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Arrays of Networked Standard Geothermal Wells

Robert Metcalfe[1], Emmanuel Lujan[1], Collin Wittenstein[1],
Andrew Inglis[2], Alan Edelman[1]

[1]Julia Lab, Computer Science & Artificial Intelligence Laboratory, Massachusetts Institute of Technology
[2]MIT Proto Ventures, Cambridge, Massachusetts, USA'
32 Vassar St, Cambridge, 02139 MA

Corresponding Author: Robert Metcalfe, etherdad@gmail.com

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ABSTRACT

Time to scale the harvesting of geothermal heat for conversion to grid electricity. And not just because geothermal is clean. No, we choose geothermal because it is firm, inexhaustible, safe, and competitively harvestable almost anywhere (cheap). How best to scale geothermal? We urge the development of… geothermal arrays. With our Internet mindsets in place, let's not continue toward ever bigger geothermal mainframes. Instead, let's deploy geothermal arrays by networking smaller, standard, competitively-sourced wells. While accelerating progress continues at the well level, in this paper let's move up to the "array" level. We engage in dialogue with a large language model (GPT) about how soon we can deliver energy with capacity factors (CFs) approaching 100% and with levelized costs of electricity (LCOE) at a new plateau, less than a cent per kilowatt-hour (<1¢/kWh).

ARTIFICIAL INTELLIGENCE LLM DISCLAIMER

What follows is based on an extended, iterative dialogue with an OpenAI ChatGPT (OpenAI, 2026) large language model (LLM). Although limitations remain, empirical evaluations indicate that LLMs can provide non-trivial and informative responses in the geothermal energy domain (Ouko et al., 2025; Weers et al., 2024; Mahjour et al., 2024; Deng et al., 2024). We continually asked the LLM for designs, calculations, and scenarios that might drive geothermal arrays toward ultra–low levelized cost of electricity (LCOE). Many of the inventive concepts, numerical estimates, and parameter sweeps presented here were first proposed by the LLM in response to open-ended prompts.

We have not independently derived or rigorously validated every equation, numerical value, or thermodynamic result produced by the LLM. Instead, our intent is to explore which ideas might be worth further analysis and simulation, while openly acknowledging that some intermediate steps may be under-developed, unoriginal, misleading, incomplete, internally inconsistent, or simply wrong. We view this as an inherent part of using LLMs as ideation engines: the value lies in surfacing potentially novel or hidden design directions—such as array-level economics, deferred drilling strategies, and high-CF micro-grid architectures—that can then be stress-tested with high-fidelity modeling and real-world data. As such, this manuscript should be read as a forward-looking, exploratory scaffold for future engineering work, not as a finalized design.

1. INTRODUCTION

1.1 What exactly is a "Geothermal Array"?

Geothermal arrays, also referred to as deep borehole heat exchanger (DBHE) arrays, have been investigated through different field experiments and a variety of numerical modeling studies (Kolo et al., 2024; Cai et al., 2021; USGS, 2025; Seib et al., 2022; Wittenstein et al., 2026; Ouko et al., 2025). In a geothermal array, each well has its own access to the subsurface (e.g., injection and production pipes, maybe coaxial, probably closed). The well also has its own working fluid (water for now), controlled circulation pump, heat exchanger, thermal to electric (T2E) converter (e.g., turbine, generator, Organic Rankine Cycle (ORC) unit), condenser, cooling fans and fins, and micro-grid connection through which to send and receive power and control. The wells have standard connections so that robot vans can deliver and automatically install boreholes and subsystems including borehole pipes, turnaround, surface exchanger, TEF (e.g., ORC), generator, cooling fans and fins, and micro-grid connection. When in operation, the wells can aggregate generated power through the array's micro-grid bus, and back up one another. It's probably not a good idea to spend too much time debating what an array is… exactly. Let's come up with some standards, build some arrays, and iterate down the learning and innovation curves.

