# Techno-Economic Study of Taiwan Advanced Geothermal Systems Technology

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## ABSTRACT

As global efforts to mitigate climate change intensify, demand for renewable energy technologies has increased substantially. Taiwan has established comprehensive energy transition policies, with geothermal energy recognized as a strategic renewable resource. However, conventional hydrothermal systems (CHS) face substantial exploration risks and limitations in scalability, creating a need for next-generation geothermal technologies. The U-shaped Closed-loop Geothermal System (UCGS), categorized as an Advanced Geothermal System (AGS), not reliant on groundwater and with minimal environmental impact, emerges as a promising technology with potential for scalable deployment.

This study utilizes the CMG STARS simulator to evaluate the modeling capabilities of UCGS through validation against the internationally recognized Eavor-Lite™ project. Subsequently, case studies incorporating geothermal reservoir parameters representative of Taiwan are conducted to assess UCGS performance. Sensitivity analyses are applied to investigate the impact of various geological and engineering parameters on heat extraction efficiency and power generation output. In addition, a preliminary techno-economic evaluation of UCGS implementation is performed.

The research demonstrates the applicability of numerical simulation for UCGS assessment and provides a quantitative foundation for evaluating thermal efficiency and power generation potential. The results show that the Levelized Cost of Energy (LCOE) for UCGS in Taiwan's present industrial environment exceeds the established geothermal Feed-in Tariff (FIT), limiting commercial feasibility in the current market context. Analysis of cost factors shows that drilling expenditures are the most influential factor for improving overall project economics. As drilling technology advances and costs decrease, UCGS could become a vital resource of Taiwan's renewable energy portfolio and support its net-zero emissions goals.

## 1. INTRODUCTION

As global efforts to reduce carbon emissions and address climate change accelerate, the development of renewable energy resources has gained significant momentum. Geothermal energy, with its high stability and low carbon emissions, is increasingly regarded as an essential component of future energy systems. Conventional hydrothermal geothermal systems are constrained by geological conditions and site selection, with potential risks of groundwater contamination and associated technical and regulatory challenges. Enhanced geothermal systems (EGS), while offering greater scalability, often require hydraulic fracturing, which may induce seismicity or contaminate groundwater, leading to public concerns.

The U-shaped closed-loop geothermal system (UCGS), classified as an advanced geothermal system (AGS), extracts subsurface thermal energy through lateral wellbores to generate electricity via heat exchange, offering broad applicability, reduced geological limitations, and minimal groundwater pollution risk. Compared with other renewables such as solar and wind power, geothermal energy provides continuous, weather-independent baseload electricity. Additionally, geothermal power generation produces negligible air pollutants, making it a highly valued source of green electricity for the industrial sector. Its relatively stable generation cost and small surface footprint highlight its considerable development potential and its essential role in supporting global renewable energy transitions and carbon neutrality targets. In this context, closed-loop geothermal systems, which provide controllability, low environmental risk, and independence from groundwater resources, are attracting increasing attention in both research and practical applications. The conceptual layout of the U-shaped closed-loop geothermal system is shown in Figure 1.

## 2. METHODOLOGY

This study employed the commercial simulator STARS, developed by Computer Modelling Group Ltd. (CMG), to perform numerical modeling of the U-shaped closed-loop geothermal system (UCGS). Using the preprocessor BUILDER, a three-dimensional model was first constructed (Figure 2), discretized into a computational mesh, and assigned reservoir parameters such as porosity and permeability for each grid block. Initial conditions, including temperature, pressure, and fluid saturation, were also defined to simulate the heat exchange behavior of UCGS underground.

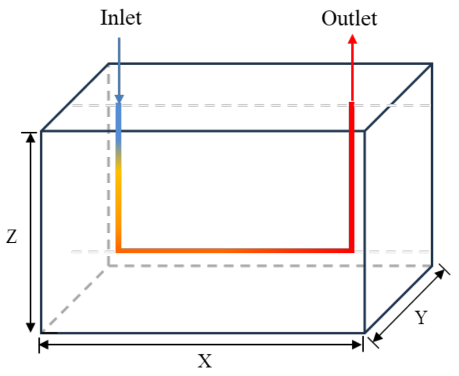


Figure 1. Conceptual schematic of a U-shaped Closed-loop Geothermal System (UCGS)

