Perfecting Hot Rocks

By John Benson

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1. Introduction

I started this journey long before I posted my first paper on Energy Central. Long before I retired in 2013 and actually in the mid-1980s. I worked for a small company that was owned by Landis & Gyr (yes, after going through many changes, they eventually morphed into Landis+Gyr). At that time my small company produced Supervisory Control and Data Acquisition (SCADA) Systems and Electric Utility Energy Management Systems (EMS). This company was in PG&E's service territory (in San Jose, CA), and PG&E needed a SCADA system for a pumped-storage hydro generation facility (Helms Pumped Storage) they were building at that time. I was involved in pursuing this opportunity, and we were successful, as was the system.

About 10 years later, PG&E needed a replacement automatic generation control (AGC) system for their Geysers geothermal generating facility, then, and still, the largest geothermal facility in the world. It currently generates 725 megawatts – enough to power a city the size of San Francisco. We and the system were also successful there. The Geysers is now owned by Calpine.[1]

Cut to the present – after I retired, I started posting papers regarding a range of energy, mobility and environmental subjects, including (eventually, in 2021) geothermal power. I called the first four of these "Hot Rocks…" and the first is called "Hot Rocks – The Perfect Renewable Energy."[2] The other three are listed and linked below.

Hot Rocks, part 2

https://energycentral.com/c/cp/hot-rocks-part-2

Hot Rocks Part 3 – Widespread Geothermal Power

https://energycentral.com/c/gn/hot-rocks-part-3-%E2%80%93-widespread-geothermal-power

Hot Rocks Part 4, 2024 Update & Next Generation

https://energycentral.com/c/cp/hot-rocks-part-4-2024-update-next-generation

So why is geothermal the Perfect Renewable Energy? Because it is fully dispatchable (can have its power output increased or decreased independent of weather, etc., within its operational limits, to follow grid dispatch requirements) and thus isn't intermittent, and doesn't require any type of fuel other than Mother Earth's deep natural radioactivity.

The above four "Hot Rocks" posts provide a reasonable tutorial on geothermal power. However recently, I thought I should revisit this subject. I found an excellent recent paper, started reading it, and was overwhelmed. First of all, it was huge (well over 10,000 words). although was very well-written, I still needed to do clean-ups before I could start condensing it into a normal-length post. The initial "clean-ups" took over half a day, mainly because the primary word-smithing authors were apparently from the UK, and used different terminology and phrasing than we use in the U.S.

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[1] https://www.calpine.com/clean-and-reliable-power/our-assets/geothermal/

[2] https://energycentral.com/c/cp/hot-rocks-%E2%80%93-perfect-renewable-energy

One of the authors is from Lawrence Berkeley National Laboratory, in the SF Bay Area (a total of five authors list affiliated organizations in the U.S., but I believe that two of these authors are from the UK). I am starting to put the summary paper (this paper) together in Mid-February, and don't expect to post it until early-April.

2. Enhanced Geothermal Systems (EGS)

Geothermal energy provides clean, steady and renewable electricity and heat, but the use of geothermal energy has conventionally been constrained to locations with adequate subsurface heat and fluid flow. Enhanced geothermal systems (EGS) enable geothermal energy usage in unconventional areas by enhancing the subsurface permeability and increasing fluid flow, which is then extracted as a carrier of the thermal energy. In this Review, we discuss the development of EGS and its role in providing energy. Some EGS are operating commercially in Europe and provide heat and/or electricity, but technical issues and concerns over induced seismicity have historically hindered the broader expansion of EGS. Adaptation of advanced drilling techniques (including the use of polycrystalline diamond compact bits, multi-well drilling pads, horizontal drilling and multistage stimulation) is enabling an increase in scale and decrease in cost of EGS projects. As a result, in the USA, enhanced geothermal is expected to achieve plant capital costs (US$4,500/kW) and a levelized cost of electricity (US$80/MWh) that will be competitive with market electricity prices by 2027. With further development of EGS to manage induced seismicity risk and increase system flexibility, EGS could provide stable baseload and potentially dispatchable electricity for clean energy systems.[3]

2.1. Hydrothermal vs. EGS

With Hydrothermal Geothermal Resources, the developers have all that need to start producing power under their feet. So theoretically, all they need to do is drill a well, albeit generally a very deep one (typically 8,500 to 16,000 feet). However, this assumes that their process does not leak any water, anywhere at any time. I don't know if any process could meet this requirement, and if it could, it's probably not worth the trouble.

