

Gemini Advanced 2.0 Flash Prompts for Geothermal Array Model 1/31/25 12:01pm.

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Let's scale geothermal energy with "arrays" of standard networked robotic wells.

Start with a table of energy sources with levelized cost of energy, LCOE, in ¢/kWh:

coal, oil, gas, hydro, solar, wind, fission, fusion, gen1 open geothermal.

Please provide best estimates of various parameters in this exploration.

Help explore a large (10x10) power plant "array" of 100 closed coaxial geothermal wells.

Closed wells -- we are striving to drill economically anywhere.

Coaxial wells -- less drilling. One borehole, outer injection pipe, inner production pipe.

Each well has a borehole with an injection pipe and coaxial production pipe inside. The injection pipe carries cooler working fluid from harvesting heat exchangers down into the well's borehole.

Descending fluid is heated by surrounding rock and feeds at the bottom into an ascending inner coaxial production pipe. Production pipe carries heated working fluid back up out of the well's borehole to its harvesting heat exchanger. The well has a heat exchanger to transfer the well's heat energy from the working fluid to another fluid to spin the turbine. The turbine spins a generator to produce electricity for the grid connect.

Valves and pumps balance temperature and pressure in the working and turbine fluids.

Surface temperature 15C.

Temperature gradient 25C/km.

Rock is sandstone.

Working fluid is water.

What follows is an initial "array" design to which we will later apply improvements.

Our main goals are gigawatts of electric power (GW) at levelized cost of energy (LCOE) measured in single digit ¢/kWh. LCOE should include "firming costs" of which geothermal has nearly none. Solar and wind energy are intermittent and require substantial firming costs (storage). Such firming costs are often left out of LCOE.

Closed geothermal wells ("gen2") recirculate working fluid. They do not require naturally occurring hot brines near the surface like hydrothermal "gen1" wells do.

The isolation of working fluids in closed wells prevents ground water pollution and seismicity.

Closed wells do not use fracking. Key question: Can closed wells harvest enough heat without the heat-exchanging surface area created by open fracked reservoirs?

EGS (engineered geothermal systems) are of two kinds. Closed EGS uses a lateral pipe between injection and production pipes. Open EGS fracks the rock between injection and production pipes. The Open EGS trick is to get injected brines to find their way through the hot frack into the ascending production pipe.

Coaxial wells have one borehole per well, which should save drilling time and money. Our next model will contrast open and closed well architectures.

OK, now create an initial design for the array and estimate its output power and LCOE.

Now let's make improvements to the initial array design. Report back important well parameters like borehole diameter, borehole depth, well separation, flow, ...

Each well in the array will be assembled in place with standard subsystems including completion, working fluid, injection pipes (outside downward, one/well), production pipes (inside upward, one/well), networking pipes, shunts, working fluid pumps, heat exchangers, turbines, generators, electric cables, grid connects. Shunts are pipes added to enable the array to route around broken wells.

The wells will be drilled in parallel by an army of robotic drilling "carts", which also serve to assemble, maintain, and repair the wells. They carry subsystems from interstate highway trucks bringing them from various factories. Subsystems will fit on standard interstate trucks. An army of array carts will run up and down the array's lanes between wells and surface the network of pipes. The carts will be electric, powered by the wells they service.

Now estimate and display the optimal well borehole diameter, well depth, well spacing, pipe insulation, and heat flow that maximizes heat production and minimizes LCOE. To make room for the solar panels, make well spacing at least 100 meters, so the array is a kilometer on a side.

Well spacing must be optimized.

Display these parameters even if they are SWAGs and labeled so.

What is the improved well depth? Rate Of Penetration (ROP) and round trips?

Estimate the cost of drilling?

Remember that we cannot drill wells too close to one another else they will lose productivity to thermal interference.

Make some reasonable estimates and get initial answers for LCOE and power.

Show a breakdown of LCOE costs. Drilling and financing costs should stick out. Show costs in ¢/kWh.

Considering thermodynamics, what will be the array's delta T?

How might LCOE be further reduced by reducing drilling costs by a factor of 2? 5? 10?

This is a key performance indicator (KPI). Higher ROP? Zero round trips? No more drilling bits? Can the array's carts drill the wells they will later maintain and repair?

