BEYOND SOLAR
An Orrerie publication

FLAGSHIP · FLAGSHIP DEEP-DIVE · HEL-0003 · 2026-06-12

Enhanced Geothermal: Techno-Economics of Firm Clean Power

How oilfield drilling turned a 1970s research program into bankable 24/7 power — and what it costs

Beyond Solar — Research Desk
Coverage: Beyond Solar

ABSTRACT

Can enhanced geothermal systems (EGS) deliver firm, around-the-clock clean power at a cost that competes with gas and beats nuclear — and how fast does the cost curve bend? This report builds a transparent levelized-cost view of EGS from primary well-performance and drilling-cost data (Fervo's Cape Station and Project Red, NREL/DOE cost models, and the millimeter-wave and closed-loop challengers), then stress-tests it across three deployment scenarios to 2035. The headline: a single Cape Station well now flows 107 kg/s and produces >10 MWe — output NREL did not expect before 2035 — while Fervo's per-well drilling cost fell from $9.4M to $4.8M across four wells, a ~49% decline. The DOE Enhanced Geothermal Shot targets $45/MWh by 2035 (≈$3,700/kW). our base case sees unsubsidized EGS LCOE reaching $60–80/MWh by the early 2030s at ~90% capacity factor — firm power priced like a peaker's fuel-free baseload. The implication: EGS is graduating from science project to the cheapest __firm__ zero-carbon resource for data-center and grid buyers, even as nearly every pure play remains private.

Keywords: enhanced geothermal, EGS, Fervo Energy, Cape Station, LCOE, firm clean power, horizontal drilling, superhot rock, Quaise, Sage Geosystems, Ormat, capacity factor, geothermal drilling cost

Executive Summary

Enhanced geothermal systems (EGS) have crossed the line from research program to bankable infrastructure faster than almost any forecaster anticipated. The pivot was not a new heat-mining concept — the U.S. government has chased "hot dry rock" since Los Alamos drilled the Fenton Hill test wells in the 1970s — but the wholesale import of shale-era **horizontal drilling and multi-stage hydraulic stimulation** into the geothermal wellbore. That borrowing collapsed both the cost and the timeline of building an engineered reservoir where nature did not supply permeable, water-charged rock.

The clearest proof point is Fervo Energy's Cape Station in Utah. A 2024 production test there flowed **107 kg/s** of fluid and produced **more than 10 MWe from a single well** — roughly triple the per-well output of Fervo's 2023 Project Red pilot, and a level of productivity NREL's own modeling did not expect EGS to reach before 2035 [1][4]. Drilling cost fell in lockstep: across the first four horizontal wells at Cape, per-well cost dropped from **$9.4M to $4.8M**, a ~49% reduction, and a later appraisal well reached **15,765 ft TVD at 520 °F in 16 drilling days**, ~79% faster than the DOE ultradeep baseline [1][3][5].

The economic stakes are firmness. EGS runs at a **~90% capacity factor**, delivering the same 24/7 profile as nuclear or gas but with no fuel and near-zero carbon [6]. The DOE **Enhanced Geothermal Shot** targets an unsubsidized **$45/MWh (≈$3,700/kW) by 2035** [2]; NREL judges a capacity-weighted deep-EGS LCOE near **$45.9/MWh** attainable if drilling costs fall ~20% and well productivity rises by 2035 [6]. our base case is more conservative on timing: **$60–80/MWh unsubsidized by the early 2030s** (Beyond Solar estimate), already competitive with new firm gas-plus-carbon and well below new nuclear.

The catch for public-market readers: the technology leaders — Fervo, Sage Geosystems, Quaise — are **private**. The listed exposure runs through the incumbent operator **Ormat (NYSE: ORA)**, the power-equipment and turbine suppliers (**GEV**), and, more loosely, the broader firm-clean-power complex serving data centers.

> **BOTTOM LINE:**
> A single Cape Station well now produces >10 MWe at 107 kg/s — output NREL did not model before 2035 — while Fervo's per-well drilling cost fell ~49% (to $4.8M) across four wells. EGS is becoming the cheapest *firm* zero-carbon resource; our base case puts unsubsidized LCOE at **$60–80/MWh by the early 2030s** (Beyond Solar estimate) at ~90% capacity factor.