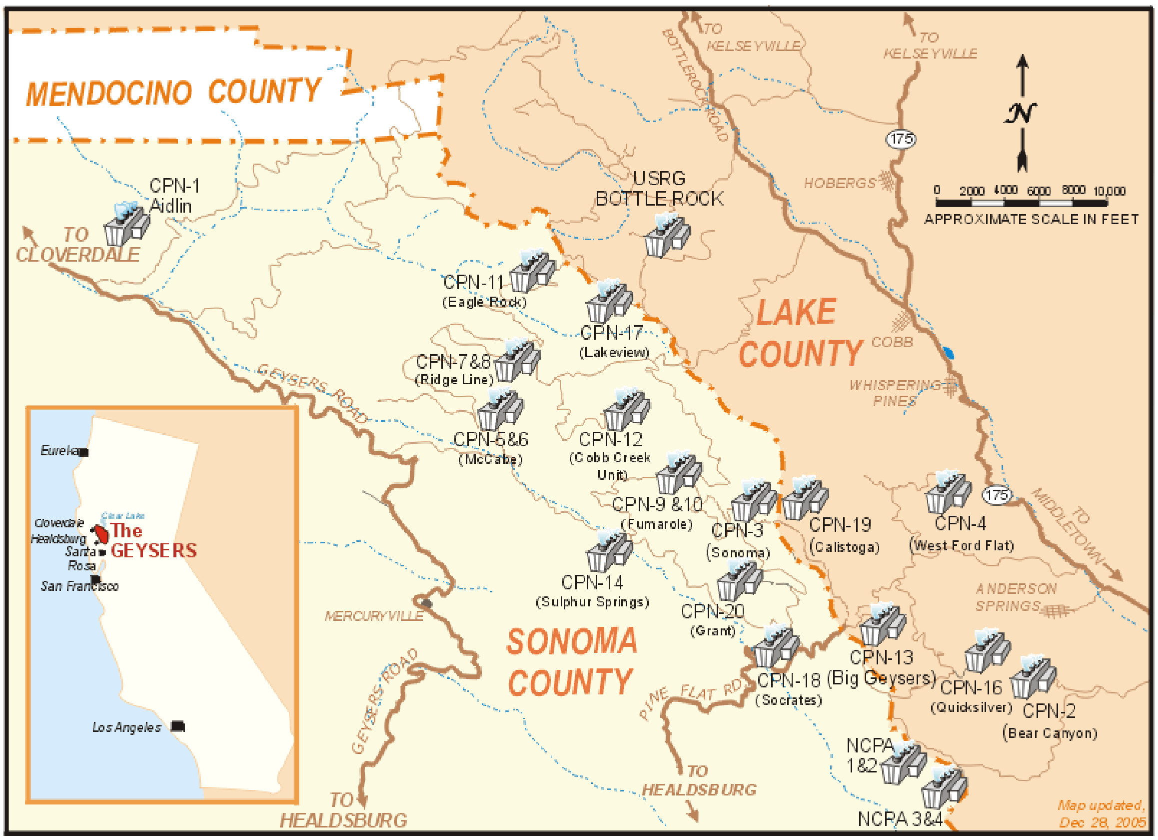
What this means is, as a minimum, they need to drill two wells: one to extract the steam, and the other to inject replacement water. The good news is that the only contaminants in the steam they need to deal with are gases. At the Geysers we needed to deal with hydrogen sulphide (H_2S), which is a pretty nasty gas (toxic, flammable and tends to corrode many metals, including copper).

Three resources are required for a hydrothermal generation: hot rocks are one, with the "hot" well above 100°C (or 212°F, the boiling temperature of water). Then you need water in contact with the hot rocks, and then you need the rocks to be fractured or porous, so that water can penetrate them and continually generate steam.