Technologies, people, equipment, and recompleted wells will be transitioned at scale from oil and gas industries. Welcome to the “transition.” We prefer the word “pivot” because it sounds faster.

LCOE might be reduced by say halving the time to revenue and thereby cutting financing costs (time is money). Since we’ll have standard subsystems, they can be delivered “just in time” (JIT) from various subsystem factories to various array locations. Subsystem inventories will be factory owned right up until they are delivered to arrays after drilling. There will be waiting cart armies.

How might LCOE be reduced by extending array life to 20? 30? 40? 50? 100? years?

How might LCOE be reduced by moving down manufacturing’s learning (experience) curve? Higher volume, faster learning, lower costs.

How might reliability be improved? Connect wells in arrays so as to use valve controls to route around any well outages in the array. Shunt pipes are included in the topology to route around well outages, which are already up >85% of the time. This routing will approach 100% array reliability.

This is an Internet-like example of how to make more reliable systems out of unreliable subsystems. Don’t get reliability by gold-plating bigger things, but by networking smaller cheaper things.

What if each well did not have all of its own subsystems. It would use its pipes and/or electric cables to share, say, a grid connect among 10 wells. Each column of the array’s 10x10 rows and columns could be served by a shared grid connect subsystem.

What about smaller and larger arrays? Do they improve LCOE?

How early in the path from well to grid should the heat in the working fluid be converted to electricity? Will the array's networking be mostly pipes of hot water or mostly wires carrying electricity?

Should we convert from fluid heat to electric power ASAP? Convert heat at each well or convert 10 at once along the top row? Converting to electricity at the originating wells would eliminate fluid pipes up and down the rows and columns, but would require 10x10 turbine generators.

What LCOE reductions and/or power output increases can be won by burying the array, allowing the array-encompassed land to be used for agriculture, solar energy, or wind energy? Unlike intermittent solar and wind energy, geothermal energy harvesting does not have to use much land area.

Is it better to network the array on top of the land or buried? Might buried pipes reduce heat loss?

Combining all these improvements, what is our latest estimate of power and LCOE? Contrast this with the initial design power and costs.

Show the table again of various energy source LCOEs. Are our well designs competitive with other sources of energy? We'd better validate these designs before the drilling begins.

How many arrays like these will we need to power the human race on Earth? We'll need say 10 terawatts total. How many geothermal arrays would that be?

End by showing table of energy sources with their levelized cost of energy, LCOE, in ¢/kWh: Include coal, oil, gas, solar, wind, fission, fusion, gen1 open geothermal.

Give the cost breakdown in ¢/kWh of LCOE after applying improvements/reductions.

Show a picture of 10x10 geothermal array with solar panels between wells, lanes, robotic carts, and grid connects.

END

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Let's explore scaling geothermal energy with arrays of networked robotic wells.

### Initial Design and Parameters:

Here's a table of levelized cost of energy (LCOE) for various energy sources (estimates, as LCOE varies greatly by location and project specifics):

Energy Source	LCOE (¢/kWh)
Coal	5-15
Oil	10-25
Natural Gas	4-10
Hydroelectric	2-8
Solar PV	3-7
Wind	2-6
Nuclear Fission	6-12
Nuclear Fusion	(Currently not commercially viable)
Gen 1 Geothermal (Hydrothermal)	4-10
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### Initial Array Design (10x10):

- **Well Type:** Closed coaxial
- **Surface Temperature:** 15°C
- **Temperature Gradient:** 25°C/km
- **Rock Type:** Sandstone
- **Working Fluid:** Water
- **Well Spacing:** 100 meters (1 km x 1 km array)
- **Initial Well Depth (SWAG):** 5 km (for illustrative purposes)
- **Initial Borehole Diameter (SWAG):** 0.3 meters
- **Initial Estimated Power Output (SWAG):** Let's assume each well produces 1 MW initially. 100 wells \* 1 MW/well = 100 MW.
- **Initial Estimated LCOE (SWAG):** A very rough initial guess, perhaps 8-12 ¢/kWh, highly dependent on drilling costs.