1. Context and Scope

Decarbonized grids have a baseload problem, not an energy problem. Solar and wind are now the cheapest *energy*, but they are not *firm*: somebody must supply power when the resource is absent. The candidates for clean, dispatchable, around-the-clock generation are short — long-duration storage, nuclear (new-build slow and expensive), hydrogen turbines (still costly), gas with carbon capture (unproven at scale), and geothermal. Of these, only geothermal is simultaneously fuel-free, high-capacity-factor, land-light, and already operating commercially. The constraint historically was geography: conventional hydrothermal power needs a rare natural coincidence of heat, water, and permeability, confining it to volcanic provinces (Iceland, the Geysers, the East African Rift). **EGS removes the geography constraint** by engineering the missing permeability into hot-but-dry rock — in principle unlocking heat almost anywhere deep drilling can reach.

This report sits at the intersection of two of our coverage domains: **enhanced/closed-loop geothermal and superhot rock**, and **the capacity factor and bankability of emerging firm tech**. The question is narrow and economic: *Can EGS deliver firm clean power at a competitive levelized cost, how fast does that cost fall, and who captures the value?*

In scope: open-loop EGS (the dominant commercial route), closed-loop/advanced geothermal, and superhot-rock concepts; well-level performance (flow, temperature, MWe, drawdown); drilling economics ($/ft and $/well); LCOE and its cost-down drivers; deployment scenarios to ~2035; and the listed-equity read. **Out of scope:** conventional hydrothermal greenfield development, ground-source heat pumps, and direct-use geothermal heating, except as cost benchmarks. Cost figures are stated in nominal USD with the source vintage flagged; NREL ATB figures are 2022$ unless noted [7].

2. Technology Landscape and State of the Art

2.1 The governing idea

A geothermal power plant is a heat engine: pull hot fluid from depth, run it through a turbine (directly as steam, or via a binary organic-Rankine cycle for lower-temperature resources), reinject the cooled fluid, repeat. Power scales with **mass flow × enthalpy** — i.e., how many kilograms per second you can circulate and how hot they are. Every EGS engineering lever ultimately serves those two terms: more flow per well, hotter rock, and a reservoir that sustains both without cooling off (thermal drawdown) for the project's 30-year life.

EGS creates the reservoir rather than finding it. The modern recipe, lifted almost wholesale from unconventional oil and gas:

1. **Drill a deep vertical section, then kick off to horizontal.** A horizontal lateral exposes far more hot rock than a vertical hole and lets a single pad host an injector–producer pair (or more) with controlled spacing.
2. **Hydraulically stimulate in multiple stages.** Pumping fluid at pressure opens and props a network of fractures connecting the two wells, manufacturing the permeability nature withheld.
3. **Circulate water in a closed loop** between injector and producer; the rock is the heat exchanger.
4. **Instrument with fiber-optic sensing** (distributed temperature/acoustic sensing) to map fracture growth, optimize spacing, and manage the reservoir in real time.

This is why the EGS cost curve looks like a shale cost curve: it inherits two decades of drilling learning-by-doing. Fervo's own framing — "we are an oilfield company that makes clean power" — is technically accurate.

2.2 Demonstrated performance — the data

The field has moved from "does it work" to "how much per well," and the numbers are public:

- **Project Red (Nevada, 2023):** Fervo's commercial pilot. Sustained flow validated the horizontal-doublet-plus-stimulation design and delivered ~3.5 MWe-class per-well output, enough to retire core technical risk [4].
- **Cape Station (Utah, 2024–):** A production test flowed **107 kg/s** and produced **>10 MWe from one well** — ~3× Project Red and a productivity NREL did not expect before 2035 [1][4]. Fervo drilled **15 wells in roughly a year** at Cape [1].
- **Drilling cost-down:** Across the first four horizontal wells at Cape, per-well cost fell from **$9.4M to $4.8M** (~49%) [1]. Fervo separately reported a **~70% reduction in drilling time** versus its own early wells, and the **Sugarloaf** appraisal well reached **15,765 ft TVD / 520 °F**

in 16 drilling days — ~79% faster than the DOE ultradeep baseline [3][5].
- **Contracts and scale:** Cape Station is being built out toward **~500 MW** (Phase I upsized from 400 MW), with an ambition stated as high as **2 GW** of total annual output as the resource is fully developed. Fervo holds the world's largest geothermal PPAs, including **320 MW with Southern California Edison** (2024) and a **31 MW deal with Shell Energy**, and secured **$421M in non-recourse project financing** for Cape [8][9][10]. Phase I is targeted to begin delivering power to the grid in **late 2026**, reaching ~100 MW by early 2027 [9].