[3] Roland Horne & William Ellsworth, Energy Science and Engineering Department, Stanford University, Stanford, CA; Albert Genter, Electricité de Strasbourg, Strasbourg, France; Jack Norbeck, ResFrac, Palo Alto, CA, USA; Mark McClure, Fervo Energy, Houston, TX, USA; Eva Schill, Lawrence Berkeley National Laboratory, Berkeley, CA, USA; "Enhanced geothermal systems for clean firm energy generation;" January 21, 2025; https://www.nature.com/articles/s44359-024-00019-9

With EGS, there are work-arounds for all three of the potentially missing resources. A lower-boiling-temperature fluid can be used to allow heat, at or below 100°C to be used. However, the efficiency plunges as this temperature goes down, and these generation systems using exotic working fluids (vs. water) are much more complex and expensive.

Water can be injected into hot, dry rocks. Non-porous rocks can be fracked (fractured). For those of you that haven't hung around the oil (or natural gas) patch lately, fracking is the process of injecting liquid at high pressure into subterranean rocks, boreholes, etc. so as to force open existing fissures and extract oil or gas. This is also called hydraulic fracturing. The good news is that fracking is widely used in the petroleum industry, and thus is developed technology. The bad news is that, unless the developers are very careful, fracking can cause minor earthquakes, and even minor earthquakes, which are common (several every year) in my area (SF Bay Area) are really poor for public relations. This is why it is good for geothermal projects should be in really remate areas (which the Geysers are, near the crest of the Mayacamas Mountains, see map below).

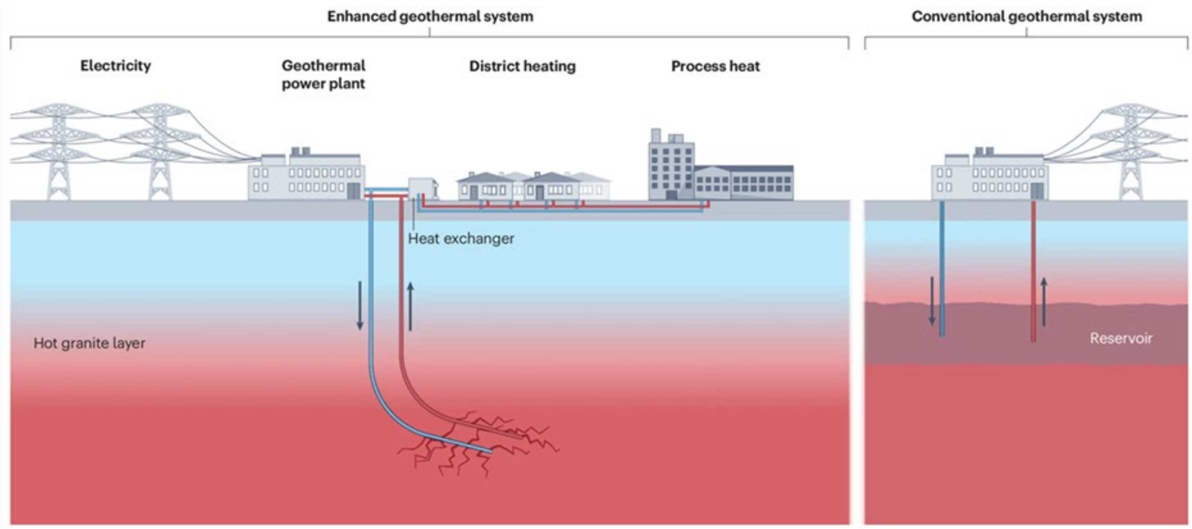


2.2. EGS History

Enhanced geothermal systems can facilitate the use of geothermal systems in suboptimal settings by stimulating permeability and increasing fluid flow through the rock, allowing the thermal energy to be swept out by the circulating fluid. Fluid flow is increased by drilling injection and production wells into hot rock and enhancing its permeability by fracturing or other means (Fig. 2, next page). Hot water and/or steam is then sent to the surface, where it can be used to generate electricity in a steam turbine or binary power plant (uses a second operating fluid with lower-temperature boiling).[3]

EGS was originally described and patented in the 1970s. Drilling started on the world's first large-scale EGS at Fenton Hill, NM, USA in 1974. By 2020, there had been more than 64 permeability enhancement projects globally, including around 20 projects that involved well-to-well permeability creation in unconventional geothermal sites

Figure 2: EGS vs. Conventional Geothermal.