To verify the accuracy of the heat transfer calculations, the model was validated against field data from the Canadian Eavor-Lite™ demonstration project. This reference system consisted of a U-shaped closed loop formed by two vertical cased wells drilled to a depth of 2400 m within quartz sandstone, connected through two lateral wells, each 1700 m in length. Upon replicating this configuration and validating its results, confidence was established in the STARS-based UCGS simulation framework. Subsequently, the model was adapted to reflect the geological parameters of Taiwan's Datun Volcanic Group. A reservoir domain measuring 4380 m in length, 1600 m in width, and extending to a depth of 1000 m from the surface was defined. The mesh resolution was designed with 371 cells in the I-direction, 43 cells in the J-direction, and 34 cells in the K-direction, with local grid refinement near the wells to improve temperature calculation accuracy. After constructing the mesh, the reservoir's initial conditions and parameter data were specified. Both wells were modeled with an internal diameter of 0.159 m, which defines the effective heat transfer surface area and governs the fluid residence time for a given flow rate. The model incorporated an injection well and a production well, each 800 m deep, connected at a depth of 800 m through a 4000 m horizontal segment. The connection point between the injection and production wells was located at the end of the horizontal segment. Studies on closed-loop geothermal systems, such as the Eavor-Lite™ project, have demonstrated that when circulation is driven by the thermosiphon effect, the achievable flow rate is fundamentally governed by the temperature-induced density difference between the injection and production wells, the vertical elevation difference, and friction losses within the loop, rather than being a controllable parameter. (Beckers et al. 2022) emphasize that under steady-state conditions, fluid circulation is fully sustained by natural buoyancy forces resulting from subsurface thermal gradients, eliminating the need for external pumping except during initial start-up phases. Consequently, the circulating flow rate in thermosiphon-driven systems is physically constrained by these thermal and geometric factors rather than being an arbitrarily set design parameter. Field measurements and techno-economic evaluations of the Eavor-Lite™ system support this understanding, confirming that the operational flow rate reflects the natural thermosiphon-driven circulation inherent to the system configuration and subsurface conditions (Beckers et al., 2022). Water was chosen as the working fluid; we prescribe a base-case flow rate of 240 $m^3$ $day^{-1}$ at an injection temperature of 80 °C, with continuous 20-year, pump-free operation consistent with the Eavor-Lite™ project. Operating conditions are summarized in Table 3. The model geometry and local grid refinement are shown in Figure 2, while reservoir properties and initial conditions are summarized in Table 1 and Table 2.

For this study, a reservoir temperature of 243 °C at 800 m depth was used as a high-temperature scenario to evaluate the upper performance limits of the U-shaped closed-loop system. While such temperatures typically indicate a permeable geothermal reservoir suitable for conventional open-loop development, the closed-loop configuration was retained here to isolate thermal performance from hydrogeological variability and to explore applications in regions where environmental or water-availability constraints limit fluid extraction.

| Parameter | Value | Unit |
|---|---|---|
| Porosity | 0.0587 | – |
| Permeability (I×J×K directions) | 0.03 | mD |
| Heat capacity (rock) | $1.68\times10^6$ | J/m³·°C |
| Thermal conductivity (rock) | 2.1 | W/m·K |
| Thermal conductivity (water) | 0.591 | W/m·K |

**Table 1. Geological Parameters for the Simulation**

| Parameter | Value | Unit |
|---|---|---|
| Surface temperature | 25 | °C |
| Reservoir temperature | 243 | °C |
| Temperature gradient | 30 (>685 m) / -4.8 (<1500 m) | °C/100 m |
| Initial pressure at 1000 m | 10.08 | MPa |

**Table 2. Initial Reservoir Conditions**

| Parameter | Value | Unit |
|---|---|---|
| Injection well depth | 800 | m |
| Production well depth | 800 | m |
| Horizontal well length | 4000 | m |
| Injection rate | 240 | m³/day |
| Injection temperature | 80 | °C |
| Simulation period | 20 | years |
| Thermal–electric conversion efficiency | 11.5 | % |

**Table 3. Operating Conditions for the UCGS Simulation**

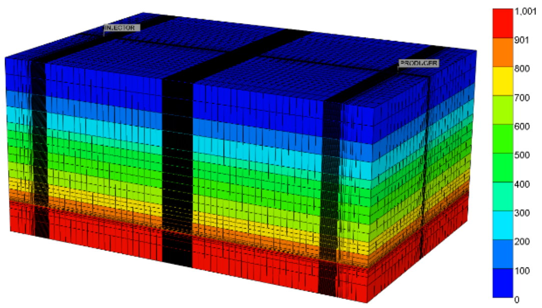


**Figure 2. Three-dimensional numerical model with refined grid around the UCGS wellbore sections. Colours indicate the grid top depth (m), as shown in the colour bar.**