The significance is that EGS performance is now improving on a **per-well, per-quarter** cadence — the signature of a manufacturing learning curve, not a one-off science result.

2.3 Competing Pathways

EGS is not monolithic. Three distinct engineering routes compete, with very different risk and maturity profiles:

Pathway	Principle	Key metric (demonstrated/target)	TRL	Status
Open-loop EGS (Fervo, hydrothermal-EGS hybrids)	Horizontal wells + multi-stage hydraulic stimulation create a fractured reservoir; circulate water through the rock	107 kg/s, >10 MWe per well; well cost $4.8M (Cape, 2024) [1]	7–8	Commercial build-out underway (Cape Station, ~500 MW, online from late 2026) [9]
Closed-loop / advanced geothermal (Sage Geosystems; Eavor-type loops)	Sealed wellbore loop — fluid never contacts rock; conduction + engineered loops; some designs also store pressure energy	Pilots and demo loops; energy-storage variants funded in 2025 [11]	5–6	Demonstration; lower induced-seismicity risk, higher heat-transfer-area challenge
Superhot rock / millimeter-wave drilling (Quaise)	Gyrotron millimeter-wave energy *ablates* rock with no downhole bit, targeting ~400 °C "superhot" rock and supercritical water	Drilled to **100 m** with millimeter-wave in field test (Texas, Jul 2025) [12]	3–4	Early field demonstration; far higher energy density per well if it scales

The three routes trade against each other on the two terms that matter. Open-loop maximizes flow and contact area but carries **induced-seismicity** and water-management risk. Closed-loop slashes seismic and water risk but fights a heat-transfer-area deficit (you only contact the rock the wellbore touches). Superhot rock chases the enthalpy term — supercritical water carries roughly an order of magnitude more energy per unit mass than 200 °C brine — but must first prove a drilling method that has reached only ~100 m. Open-loop EGS is the only route in commercial construction today; the other two are the option value on the next cost-down step.

3. Techno-Economic Analysis

3.1 Cost Model and Assumptions

EGS economics are **capex-dominated and drilling-dominated**: there is no fuel, O&M is modest, and the wells can be 50%+ of total project cost. That makes LCOE a near-linear function of (a) drilling $/well, (b) MWe per well, (c) capacity factor, and (d) cost of capital. The transparent assumption set below underpins our scenario range; every input is sourced or flagged as an estimate.

Parameter	Value	Unit	Basis / Source
Per-well drilling cost (current best)	4.8	$M/well	Fervo Cape, 4th well, 2024 [1]

Per-well drilling cost (early Cape)	9.4	$M/well	Fervo Cape, 1st well, 2024 [1]
Flow rate (best single well)	107	kg/s	Cape production test, 2024 [1]
Per-well electrical output (best)	>10	MWe	Cape production test, 2024 [1]
Reservoir temperature (deep appraisal)	~270 (520 °F)	°C	Sugarloaf well, Fervo [5]
Capacity factor	~90	%	NREL ATB / GeoVision basis [6][7]
DOE Enhanced Geothermal Shot CAPEX target	3,700	$/kW	DOE/NREL, 2035 target [2]
DOE Enhanced Geothermal Shot LCOE target	45	$/MWh	DOE/NREL, 2035 target [2]
NREL deep-EGS achievable LCOE (2035, ~20% drilling cost cut)	45.9	$/MWh	NREL Enhanced Geothermal Shot analysis [6]
Representative EGS plant size (ATB)	40	MWe	NREL ATB 2024, base case [7]
Drilling-cost decline applied in ATB 2024 vs 2023	7	%	NREL ATB 2024 [7]
Discount rate (analysis WACC)	7	% real	Beyond Solar estimate (utility-scale firm asset)
Plant life	30	years	Industry standard; Beyond Solar estimate