Enhanced geothermal systems access areas not suitable for conventional geothermal systems by increasing the permeability of hot rock. Water is pumped from a surface station to a hot reservoir, where it is heated. The hot water is then extracted to the surface, where it can be used for heating and/or converted into electricity. Electricity is often generated through steam turbines or in binary cycle power plants. Conventional geothermal systems also extract hot water and steam, but rely on natural reservoirs and tend to be shallower.

These projects have mainly been government research projects or commercial operations at a small scale (a few megawatts electrical), and only a few EGS sites produce energy commercially. However, since 2020, new projects have commenced development at much larger scale, using innovations in technology and substantial reductions in development cost, representing a major change in direction and outlook for EGS projects.

In this Review, we address the scientific and technical issues involved in scaling up EGS deployment, focusing specifically on the well-to-well concept. We discuss where EGS has been developed (mainly in the U.S.) and the kinds of geology that are most suitable. We describe drilling and stimulation of EGS with the least risk of induced seismicity. Finally, we examine the applications and economics considerations of these systems in a transitioning energy system.

2.3. EGS locations and Geological Settings

Successful EGS prototypes have fluid flow mainly in the granite basement and, where connected through faults or fracture systems to the granite basement, in its overlying sedimentary cover. Broadly, EGS can be categorized as convective-dominated systems (which have some open natural fractures) or conductive-dominated systems (with few natural fractures). The two types of systems can require different borehole trajectories, stimulation strategies and geothermal targets. This section examines the settings in which EGS are and could be hosted and the interactions between the natural and engineered fractures that allow fluid to flow.

2.3.1. Convective Systems

Convective-dominated EGS are in geologically active tectonic settings and involve naturally fractured rocks that have sealed or poorly connected fractures and therefore need to be stimulated to enhance the flow rate. Then, natural fluids within the fracture system can be circulated via suitable borehole placement. Such systems can be found in geothermal regions that do not active magma-flow.

Convective systems are mostly found in Europe and Australia.

2.3.2. Conductive Systems

The second geological setting for EGS prospects, conductive-dominated systems, is in formations with relatively low intrinsic permeability and no hydrothermal activity. In these low-permeability formations, geothermal wells must be stimulated to achieve commercially viable production rates. New localized vertical induced fractures can be created using stimulation techniques in horizontal or angular borehole trajectories (fracking). Those engineered fractures connect the wells by acting as local heat exchangers for heating injected fluids by conduction.

There have been successful conventional geothermal projects in the Basin and Range province in the Western USA, where temperatures range from 200°C to 250 °C in geothermal reservoirs. Geothermal reservoirs form within a number of basement rock-types and are bordered by vertical faults with up to 400 m of offset. However, it has not always been possible to reach commercial flow rates in some locations of the Basin and Range and the Great Basin more broadly. Hence, EGS could be a good alternative approach in these locations where the primary permeability is the limiting factor rather than heat.

Many conductive EGS sites are found in the Great Basin region of the USA (which includes the Basin and Range). There, pilot EGS projects in Coso, Desert Peak, Blue Mountain and Utah FORGE are in active extensional regimes with normal faulting, low permeability and high regional heat flow (Fig. 3, next page). At Desert Peak, the injectivity index is substantially below the typical threshold for commercial geothermal wells, and a nearly 60-fold increase in injectivity was achieved after a series of stimulation operations. However, it was far below the value that was classified as a very good post-stimulation injection well in Europe. The Utah FORGE EGS site (in Utah, USA) is mainly governed by a low permeability conductive thermal regime. This conductive area is separated from the nearby convective Roosevelt Hot Springs (Blundell) geothermal system by a local fault (Fig. 3). At Utah FORGE, crystalline rocks are faulted and fractured with various orientations, dipping from high to low angles and measured permeabilities are less than 30 microdarcies.[4]