## 3. RESULTS AND DISCUSSION

### 3.1 Model Validation Results

To verify the ability of the CMG-STARS simulator to accurately calculate heat transfer behavior in closed-loop geothermal systems, a three-dimensional model was first constructed based on the Canadian Eavor-Lite™ project. This system consists of two vertical wells approximately 2400 m deep, connected by two horizontal sections, each 1700 m in length, forming a closed U-shaped loop through which the working fluid absorbs subsurface heat and returns to the surface. The simulation adopted well depths, lateral lengths, and reservoir parameters consistent with those reported for the field, along with published injection rates and initial temperature conditions.

To further verify the model, the U-shaped closed-loop geothermal system was divided into three parts for validation: (1) the injection section, (2) the horizontal section, and (3) the production section. For each case, the numerical results were compared with the corresponding Ramey analytical solution for a cold water injection problem. Temperature continuity was imposed by setting the outlet temperature of the injection section equal to the inlet temperature of the horizontal section, and the outlet temperature of the horizontal section equal to the inlet temperature of the production section (Figure 3). This design preserves continuous heat flow along the loop and allows the simulated heat exchange to reflect realistic conditions, thereby verifying the simulator's heat transfer calculations

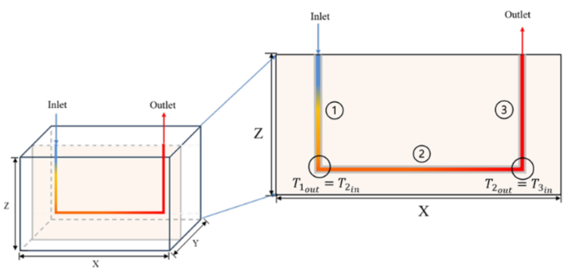


**Figure 3. U-loop validation: three segments: injection, horizontal, production**

The simulation results showed that the production well outlet temperature was approximately 51.25 °C, showing excellent agreement with the observed field value of 50 °C, thereby validating the accuracy of the constructed numerical model and supporting its application to subsequent simulations under Taiwanese geological conditions. Key parameters for the Eavor-Lite™ validation are listed in Table 4.

| | Parameter | Value | Unit |
|---|---|---|---|
| Geological Parameters | Water thermal conductivity | 50630.4 | J/m/day/°C |
| | Rock thermal conductivity (near-well region) | $1.94 \times 10^5$ | J/m/day/°C |
| | Rock thermal conductivity (formation scale) | $4.01 \times 10^5$ | J/m/day/°C |
| | Rock density | 2663 | kg/m³ |
| | Rock specific heat | 1112 | J/kg/K |
| | Rock volumetric heat capacity | $2.96 \times 10^6$ | J/K/m³ |
| | Core porosity | 2~28 | % |
| | Core permeability | 0.01~108 | mD |
| Initial & boundary conditions | Formation temperature @2400m | 78 | °C |
| | Geothermal gradient | 0.03 | °C/m |
| | Surface temperature | 5 | °C |
| Well design | Casing outer diameter (OD) | 0.178 | m |
| | Casing inner diameter (ID) | 0.159 | m |
| | Cement thickness | 0.035 | m |
| | Horizontal lateral length | 1700 | m |
| | Vertical well depth | 2400 | m |
| | Cemented interval | 610 | m |
| | Thermal conductivity (cement) | $1.04 \times 10^5$ | J/m/day/°C |
| | Thermal conductivity (casing) | $3.73 \times 10^6$ | J/m/day/°C |

**Table 4. Geological parameters and initial conditions for the Eavor-Lite™ validation case**

### 3.2 Case Study in Datun

After completing the Eavor-Lite™ model validation, this study further developed a three-dimensional numerical model using the Datun Volcanic Group as a representative geological setting to assess the geothermal potential of a U-shaped closed-loop geothermal system (UCGS) under local conditions. The Datun volcanic area is characterized by significant geothermal anomalies and a history of volcanic activity, with a high geothermal gradient, making it a key indicator region for evaluating closed-loop geothermal prospects.