3.2 Levelized Cost / Unit Economics

The cost stack of an EGS plant is unusual. Where a gas plant is fuel-heavy and a solar plant is module-and-inverter-heavy, an EGS plant is **subsurface-heavy**: the wells and reservoir dominate, the surface power island (turbine, generator, cooling, ORC where applicable) is a smaller and more mature cost, and fuel is zero. our indicative cost stack:

Cost component	Share of LCOE (indicative)	Notes
Drilling & well construction	~45–55%	The dominant lever; falling fastest [1][3]
Reservoir stimulation & completion	~10–15%	Multi-stage frac; benefits from oilfield supply chain
Surface power plant (turbine/ORC/cooling)	~20–25%	Mature; supplied by ORA, GEV and others
Balance of plant, interconnection, dev	~10–15%	Permitting, transmission, financing
Fuel	0%	Structural advantage vs gas/nuclear

Source: our model, allocated from NREL GETEM cost structure [6][7] and Fervo well-cost disclosures [1]; shares are Beyond Solar estimates.

Because drilling is half the stack and is falling ~7–10% per ATB revision and ~49% across four Cape wells, **LCOE is mechanically geared to the drilling learning rate**. NREL's headline: a capacity-weighted deep-EGS LCOE of **~$45.9/MWh by 2035** is attainable with a ~20% average drilling-cost reduction plus productivity gains [6] — and Cape's per-well economics already exceed the productivity assumption embedded in that path. The DOE Shot target of **$45/MWh** is, in NREL's framing, ambitious but achievable [2][6].

our base case is deliberately more conservative on **timing** than the agency targets, because the published targets blend the best wells in the best resource with a fleet that must include harder, deeper, cooler sites. Beyond Solar estimates **unsubsidized fleet-average EGS LCOE of $60–80/MWh by the early 2030s** (Beyond Solar estimate), converging toward the DOE $45/MWh figure only at the back end of the decade and only in premier resource. For context, that $60–80/MWh band already undercuts new nuclear (typically $110–180/MWh, agency ranges) and is competitive with new firm gas once any carbon cost is applied — while delivering the same ~90% capacity factor [6][7].

THE TAKE:
The right comparison for EGS is not solar or wind — it is the **firm** resource it displaces. At ~90% capacity factor, an $70/MWh EGS plant delivers roughly the same annual energy as a gas peaker running baseload, with **zero fuel-price risk and zero carbon exposure**. The implied value is a fuel-free, inflation-proof, dispatchable MWh — which is why hyperscalers signing 24/7 carbon-free PPAs are paying for EGS firmness, not its raw energy price. Beyond Solar estimates the *firmness premium* embedded in recent EGS PPAs is on the order of **$15–30/MWh** versus an equivalent-energy intermittent contract (Beyond Solar estimate, derived from the spread between firm-CFE and unbundled-REC pricing) — and that premium, not the headline LCOE, is what makes EGS bankable today.

3.3 Sensitivity

LCOE moves most on the drilling and productivity terms; cost of capital is a close third for a capex-heavy asset. One-way sensitivity around our base case (≈$70/MWh):

Driver	Low case	High case	Approx. LCOE swing	Direction
Per-well drilling cost	$3.5M	$9.4M	±$20–25/MWh	Dominant lever [1]
MWe per well	6 MWe	12 MWe	-/+$15–20/MWh	More MW spreads well cost [1]
Discount rate (WACC)	5%	9%	±$10–15/MWh	Capex-heavy asset
Capacity factor	85%	95%	-/+$5–8/MWh	Already high; limited room [7]
Thermal drawdown over life	mild	severe	±$5–12/MWh	The key reservoir-life risk

Source: our model; swing magnitudes are Beyond Solar estimates around a ~$70/MWh base.

The asymmetry matters: the two largest levers (drilling cost and MWe/well) are **both improving** at Cape, while the variable that could move against the project — **thermal drawdown** as the reservoir cools over decades — is the one with the least public operating history. EGS reservoirs simply have not run for 30 years yet.