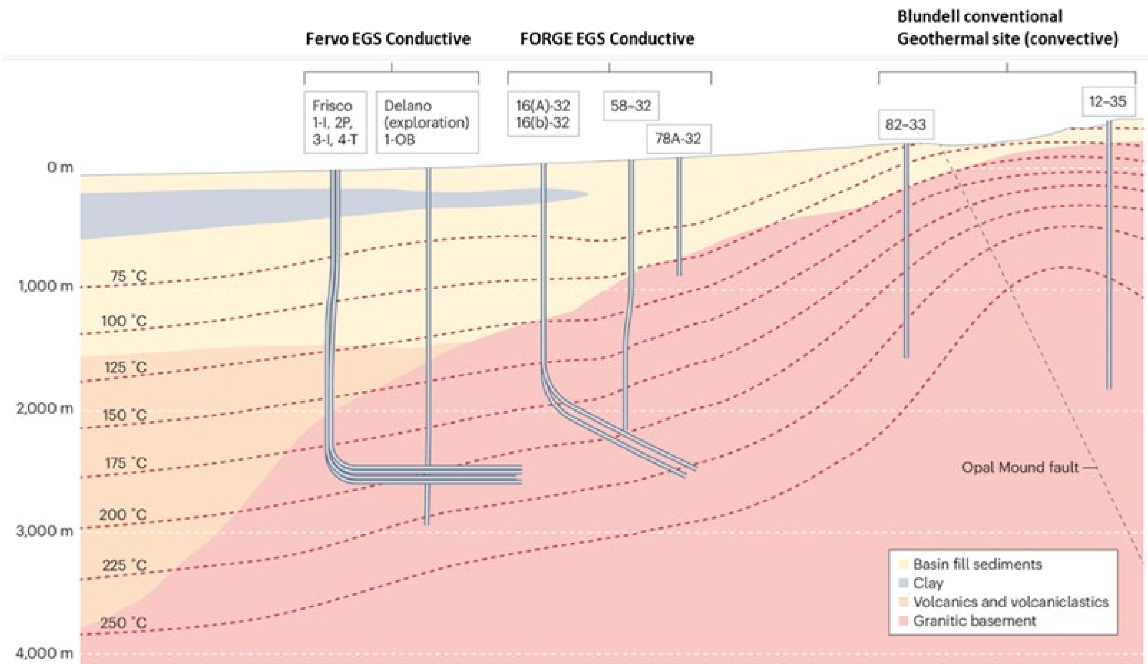
2.4. Drilling technology and performance

The economic viability of conventional geothermal projects depends heavily on drilling performance. Historically, drilling costs typically account for ~50% of the total project cost and have a substantial role in determining the overall feasibility of these projects. The role of drilling cost in economic viability is expected to also be the case for EGS. However, compared with conventional systems or earlier EGS, more recent EGS projects have improved drilling performance and reduced costs.

[4] A medium with a permeability of 1 darcy permits a flow of 1 cm^3/s of a fluid with viscosity 1 cP (1 mPa·s) under a pressure gradient of 1 atm/cm acting across an area of 1 cm^2. See https://en.wikipedia.org/wiki/Darcy_(unit)

Examples are FORGE and in Fervo projects in Nevada and Utah. One general advantage is that EGS wells are drilled at designed locations rather than needing to seek optimal geological structures as a conventional geothermal development would. EGS projects typically target geothermal formations with a predictable and uniform temperature distribution at depth, which allows a target production temperature selection and power generation facility optimization early in the project life.