1.2 Driving By A Geothermal Array

We see in the distance an electricity substation at the corner of one of our larger geothermal arrays. It's a 10x10 array with 200 meter separations covering 4 square kilometers (including perimeter spacing). That's around 1000 acres generating maybe a gigawatt (GW) of electricity. Each element of the 100-well array is a pad about 200 meters away from its neighbors. This leaves plenty of room between the well pads to avoid interference among their megawatt (MW) plumes—cooling plumes below ground and heating plumes above ground. Each well has fans and fins for dispersing waste heat. It has lanes up and down the rectangle providing well access for competing fleets of configurable robot vans. The vans are deployed as needed by array controls. At the array the vans drill boreholes, perform subsystem installation, (re)drill, and continue maintenance of the automated array. Robot vans drilled and completed wells that would later power them. They installed the array's surface subsystems including, say, four redundant and shared points of interconnection (POIs) to grid substations. The robot vans are then dispatched to their next well assignments after an Uber-like process among competing van fleets. Growing armies of robot vans use power from early wells to drill and power later wells, and to recharge the vans. No diesel.

Below ground, a micro-grid carries a direct current (DC) power bus and Ethernet (;->) control network. Each well is connected one way or another to all the other wells. At each corner of the rectangular array are redundant utility grid interconnects. Micro-controllers monitor array operation and reconfigure using pumps, valves, switches, software, and robots. When wells fail, others come to the interim rescue—the array has plenty of power headroom (~5%). Arrays might even network with distant arrays for added help adding power to the grid. Individual geothermal wells have capacity factors (CFs) of perhaps 95%, way higher than wind or solar. By using redundant micro-grid connections, the array as a whole has a CF approaching 100%. What's that worth?

Subsystems of the array are built by fiercely competing third parties, far away, according to open industry standards. One obvious array standard is for subsystems delivered in interstate trucks, no wider than 2.6 meters. Meeting this standard, well subsystems can be manufactured competitively and delivered from afar without escorted wide loads. Another key standard is for the fittings on which the van robots drop and fasten subsystems. These sit atop standard power and control jacks, injection and production pipes, and exhausts to cooling fans and fins. These trucks carry standard subsystems from their suppliers. The trucks offload their cargos, for example reusable drilling pipes and circulation pumps, onto the robot vans, which install them, or carry them for storage on shelves along the lanes.

As decades go by, wells evolve and subsystems wear at different rates. Sensors and software catch the different changes and forecast operation at the 100 thermal management points. Each well is managed independently and yet in coordination with the array. Micro-controllers reconfigure the array by tweaking pumps and valves, by dispatching vans. As well drawdowns diverge over the decades, vans (re)drill, repair, and upgrade the wells at various depths. Wells can be added according to demand or decommissioned when drawn down. More efficient T2E converters (e.g., ORCs) can be substituted. Each well can be moved back and forth between mining mode and recharging mode.

When power is abundant, because of increasing supply or decreasing demand, well circulation pumps can be slowed or stopped, leaving the extra heat in the Earth. Better, any excess heat might be converted to electricity and used to power flexible energy users like data centers, water desalination, hydrogen electrolysis, electric vehicles, bitcoin mining... They will take all the excess power they can get.

Imagine the grid controllers discovering that more power is needed soon. Instead of just drilling a new well at their array's frontier, they might order the replacement of an existing well with much higher efficiency subsystems. The well attachment standard should accommodate technology upgrades like this. Out with the old well subsystems, in with the new. No redrilling required. Or maybe redrilling an existing well will suffice in meeting increased power demand.

With ongoing maintenance, replenishment, and upgrades, geothermal arrays might last forever. Or, arrays might be retired sooner than forever by learning curves and technological obsolescence. Each well also serves its array as exploration. Early drilling and operating results might cause some unpromising wells to be skipped or others to be drilled between high producing wells.

As we drive on past the array, we wave at the ORCs cooling their fins, and several robots scurrying around. We'll need ~10,000 geothermal arrays of about this size to solve energy.

2. SUB-CENT LCOE GEOTHERMAL WELL ARRAYS

This section presents LLM-generated results exploring the design and techno-economic performance of closed geothermal well arrays targeting sub-cent per kilowatt-hour electricity costs.

2.1 Levelized Cost of Electricity and Capacity Factor for Geothermal Arrays

Levelized Cost of Electricity (LCOE) is adopted as the key performance indicator for assessing the economic competitiveness of geothermal arrays. LCOE accounts for the time value of money by discounting capital and operating expenditures and electricity revenues over the project lifetime. Recent new-build benchmarks (Lazard Ltd, 2025) indicate typical LCOE values of about 7.8 ¢/kWh for utility-scale solar PV, 8.6 ¢/kWh for onshore wind, ~11 ¢/kWh or higher for new geothermal, 17–22 ¢/kWh for coal and nuclear, and above 25 ¢/kWh for gas peakers. These figures motivate a strategic target of reducing the LCOE of geothermal arrays to below 1 ¢/kWh, establishing a new cost plateau for firm, low-carbon electricity.