The three-dimensional geological model covered an area of 4380 m × 1600 m × 1000 m extending downward from the surface. The injection and production wells were each designed with a vertical depth of 800 m, connected at the target reservoir depth through a 4000 m horizontal lateral section. The internal grid resolution was refined to enhance simulation accuracy, with 371 cells in the I-direction, 43 cells in the J-direction, and 34 layers in the K-direction. Further local grid refinement was applied near the wellbores to accurately capture near-well thermal variation and heat transfer behavior.

Reservoir parameters, including rock heat capacity, thermal conductivity, specific heat, porosity, and permeability, were assigned based on literature data and exploration reports. Water was used as the working fluid, with an injection and production flow rate of 240 m³/day and an injection temperature of 80 °C, simulating the thermosiphon effect.

The simulation period was set to 20 years, with monthly outputs of wellhead temperature and related data. Results indicated that the UCGS maintained high thermal stability under these conditions, with the production well outlet temperature rapidly increasing to approximately 154 °C in the initial simulation stage and remaining stable with no significant decline over the entire simulation period. The 20 year outlet-temperature trajectory is shown in Figure 4.

Temperature profiles along the lateral segment showed that the working fluid, upon entering the reservoir at 80 °C, was rapidly heated to over 150 °C and maintained a stable temperature in the middle section of the lateral well. This result demonstrates the high heat exchange efficiency of the wellbore system. Overall, the temperature profiles confirmed that the closed-loop design effectively facilitated long-distance heat exchange, with the horizontal lateral section continuously and efficiently absorbing geothermal energy.

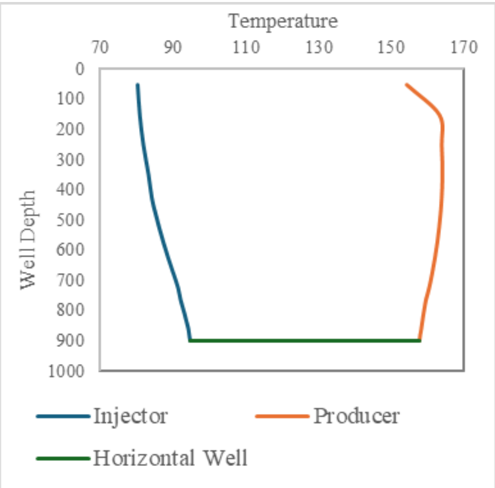


**Figure 4. Temperature Profile Along Injection, Horizontal, and Production Well Sections in the UCGS Model.**

**3.3 Sensitivity Analysis**

To investigate the influence of well segment design on the system's heat exchange performance, this study conducted a sensitivity analysis by varying the horizontal well length. Under otherwise identical simulation conditions—including injection and production well depths of 800 m, injection rate, and reservoir parameters—horizontal well lengths of 1000, 2000, 3000, 4000, 5000, 6000, 7000, and 8000 m were modeled, and their production well outlet temperature performances were compared. Representative 20-year outlet-temperature time series for different lateral lengths are shown in Figure 5.

The results indicated that the outlet temperature increased with longer lateral well segments. For the shortest lateral well of 1000 m, the outlet temperature was only about 125.5 °C, whereas it rose to 154.3 °C at 4000 m, reaching its maximum. When the lateral length continued to extend to 8000 m, the outlet temperature slightly declined to 151.8 °C, suggesting the existence of an optimal heat exchange range; beyond a certain length, the marginal thermal benefit plateaued or even declined, potentially due to reduced heat transfer efficiency.

These findings highlight lateral well length as a key parameter controlling thermal performance. While appropriately extending the lateral segment improves heat extraction, it is also necessary to consider the diminishing heat exchange efficiency. Future practical applications are recommended to integrate economic and engineering feasibility assessments to determine the optimal well length range.