Fig 3: Three US Geothermal Systems' Geological Settings

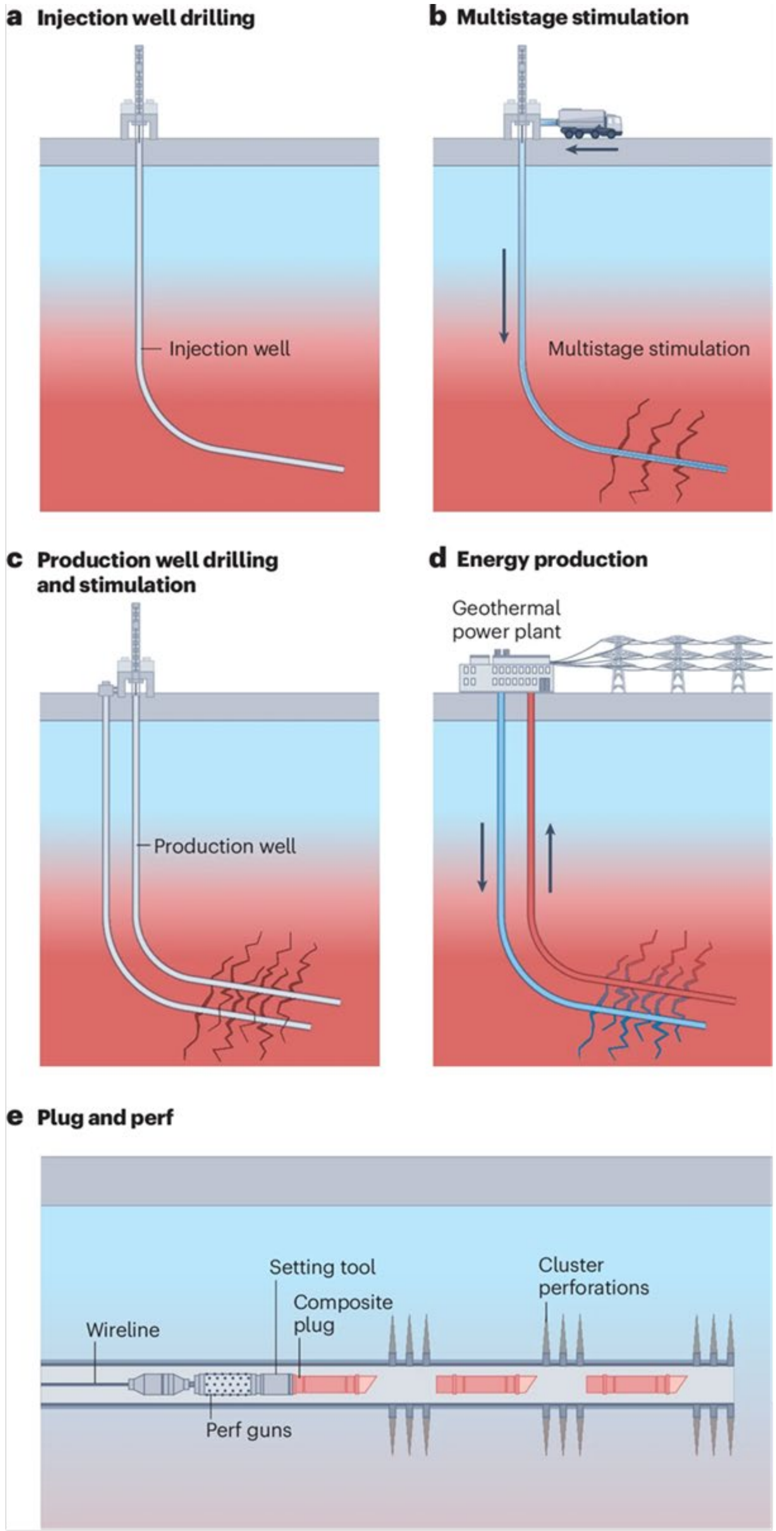


Three geothermal systems are operational in Utah, USA. Two conductive enhanced geothermal systems (EGS) are located within 1 km (Fervo and FORGE). These systems near (<2 km) the Blundell conventional geothermal system, which is convective owing to water moving through the naturally occurring Opal Mound Fault.

Improvements in EGS drilling performance and cost are largely related to technology. Modern drilling technologies from the shale industry (such as horizontal drilling, multistage stimulation and use of polycrystalline diamond compact (PDC) bits) are being brought into the geothermal industry and have improved drilling performance. Previously, conventional geothermal and EGS wells were more commonly drilled with conventional tri-cone roller bits, which wore out faster (requiring more trips to the surface for bit-replacement) and could not drill as fast owing to limitations on the weight that could be placed on the bit. The newer horizontal drilling and multistage stimulation approaches allow consistent access to a reservoir volume sufficient to sustain an EGS project over the life of the power station (Fig. 4, next page).

Some EGS drilling designs have borrowed from oil and gas shale practices by drilling multiple wells from a single pad. The multi-well pads can host eight or more wellheads, each spaced ~5 m apart. This approach reduces geological risks by ensuring that the vertical sections of each well encounter similar rock-types. Multi-well pad usage enables fewer rig mobilizations, as modern drilling rigs are able to skid between wellhead locations within hours instead of days. Additionally, by grouping wellheads close together and placing the well pads closer to the power plant facility, it is possible to concentrate surface pipelines and reduce the total length of pipelines required and hence the capital cost of the project.

Fig. 4: EGS Project Phases:



a, Enhanced geothermal system development begins with drilling of an injection well. b, Fractures are created using multistage stimulation. c, A production well is then drilled and stimulated. d, Energy is produced from the wells. e, Plug and perf technology to control stimulation.