4. Market and Demand Outlook

Demand for firm clean power is being pulled forward by an unexpected buyer: the **data center**. AI and cloud build-outs need large, dependable, 24/7 carbon-free supply on multi-year horizons — exactly the profile EGS sells, and exactly why Fervo's PPAs are with utilities and energy marketers serving load growth [8][9]. On the supply side, NREL/DOE see U.S. geothermal scaling to as much as **90 GWe of installed capacity by 2050** under favorable cost trajectories — versus ~4 GW today — a >20× expansion almost entirely enabled by EGS [6].

our analysis frames the trajectory in three scenarios to 2035, varying the drilling learning rate and the policy environment:

Scenario	2035 fleet LCOE (unsubsidized)	U.S. EGS deployment context	Premise
Bear	~$90–110/MWh	Niche; a few flagship projects	Drilling learning stalls; a seismic or drawdown setback chills financing; ITC/PTC parity erodes
Base (our view)	~$55–75/MWh	Multi-GW; EGS a standard firm-power option in the West	Cape-class learning continues fleet-wide; firm-CFE demand sustains PPAs

Bull	~$40–50/MWh (meets DOE Shot)	Tens of GW; national resource	Drilling cost-down compounds; closed-loop or superhot adds a step-change; supportive policy [2][6]

Source: our scenario model; LCOE figures are Beyond Solar estimates anchored to DOE/NREL targets [2][6].

The deployment spread is wider than the cost spread because EGS is **financing-gated, not technology-gated**. The technology works; whether tens of GW get built depends on whether project finance treats EGS wells like de-risked oilfield assets (cheap capital) or like exploratory science (expensive capital). Every additional successful Cape-class well nudges the market down the WACC curve.

5. Feasibility, Scale-Up, and Risk

EGS earns a **conditional go**: the core technology is demonstrated at commercial scale, the cost curve is bending, and offtake exists — but the route to tens of GW runs through induced-seismicity management, water, drilling-rig and supply-chain capacity, and unproven multi-decade reservoir behavior.

5.1 Risk Register

Risk	Likelihood	Impact	Mitigation
Induced seismicity from stimulation (the issue that shut Basel, 2006)	Medium	High	Traffic-light protocols, fiber-optic monitoring, depth/spacing control; siting away from population
Thermal drawdown — reservoir cools faster than modeled over 30 yr	Medium	High	Well spacing optimization, fiber sensing, redrill/infill option; conservative reserve sizing
Drilling-cost learning stalls below current trajectory	Low–Medium	High	Diversify rigs/contractors; standardize well design; oilfield-services competition
Water sourcing/management in arid Western basins	Medium	Medium	Closed-loop circulation; produced-water reuse; closed-loop EGS variants
Policy/tax-credit erosion (ITC/PTC parity for geothermal)	Medium	Medium	Long-dated PPAs; firm-CFE premium reduces subsidy dependence
Permitting & transmission delays on federal land	Medium	Medium	BLM categorical exclusions for geothermal; co-location with load
Capital availability if a flagship project disappoints	Medium	High	Non-recourse project finance track record (Cape's $421M) builds comps [10]

The honest weak point is the **30-year reservoir question**: no EGS reservoir has yet operated for its full design life, so drawdown remains a modeled rather than measured risk. The honest strength is that none of these failure modes is novel physics — they are operational risks the oil-and-gas industry already manages at scale.

6. Market and Equity Implications

The defining feature of EGS for a public-market reader is that **the leaders are private**. Fervo, Sage Geosystems, and Quaise are venture/project-financed (Fervo's Series E was $462M) [11], so there is no pure-play listed equity that captures the cost-down directly. Exposure is therefore *indirect* — through the incumbent operator, the equipment supply chain, and the firm-clean-power complex EGS feeds.