Capacity factor (CF), defined as the ratio of actual energy produced to the energy that would be generated at continuous nameplate operation, is a complementary performance metric. While solar and wind typically exhibit CFs of 15–30% and 30–45%, respectively, geothermal systems can sustain CFs above 90% due to the continuous availability of subsurface heat. Closed and networked geothermal arrays further enhance reliability and redundancy, potentially driving system-level CFs toward unity. The combination of very high capacity factors, aggressive cost reduction through standardization and large-scale deployment, underpins the feasibility of achieving sub-1 ¢/kWh LCOE for geothermal arrays.

2.2 Baseline: Closed Geothermal Well

Using ChatGPT 5.2 (OpenAI, 2026) as an exploratory design and reasoning tool, we queried it for a representative baseline configuration of a deep, coaxial, closed geothermal well and for approximate performance and cost estimates. The LLM proposed a pipe-in-pipe configuration in a single borehole, with cold working fluid injected downward through the annulus, heated conductively by the surrounding formation, and returned to the surface through an inner production pipe. A sealed U-turn at the bottom was assumed to ensure fully closed operation without formation fluid production. Surface heat conversion was assumed to be performed by a conventional ORC.

For an illustrative case corresponding to a depth of 5 km, a geothermal gradient of 25 °C/km, and a mass flow rate of 50 kg/s, the LLM estimated a well's thermal power output of approximately 14–16 MWth and a net electrical output of about 1–1.5 MW, assuming ORC efficiencies and capacity factors (90–95%) consistent with current technology. On this basis, the model predicted a LCOE of roughly 11.2 ¢/kWh, well above the target of <1 ¢/kWh.

When prompted to explore optimistic technological improvements—such as the use of conductive cement, vacuum-insulated tubing, and a 50% reduction in drilling costs—the LLM predicted that the LCOE could be reduced to approximately 5.6 ¢/kWh, but still not to the sub-cent regime. Within the internal logic of these LLM-generated scenarios, this indicates that incremental, single-well enhancements by themselves may be unlikely to reach <1 ¢/kWh. Array-level deployment could be a plausible pathway to further cost reductions, through mechanisms such as shared surface infrastructure, learning-curve effects in drilling and power conversion, and system-level capacity factors approaching unity, which together could potentially enable substantially lower LCOE.

2.3 A Pathway to Sub-Cent LCOE: Closed Geothermal Well Arrays

Here, we present a design proposed by the LLM for a deep, closed, coaxial geothermal well module intended for deployment in large, standardized well arrays. The objective is to identify the conditions under which a LCOE below 1 ¢/kWh can be achieved.

2.3.1 System Concept and Architecture

The array concept consists of a vertical, sealed, pipe-in-pipe (coaxial) well drilled to 8 km true vertical depth in a conductive geothermal gradient of 25 °C/km, a surface rock temperature of 15 °C, yielding a formation temperature of approximately 215 °C at total depth. Fluid circulation occurs in a closed loop: cold working fluid is injected downward in the annulus, heated conductively by the surrounding rock, and returned to the surface through an insulated inner production pipe. No formation fluids are produced, and no hydraulic stimulation is employed. The well terminates in a sealed U-turn at depth, enabling continuous circulation without reservoir depletion.

At the surface, thermal energy is transferred through a heat exchanger to a centralized, air-cooled ORC plant shared among many identical wells. This array-optimized architecture eliminates the cost penalty of bespoke per-well power blocks and enables economies of scale in turbomachinery, cooling, and balance-of-system infrastructure.

2.3.2 Heat-Transfer Enhancement

The array configuration incorporates three mandatory completion features:

1. Vacuum-insulated tubing (VIT) in the upper 2 km to suppress parasitic heat losses to cooler formations and preserve produced fluid temperature.
2. High-conductivity cement (effective thermal conductivity ≥ 5 W m^{-1} $°C^{-1}$) over the lower 2 km to enhance radial heat flux from the hottest rock.
3. A sealed "radiator" section of approximately 1 km at the bottom of the well, employing enlarged outer-diameter liners and high-conductivity materials to increase effective heat-exchange surface area without inducing fluid exchange or fracturing.

Together, these measures raise the formation-to-fluid heat-transfer coefficient sufficiently to sustain a mass flow rate of 90 kg s^{-1} with a surface temperature lift of roughly 150 °C.