Advancements in drilling technology commonly follow a learning curve, in which the learning rate is the percentage cost reduction for every doubling of total wells drilled. Learning rates of ~18% have been demonstrated in the shale gas industry, suggesting that similar improvements could be achieved in the geothermal sector. As shown in field applications, EGS drilling performance also follows a learning curve, with the opportunity for the application of workflow to remove barriers and overcome errors, leading to cost reductions as the technology scales in the future (Fig. 5, next page). For example, at the Utah FORGE site, two highly deviated geothermal wells were drilled in a granite formation using PDC[5] bit technology, achieving rates of penetration of more than 30 m/h. Fervo Energy has reported drilling results from eight horizontal wells drilled across two different basins in Nevada and Utah, also using PDC bits. There was a 60% reduction in drilling days over this series of eight wells, equating to a 35% learning rate.

2.5. Stimulation to create EGS

EGS stimulations occur through the propagation of artificially created fractures and/or opening and shearing of pre-existing fractures that occur naturally in the rock. Stimulation is key to allowing fluid flow in EGS, but can also induce seismicity, which must be managed. This section describes stimulation mechanisms and management and highlights results from early stimulation efforts and from projects in the 2020s.

2.5.1. Stimulation mechanisms and techniques

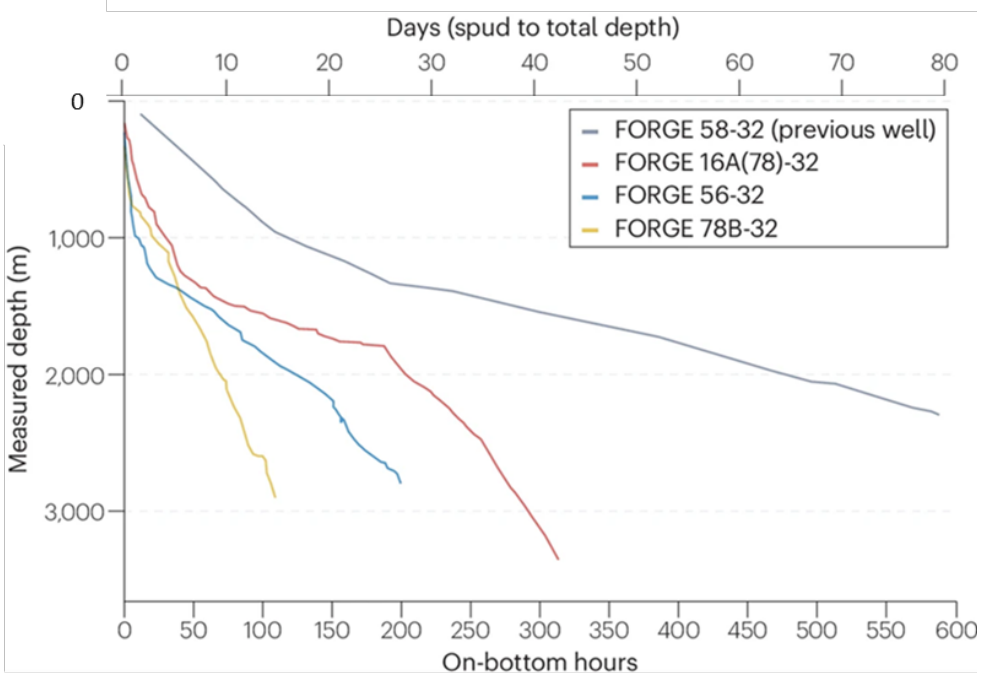
Hydraulic stimulation is performed with high-rate and high-pressure injection of fluid (usually water), which can also contain proppant[6]. Stimulation occurs through propagation of newly forming fractures and/or shear stimulation of pre-existing fractures. Shear stimulation occurs when fluid injection increases pressure and induces slip, which increases natural fracture conductivity. Newly forming fractures can initiate from the well or from pre-existing fractures and flaws. Initiation from the wellbore can be a complex process, depending on wellbore orientation with respect to the stress state. Once initiated, fractures can propagate as long as their internal fluid pressure exceeds the magnitude of the minimum principal stress, plus a small additional net pressure that is determined by the fracture toughness. Even if the fluid pressure is less than the minimum principal stress, fracture slip can create splay or wing cracks, opening mode features that propagate a limited distance from the shearing feature.