### Improvements and Optimization:

- **Well Depth Optimization:** Deeper wells access higher temperatures. However, drilling costs increase significantly with depth. An optimal depth needs to balance heat gain with cost. Let's assume after optimization the depth is 7 km.
- **Borehole Diameter Optimization:** A larger diameter can increase heat flow but also increases drilling costs. Let's assume an optimized diameter of 0.4 meters.
- **Well Spacing Optimization:** Closer wells can experience thermal interference. 100 meters is a reasonable starting point. It is important to check for thermal interference and to optimize well spacing.
- **Pipe Insulation:** Essential to minimize heat loss during fluid transport. High-quality insulation is crucial.
- **Heat Flow Optimization:** Maximizing heat extraction requires careful design of the coaxial pipes, flow rates, and working fluid properties.

### Improved Well Parameters (SWAGs):

- **Borehole Diameter:** 0.4 meters
- **Well Depth:** 7 km
- **Well Spacing:** 100 meters
- **Pipe Insulation:** High-quality, minimizing heat loss to <1% per km.
- **Heat Flow (SWAG):** Let's assume we can increase heat flow per well to 2 MW with optimization.

### Improved Array Performance (SWAGs):

- **Power Output:** 100 wells \* 2 MW/well = 200 MW
- **Estimated LCOE (after improvements):** 5-8 ¢/kWh (still highly dependent on drilling costs).

### Drilling Costs:

Drilling costs are a major factor in LCOE. Estimating them requires detailed geological information and local labor rates. A very rough estimate for a 7 km well could be several million dollars. Rate of penetration (ROP) and round trips significantly affect drilling time and cost.

### LCOE Breakdown (SWAGs):

- **Drilling:** 3-5 ¢/kWh (This is a *very* rough estimate and needs careful analysis)
- **Financing:** 1-2 ¢/kWh (dependent on interest rates and project duration)
- **Operations and Maintenance:** 1-2 ¢/kWh
- **Other Costs:** 1 ¢/kWh

### Delta T:



Delta T (temperature difference between injection and production fluids) is crucial. A larger delta T means more heat extracted. This depends on well depth, rock temperature, flow rate, and heat exchanger efficiency. A SWAG might be 100°C.

### **LCOE Reduction Strategies:**

- **Drilling Cost Reduction:** This is the biggest lever. Doubling, quintupling, or tenfold reductions in drilling costs would have a large impact on LCOE. Advanced drilling technologies, automation, and reduced round trips are crucial.
- **Extended Array Life:** Increasing array life to 30, 40, 50, or even 100 years amortizes initial costs over a longer period, reducing LCOE.
- **Learning Curve:** Manufacturing efficiencies and experience can reduce costs over time.
- **Reliability:** The proposed shunt system will improve reliability and reduce downtime, which can lower LCOE.
- **Shared Subsystems:** Sharing grid connections or other subsystems could reduce capital costs.
- **Array Size:** Optimizing array size may yield small improvements to LCOE.
- **Heat Conversion Location:** Converting heat to electricity at each well would eliminate fluid pipes but require many generators. Centralized conversion could be more efficient. This needs more study.
- **Buried Arrays:** Burying arrays could reduce heat loss and allow for multiple land uses (agriculture, solar). This could reduce LCOE.

### **Final Estimated Power and LCOE (SWAGs - after improvements):**

- **Power:** 200 MW
- **LCOE:** 4-6 ¢/kWh

### **Number of Arrays for 10 TW:**

10 TW / 200 MW/array = 50,000 arrays.

### **Final LCOE Table (SWAGs):**

<b>Energy Source</b>	<b>LCOE (¢/kWh)</b>
Coal	5-15
Oil	10-25
Natural Gas	4-10
Hydroelectric	2-8
Solar PV	3-7
Wind	2-6
Nuclear Fission	6-12
Nuclear Fusion	(Currently not commercially viable)
Gen 1 Geothermal (Hydrothermal)	4-10

Gen 2 Geothermal (Optimized Array) 4-6  
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**(Picture of 10x10 array with solar panels, carts, etc. would be inserted here)**

It's important to emphasize that these are SWAGs. Detailed engineering and geological studies are essential to validate these estimates. Drilling costs are the biggest uncertainty. Further research and development are needed to make geothermal energy a major contributor to global energy needs.