2.3.3 Steady-State Thermodynamic Performance

Injection temperature at the surface is assumed to be 50 °C after heat extraction in the ORC condenser, while the produced fluid temperature is maintained near 200 °C owing to the combined effects of depth, insulation, and enhanced conduction.

The resulting steady-state thermal power delivered to the surface heat exchanger is

$\dot{Q} = \dot{m}\, c_p\, \Delta T \approx 90 \times 4.2 \times 150 \approx 56.7$ MWth.

Assuming a net ORC conversion efficiency of 18%, consistent with air-cooled systems operating at 200 °C source temperature, the net electric output per well is approximately 10 MWe. With an array-level capacity factor of 97%, enabled by closed-loop operation and modular redundancy, the annual energy production per well reaches approximately 85 GWh.

2.3.4 Economic Assumptions and Array Cost Allocation

The economic model departs explicitly from the traditional "one well–one power plant" paradigm, by sharing surface power conversion, cooling, and electrical infrastructure costs across a large number of identical wells, getting to greatly reduced per-well allocations (Table 1).

Table 1: Component costs for closed geothermal well arrays.

Component	Cost (USD, per well allocation)	Notes
Drilling + casing + completion	2.4 M	Learning-curve cost at scale
Vacuum-insulated tubing (2 km)	0.6 M	Loss suppression
Conductive cement + radiator	0.9 M	UA enhancement
Shared surface plant & BOS	1.5 M	ORC, cooling, grid
Total CapEx	5.4 M	Real USD

Fixed operation and maintenance costs are taken as 2% of capital per year. Financial evaluation is performed using a real weighted average cost of capital of 6% and a project life of 30 years, corresponding to a capital recovery factor of 0.07265.

2.3.5 Levelized Cost of Electricity

Annualized capital cost is therefore approximately 392 kUSD per well, and annual O&M adds 108 kUSD, for a total annual cost of 500 kUSD. Dividing by the annual energy production of 84.97 GWh yields

$\mathrm{LCOE} \approx 500{,}000 / 84.97\times10^{6} \approx 5.9\times10^{-3}$ USD $\mathrm{kWh}^{-1} \approx 0.589$ ¢ kWh^{-1}.

Under the stated thermodynamic and financial conditions, this configuration satisfies the sub-1 ¢/kWh target with substantial margin.

2.3.6 Sensitivity and Design Validity

The feasibility of this result rests on several non-negotiable requirements:

- Net electric output per well must remain in the multi-megawatt range; reducing output from 10 to 5 MWe approximately doubles LCOE.
- Total capital expenditure per well must remain below ~10 MUSD.
- Produced surface temperature must exceed ~180 °C to sustain ORC efficiencies near 18%.
- Surface facilities must be shared at array scale and capacity factor must exceed ~90%.

These constraints indicate that sub-cent geothermal electricity is not a generic property of closed systems, but rather the consequence of a tightly coupled set of thermal, mechanical, and economic design conditions.

2.3.7 Design Envelope for Sub-Cent LCOE

The deep coaxial closed well, when deployed as part of a large-scale array and equipped with targeted heat-transfer enhancements, demonstrates that sub-1 ¢/kWh electricity is plausible. The dominant enablers are access to >200 °C rock, aggressive suppression of upper-well heat losses, substantial augmentation of formation-to-fluid heat-exchange area, and industrialized drilling and surface-plant cost sharing. While not a proof of commercial existence, the array configuration defines a quantitatively performance–cost envelope against which future closed geothermal developments may be benchmarked.

3. PATHWAYS FOR FURTHER LCOE REDUCTION

This section presents additional LLM-suggested strategies for minimizing the levelized cost of electricity in geothermal well arrays.

3.1 Drilling Cost Reduction: Deferred Drilling and Redrilling

Array-based geothermal development could enable cost reductions that are unattainable at the single-well scale by exploiting shared infrastructure, standardization, and inter-well coordination. Economies of scale lower per-well overhead, while process learning yields drilling and surface-facility cost reductions on the order of 10–20% for each cumulative doubling of installed capacity. In parallel, temporal optimization of capital deployment through deferred drilling could further decrease the LCOE by shifting high-cost expenditures into the future, where they are discounted and benefit from technological progress.