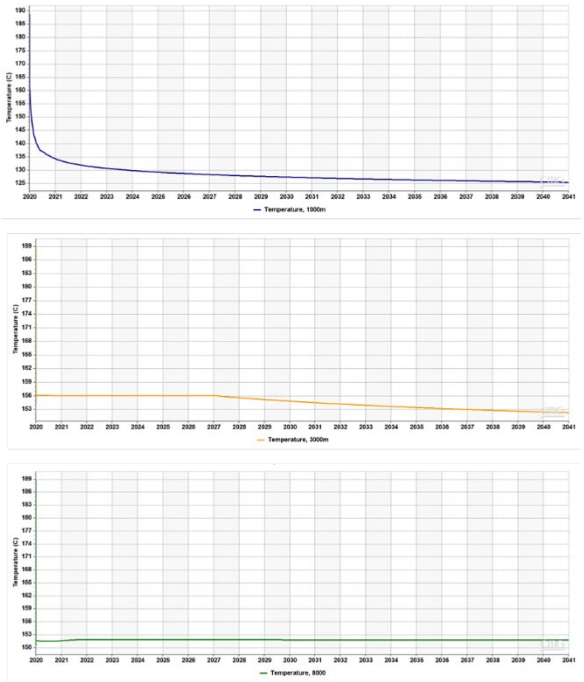

**Figure 5. Temporal variation of production well outlet temperatures over a 20-year simulation period for three representative lateral well lengths: (a) 1000 m, (b) 3000 m, and (c) 8000 m.**

**4. Techno-Economic Assessment**

**4.1 Analytical Method**

To evaluate the economic feasibility of U-shaped closed-loop geothermal systems (UCGS) in Taiwan, this study employed the levelized cost of energy (LCOE) as the primary techno-economic indicator to estimate the total cost per unit of generated electricity as defined in Equation (1). The LCOE framework comprehensively accounts for initial capital expenditures, operating costs over the system lifetime, installed capacity, and capacity factor.

In this study, the simulation scenarios considered injection and production wells with depths of 800 m and horizontal lateral sections ranging from 1000 to 8000 m. Based on the simulation results, thermal outputs and installed capacities were determined for each configuration and then converted using a thermal-to-electric conversion efficiency of 11.5%

(Table 4). For example, with a 4000 m lateral length, the outlet temperature reached approximately 154.3 °C, corresponding to an enthalpy of 650.88 kJ/kg and an installed capacity of 101.02 kW.

The LCOE was calculated as:

$$LCOE = \frac{C_{capital} \cdot CRF + C_{O\&M}}{W \cdot CF \cdot 8760} \qquad (1)$$

Where $C_{\text{capital}}$ represents the total system capital investment, including well construction, surface facilities, and power plant installation, amounting to USD 12.83 million. The annual operating and maintenance cost $C_{O\&M}$ comprises well maintenance USD 59,563, plant maintenance USD 84,063, and labor costs USD 270,375, totaling USD 414,000 per year. Limitations and implications. LCOE is a static average and does not account for temporal variability, curtailment, market-price dynamics, or policy transfers. Holding $C_{\text{capital}}$ and $C_{O\&M}$ constant, LCOE decreases only as annual energy increases.

The discount rate was set at 5.25%, based on Taiwan's Ministry of Economic Affairs' 2024 renewable feed-in tariff report, and the project lifetime was assumed to be 20 years. Consequently, the capital recovery factor (CRF) was calculated as 0.0819. The capacity factor (CF) was set to 0.731, based on the stable operation characteristics of closed-loop systems and international operational data.

These parameters collectively allowed for the estimation of the LCOE, which could then be compared with the current geothermal feed-in tariff (FIT) to assess the potential investment value of closed-loop systems under Taiwanese conditions.

| Well Length (m) | Outlet Temperature (°C) | Enthalpy (kJ/kg) | Installed Capacity (kW) | C_capital (million NT$) | LCOE (NT$/kWh) |
|---|---|---|---|---|---|
| 1000 | 125.5 | 527 | 61.4 | 82.1 | 50.83 |
| 2000 | 140.2 | 589.9 | 81.5 | 114 | 43.32 |
| 3000 | 152.3 | 642 | 98.2 | 146.1 | 40.13 |
| 4000 | 154.3 | 650.9 | 101 | 178.1 | 43.06 |
| 5000 | 153.1 | 645.4 | 99.3 | 210.1 | 47.95 |
| 6000 | 152.1 | 641.1 | 97.9 | 242.1 | 52.8 |
| 7000 | 151.6 | 639.1 | 97.3 | 274.2 | 57.35 |
| 8000 | 151.8 | 640 | 97.5 | 306.2 | 61.39 |