Company (Ticker)	Exposure	Reasoning (tied to the thesis)	Horizon
Ormat Technologies (NYSE: ORA)	Positive (with nuance)	The only listed geothermal pure-ish play; ~1,835 MW operating portfolio across geothermal/storage, targeting 2.6–2.8 GW by 2028; FY2024 revenue +6.1% [13]. Validation of EGS expands the resource base Ormat can develop and supplies turbine/ORC know-how — but Fervo's success also intensifies competition for the best resource.	2–5 yr
GE Vernova (NYSE: GEV)	Positive (diffuse)	Supplies steam/ORC turbines, generators and grid equipment into firm-power build-outs; a geothermal scale-up is incremental demand, though small relative to its gas/grid/wind core.	2–5 yr
First Solar (NASDAQ: FSLR)	Neutral / adjacent	Not an EGS play; named as the firm-vs-intermittent counterpoint. EGS firmness competes for the *same 24/7-CFE buyers* (data centers) that drive solar-plus-storage demand — a substitution risk at the margin, not a direct threat.	3–7 yr

Company facts from public sources [13]; no forward financials are projected here.

> **THE TAKE:**
> The non-obvious market read is that the **biggest beneficiaries of EGS are not listed at all** — they are the oilfield-services and drilling-rig ecosystem (largely private or buried inside diversified oil-services majors) whose horizontal-drilling expertise is the actual moat. Public-market investors who want the EGS cost-down can only get it second-hand today; the cleanest expression is **ORA as a call option on EGS validation**, paired with awareness that a Fervo IPO — if it comes — would instantly become the sector's reference equity and likely reprice ORA's geothermal multiple. Until then, EGS is a *thesis without a clean ticker*, which is precisely why it is mispriced relative to its strategic importance to firm-power-hungry data-center demand.

7. Outlook and Strategic Implications

EGS has done the hard part: it has shown that an engineered geothermal reservoir can be built, on schedule, with falling cost, and sold under bankable long-term contracts. The remaining questions are not "does it work" but "how cheap, how fast, and how widely" — and those are answered well by well, quarter by quarter, on a learning curve the oil-and-gas industry has already proven it can ride.

For an operator or investor, the decision-grade takeaways: (1) EGS is now the **strongest candidate for cheap firm zero-carbon power** in resource-rich regions, with our base case at **$60–80/MWh by the early 2030s** (Beyond Solar estimate) and a credible path to the DOE's **$45/MWh** by 2035 [2][6]; (2) the value proposition is **firmness, not cheap energy** — buyers are paying a firmness premium that makes the economics work today; (3) listed exposure is thin and indirect, with **ORA** the closest proxy and a potential Fervo IPO the catalyst that would re-rate the space.

WHAT TO WATCH:
(1) **Cape Station Phase I first power, late 2026** — on-time, on-cost grid delivery is the bankability proof [9]. (2) **The next per-well cost print** below ~$4M — confirmation the drilling learning rate is holding [1]. (3) **A Fervo financing or IPO move** — would establish the sector's reference valuation. (4) **Quaise millimeter-wave progress past ~100 m toward kilometer depths** — the option on a superhot-rock step-change [12]. (5) **Any induced-seismicity incident** at a flagship project — the single fastest way to chill EGS financing.

Disclosures & Disclaimer

Methodology and Assumptions

The techno-economic view is built bottom-up from primary well-performance and drilling-cost disclosures (Fervo Energy press releases and presentations for Project Red and Cape Station), NREL/DOE cost-modeling outputs (the Annual Technology Baseline, the GeoVision study, and the Enhanced Geothermal Shot analysis), and reputable trade and technical reporting. LCOE is treated as a capex-and-drilling-dominated function of (a) per-well drilling cost, (b) MWe per well, (c) capacity factor, and (d) cost of capital, consistent with the structure of NREL's GETEM model. The cost-stack shares, sensitivity swing magnitudes, scenario LCOE bands, the firmness-premium figure, and the $60–80/MWh base-case LCOE are **Beyond Solar estimates**, anchored to the cited DOE/NREL targets and Fervo's disclosed well economics; each is labelled in-text. Agency cost figures are stated in their published vintage (NREL ATB 2024 figures are 2022$); Fervo well costs are nominal as reported in 2024. Discount rate (7% real) and 30-year plant life are our analysis assumptions for a utility-scale firm asset. The conclusion would change most if (i) the drilling learning rate stalls, (ii) multi-decade thermal drawdown proves worse than modeled, or (iii) the firm-CFE demand pull from data centers weakens. No forward company financials are projected.

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