Recent advances in drilling and completion technology have demonstrated cost reductions of approximately 50%. Given that drilling accounts for roughly 70% of baseline capital expenditure, such improvements reduce total installed cost from approximately USD 30 million to USD 19–20 million per well pad, yielding substantial LCOE declines across a range of plant capacities and capacity factors.

Deferred drilling strategies exploit the super-linear relationship between well depth and drilling cost by initially drilling only to the minimum depth required to meet ORC inlet temperature thresholds. Wells are subsequently deepened only when thermal drawdown degrades performance below economic limits. This approach reduces the net present value of drilling expenditures through (i) discounting of future capital outlays, (ii) learning-curve effects in drilling technology, and (iii) selective reinvestment based on individual well performance. Compared with conventional "all-at-once" drilling, such staging can lower effective drilling costs by approximately 10–30%, and when combined with technological learning, reduce effective pad-level capital expenditure to the USD 14–16 million range at scale.

At the system level, underground DC micro-grid architectures with redundant interconnection and automated control enable dynamic reconfiguration, fault isolation, and power rerouting among wells. By exploiting reserve capacity ("headroom") and N+1 redundancy, array-level capacity factors approaching unity become achievable. Distributed control systems further support predictive maintenance, adaptive flow management, and scheduled re-drilling, allowing wells to function as long-lived, re-enterable platforms optimized over multi-decadal operating horizons.

3.2 Learning Curve, Wright's Law, and Innovation Curve

Achieving LCOE below 1 ¢/kWh is contingent upon the application of learning curves to drilling operations and surface equipment manufacturing. Historical cost trajectories in solar photovoltaics and wind energy, which have exhibited order-of-magnitude and threefold reductions over multi-decadal deployment, respectively, indicate that comparable improvements in geothermal systems are plausible under sufficient cumulative production. A deferred drilling strategy further enhances project net present value by exploiting the time value of money while allowing technological learning and innovation to reduce future capital expenditures.

Networked geothermal arrays already demonstrate competitive firm-power economics (LCOE 1.3–3.5 ¢/kWh) and possess a credible pathway toward sub-cent LCOE through scale, standardization, and manufacturing learning. Under Wright's Law, costs decline by a constant fraction with each doubling of cumulative output. Assuming a 20% learning rate and scaling from a single well to a 100-well array (6.64 doublings), unit costs are reduced by a factor of 0.227, implying a potential LCOE of approximately 0.68 ¢/kWh from a 3 ¢/kWh baseline.

Beyond learning effects, innovation dynamics driven by cumulative research and development are expected to further compress costs. The convergence of modular well manufacturing, geothermal cogeneration (electricity, recovered heat, photovoltaics, and wind), and competitive market structures suggests strong positive feedback between deployment, cost reduction, and demand. Realizing these trajectories will require standards and industrial organization capable of supporting the production of more than one million wells across approximately 10,000 geothermal arrays.

3.3 Scaling and Deployment Scenarios

At moderate deployment scales, geothermal arrays consisting of approximately 20–50 wells can deliver tens of megawatts of firm electrical capacity suitable for industrial facilities or regional grids. Expansion to 100–200 wells enables gigawatt-class installations while preserving the modularity and fault tolerance inherent to distributed well architectures. Land use scales efficiently with array size. For inter-well spacing in the range of 150–300 m, thermal interference remains limited, while excessive surface infrastructure and trenching costs are avoided. Within this interval, levelized cost of electricity is relatively insensitive to spacing, with 200 m representing a practical baseline. A 10×10 configuration at this spacing occupies roughly 4 km² (≈1000 acres), including access corridors and surface equipment. Such spacing accommodates subsurface thermal isolation, buried electrical and fluid networks, installation of surface power conversion units, safe dissipation of waste heat, and robotic access for maintenance. The resulting power density exceeds that of most renewable technologies while maintaining continuous, dispatchable output, enabling replication across geographically diverse regions, including areas lacking high-temperature hydrothermal resources.

3.4 Jump-Start Protocol and Geothermal Storage

A battery-based robotic system (2–5 MWh, 2–4 MW) is proposed to energize the DC micro-grid bus and initiate operation in an initial subset of 5–10 geothermal wells. Once these wells attain steady-state output, they recharge the robot and sequentially activate additional idle pumps, enabling the array to reach more than 80 operating wells within approximately 60–120 minutes, contingent on ambient conditions and start-up sequencing. Given an expected capacity factor exceeding 95%, only a single start-up event is anticipated over the 30-year service life of the array. In the event of individual well failure, overall array output is maintained at nameplate capacity while an autonomous maintenance robot replaces faulty field-replaceable units, restoring the affected well to service. The same jump-start capability can support phased deployment during drilling, whereby early wells supply power for subsequent installations, thereby reducing levelized costs through deferred capital expenditure. More broadly, the system architecture enables a standardized, competitive robotics ecosystem for construction and maintenance, while distributed micro-grid operation and limited well-level buffering provide inherent energy storage and operational resilience, supplemented by mobile battery platforms and the subsurface thermal reservoir itself.

