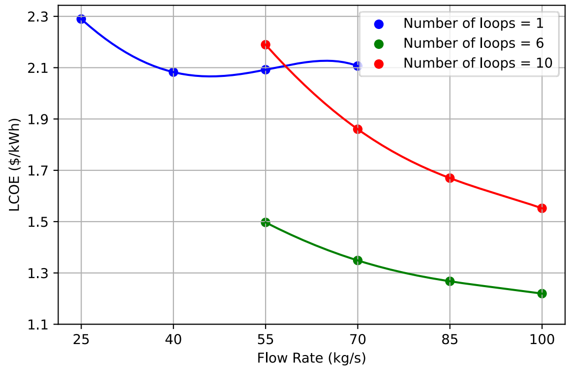

Figure 5: Variation of levelized cost of electricity with flow rate for AGS using CO_2 as the working fluid.

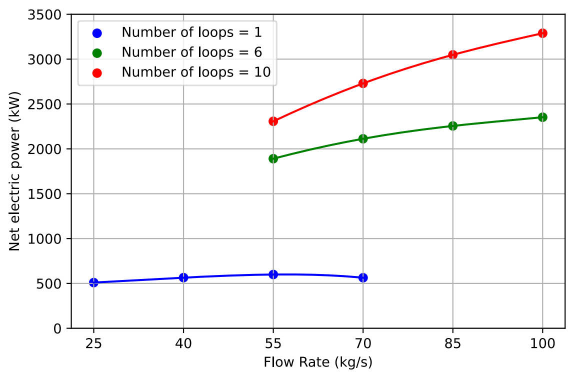

Figure 6: Variation of net electric power with flow rate for AGS using CO_2 as the working fluid.

4.2. Water as working fluid

A similar performance trend is observed for water-based AGS configurations; however, the resulting energy costs are significantly higher, compared to CO_2-based systems (Figures 7 and 8). This disparity is not due to increased capital expenditures but rather stems from the lower energy conversion efficiency at the surface. Specifically, Organic Rankine Cycle systems—commonly used for low-temperature geothermal applications—typically exhibit conversion efficiencies below 10%, with further reductions occurring at lower extraction temperatures. This inherently low efficiency is the primary driver behind the elevated LCOE values observed in water-based AGSs. The minimum LCOE values for single-loop, 6-loop, and 10-loop systems are achieved at approximately 50 kg/s, 73 kg/s, and 100 kg/s, respectively. While increasing the flow rate could theoretically yield higher power output, this study is constrained by a maximum flow rate of 100 kg/s in order to maintain wellbore integrity.

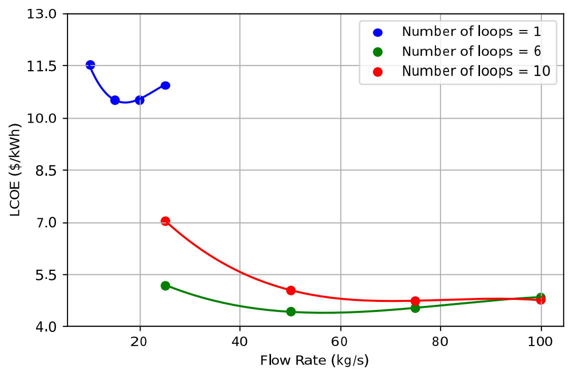

Figure 7: Variation of levelized cost of electricity with flow rate for AGS using Water as the working fluid.

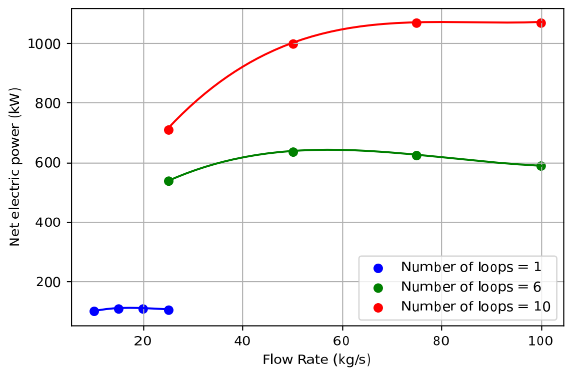

Figure 8: Variation of net electric power with flow rate for AGS using Water as the working fluid.

5. CONCLUSIONS

In this study, we integrated high-fidelity subsurface simulations of Advanced Geothermal Systems (AGSs) with surface plant modeling using the TANGO modeling framework—an advanced platform for the techno-economic analysis of geo-energy operations. Our analysis reveals that while current energy costs remain above the threshold for economic viability, they are not prohibitively high, particularly for CO_2-based AGS. In some scenarios, the levelized cost of electricity (LCOE) approached \$1/kWh, suggesting that with continued advancements and reductions in drilling costs, AGS have the potential to become a leading technology for geothermal power generation. Additionally, incorporating multiple subsurface loops was found to significantly lower energy costs, provided that flow rates are carefully optimized to enhance power output without overextending system constraints. The results further demonstrate that CO_2-based systems outperform water-based counterparts in terms of cost efficiency, primarily due to the higher energy conversion rates achievable with CO_2-based surface plants compared to traditional Organic Rankine Cycle (ORC) systems.

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