**Table 5. Sensitivity Analysis Results for Different Horizontal Well Lengths**

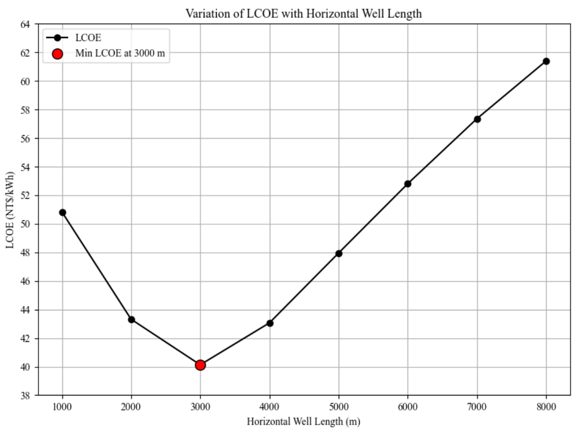


**Figure 6. Variation of the levelized cost of energy (LCOE) with horizontal well length.**

### 4.2 LCOE Calculation Results and Comparative Analysis

According to the simulation results, the UCGS system with a lateral length of 4000 m achieved an installed capacity of 101.02 kW and an average enthalpy of 650.88 kJ/kg. Using the techno-economic model, the calculated LCOE was NT$43.06 per kWh, which still exceeds Taiwan's current geothermal feed-in tariff (FIT) of NT$5.80 per kWh despite being more cost-effective than shorter lateral designs, highlighting challenges for commercial deployment under existing cost structures.

To further explore the economic impact of lateral well length, this study integrated simulation results of thermal output, installed capacity, and drilling cost variations across lateral lengths from 1000 to 8000 m. The results revealed that installed capacity increased significantly with lateral length, from 61.4 kW at 1000 m to 101 kW at 4000 m, while the LCOE exhibited a decreasing-then-increasing trend (Figure 6), reaching its lowest value of NT$40.13 per kWh at a lateral length of 3000 m, representing the most economically favorable scenario. Beyond this length, although installed capacity and outlet temperatures remained high, the increased drilling costs caused the LCOE to rise, reducing overall cost competitiveness.

Shorter lateral configurations, such as 1000 to 2000 m, were found to suffer from lower outlet temperatures due to limited reservoir contact area and shorter residence time, resulting in lower enthalpy and installed capacity, which in turn increased the unit cost of electricity. In contrast, medium-length laterals (3000–4000 m) achieved a favorable balance between efficiency and investment costs, making them the most promising practical design range.

In summary, although the estimated LCOE values in this study did not meet the current geothermal feed-in tariff, future advances in drilling technology, improvements in thermal-electric conversion efficiency, and supportive policies could enable UCGS to become a viable and stable renewable energy option.

## 5. Conclusions

This study evaluated the technical and economic potential of U-shaped closed-loop geothermal systems (UCGS) in Taiwan by combining three-dimensional numerical simulations with a cost assessment approach. The CMG-STARS simulator was utilized, first validating the model against field data from the Canadian Eavor-Lite™ project, and then applying geological parameters of the Datun Volcanic Group to develop a parametric model covering horizontal well lengths from 1000 to 8000 m. The feasibility of closed-loop systems under Taiwanese geothermal conditions was analyzed based on these models.

The simulation results demonstrated that UCGS systems could maintain stable thermal output over a 20-year operating period. Under well designs with lateral lengths of 3000–5000 m, outlet temperatures at the production well exceeded 150 °C, indicating good thermal stability and predictable long-term operation. The results further highlighted that the 3000–5000 m range achieved the highest outlet temperatures, representing the best operational performance and confirming the practical potential of closed-loop systems for Taiwan's geothermal resources.

The economic calculations revealed that the installed capacity of UCGS systems increases with lateral well length, while the LCOE exhibited a decreasing-then-increasing trend. This reflects that the economic benefits of extended lateral lengths diminish beyond a certain range. At a lateral length of 3000 m, the lowest LCOE was calculated as NT$40.13 per kWh, representing the most favorable configuration in this study. Nevertheless, the overall LCOE remained higher than the current geothermal feed-in tariff of NT$5.80 per kWh, indicating that the primary challenge for UCGS deployment in Taiwan is the high drilling and construction cost.

Despite these challenges, UCGS offers significant advantages in technical safety and environmental friendliness due to its closed and modular design, which effectively avoids the environmental risks associated with hydrothermal and enhanced geothermal systems, such as induced seismicity and groundwater contamination. With future advances in localized drilling technology, improved thermal-to-electric conversion efficiency, reduced construction costs, and the support of carbon pricing mechanisms or government subsidies, UCGS could become a stable renewable energy supply option in Taiwan's energy portfolio, providing a flexible and sustainable geothermal solution for the path toward net-zero transformation.

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