3.5 To frack or not to frack: Value of Closed Frack

Hydraulic stimulation of the surrounding formation could increase effective heat transfer by enhancing permeability and local convection while preserving a closed working-fluid loop. However, even "closed" stimulation would likely be perceived as conventional fracking by regulators and investors, requiring mitigation of induced-seismicity and groundwater-protection concerns. The potential thermal gains must therefore be weighed against regulatory, social-license, and financing risks, which may offset any marginal reduction in LCOE.

3.6 Geothermal Cogeneration

Only a fraction of the extracted geothermal heat is converted to electricity, with the remainder rejected at low enthalpy through surface cooling systems. This substantial thermal resource can be directly valorized via cogeneration, supplying district heating, industrial process heat, or agricultural applications without additional thermal-to-electric conversion. Spatial co-utilization of land—such as integrating photovoltaic systems above well pads and routing waste heat through horizontal collectors—offers a pathway to maximize exergy utilization and overall energy productivity of geothermal arrays

3.7 Emission and Capacity Factor Credits

Closed geothermal arrays provide firm, zero-emission power with capacity factors exceeding 95%, attributes that are not fully internalized in conventional LCOE metrics. The avoided cost of CO_2 emissions and the system-level value of near-baseload availability (e.g., reduced need for backup generation and storage) constitute implicit economic credits that, if monetized, would further improve the competitiveness of geothermal arrays relative to variable renewables.

4. CONCLUSIONS

This paper frames a roadmap for scaling closed geothermal arrays toward LCOE below 1 ¢/kWh. The results presented here were obtained via an iterative, prompt-based dialogue with an LLM, used to generate designs, estimate performance, and explore techno-economic scenarios for array-scale geothermal systems.

Baseline 5 km deep, coaxial, closed wells yield net electrical outputs on the order of 1–2 MWe. Achieving multi-megawatt-class performance per pad (≈10 MWe) requires access to deeper and hotter formations, coupled with enhanced heat-transfer and thermal-loss mitigation. Vacuum-insulated tubing (VIT) and conductive cement (CC) are projected to increase net power by 20–35% with modest incremental capital expenditure. Concurrently, drilling cost reductions of approximately 50%—consistent with learning-curve and automation trends—enable LCOE reductions into the 2.6–5.3 ¢/kWh range. Optimal circulation rates of 70–100 kg s^{-1} balance thermal throughput, temperature approach, and pumping power, while deferred drilling strategies further reduce effective capital cost by 10–30% through time-value discounting and learning-curve capture.

At the array level, standardized 10×10 well layouts with inter-well spacing near 200 m and capacity factors exceeding 95% yield firm LCOE values in the range 1.3–3.5 ¢/kWh. Continued convergence of learning curves, standardization, and economies of scale—combined with higher per-pad power (10–20 MWe), improved thermal management, and automated operations—define credible pathways to sub-cent electricity. Scenario analyses indicate that, under aggressive but internally consistent assumptions (e.g., 10 MWe per pad, 95% capacity factor, and capital costs of $7–10M), LCOE values of 0.85–1.2 ¢/kWh become attainable.

The proposed array architecture—comprising standardized wells, modular surface plants, networked DC micro-grids, robotic drilling and maintenance, and distributed control with redundancy—supports rapid deployment, high availability, and continuous cost reduction. Future work will focus on rigorous validation of these projections through high-fidelity transient thermal modeling in Julia, site-specific geological characterization, pilot demonstrations of VIT and CC technologies, field trials of deferred drilling and re-drilling strategies, development and testing of micro-grid control systems, and long-term performance monitoring. These efforts aim to establish geothermal arrays as a cornerstone architecture for delivering firm, zero-emission electricity at globally transformative cost levels.

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DATA AVAILABILITY

Supplementary materials containing raw information from LLM-assisted analyses are available at https://github.com/BobMetcalfe/GEO.

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