Splay fractures are associated with fault formation in granite and brittle compressive failure of intact rock. However, it is unlikely that EGS stimulation leads to the formation of entirely new shear faults through the brittle compressive failure of intact rock. The compressive strength of rock is high, especially under confining stress and in the crystalline rock-types where EGS is typically performed. Stimulation might advance fault development incrementally through fracture link-up, but overall, the development of fault zones in crystalline rock is a complex, progressive process that requires a larger magnitude of strain than results from stress release due to high pressure injection.

[5] PDC: polycrystalline diamond compact bits
[6] Proppant: a particulate material such as coarse sand to keep fractures open.

Under some conditions, hydraulic fracture propagation can be arrested by interaction with a pre-existing plane of weakness. This observation has been formulated into numerical modelling codes that predict volumetric, branching fracture networks. However, during practical field-scale fracturing, several factors can limit the effect of termination: cementation that gives natural fractures cohesion; the ability to propagate over and around pre-existing fractures; and the reinitiation of a new hydraulic fracture a short distance after termination.

Fig 5: Drill rate at Utah FORGE



Some EGS projects in the USA since 2022 have used plug and perf completion, in which casing pipe is cemented into the wellbores (see figure 4e on page 7). Then, fluid is injected into the formation from holes in the pipe called perforations, along with proppant[6] to hold open the fractures after shut-in. This stimulation design targets creation of newly formed fractures, rather than stimulating natural fractures (which can no longer be accessed directly by the well because the steel pipe is cemented into the wellbore). These designs have yielded EGS wells with reported circulation rates up to 100 kg/s). The advantage of plug and perf completion with proppant is that it gives engineers more control over the fracturing process. Rather than hoping that natural fractures will have optimal characteristics for effective shear stimulation, engineers create new fractures in an arrangement of their own design. Perforation clusters are placed and injection schedules are optimized to control the size, spacing and conductivity of the fractures. Achieving a distributed set of fractures, flowing uniformly, is advantageous to the convective heat recovery of a substantial volume of hot rock. However, relative to earlier EGS designs, the main drawback to plug and perf completion is cost. Earlier designs avoided the expense of steel casing and cement in the productive interval, and they did not require proppant, plugs or perforation guns.

The need for proppant[6] in stimulation is not universally accepted throughout the EGS community. In oil and gas well stimulations, the rock types are usually sedimentary and compliant, so newly forming fractures nearly always require proppant to maintain substantial conductivity after shut-in, when the pressure falls below the minimum principal stress and the fracture closes mechanically. However, as some EGS projects have shown, fractures in hard crystalline rocks can self-prop owing to the displacement and subsequent mismatch between rock surface irregularities. This reduces or eliminates the potential benefit from placing proppant.

There are other stimulation approaches that are not hydraulic. Chemical stimulation has been used successfully in some EGS projects. These approaches could require less fluid injection and so have lower potential for induced seismicity. However, these approaches — on their own — have not yet achieved commercially viable circulation rates in EGS.

EGS projects tend to be located in crystalline basement rock, which deforms in a brittle manner with minimal ductile deformation. Superhot geothermal (above 400 °C) is an exception — at these temperatures, ductile deformation becomes meaningful. Mechanisms of stimulation under these conditions could be substantially different, and this topic remains an area of active research.

2.5.2. Stimulation Results in EGS Projects

Reservoir conductivity at Utah FORGE has been enhanced by two high-pressure hydraulic stimulations (multistage stimulation) of the granite rock mass, opening new hydraulic fractures and/or activating pre-existing natural fractures. The FORGE project used multistage stimulation along a highly deviated lateral and experimented with two different stimulation strategies. The first set of stimulations, in July 2023, were performed along three stages at the toe of the well and did not use proppant. An inter-well circulation test achieved a low circulation rate, 0.44 kg /s. The second set of stimulations, from March to April 2024, was performed with proppant in six new stages. In addition, a previous stage was restimulated and the production well was also stimulated. A subsequent 10 h circulation test achieved a production rate of 22 kg/s from an injection rate of 35 kg/ s, with the production rate still increasing steadily when the test was ended.

In 2023, production testing of a horizontal well EGS was completed at Project Red in northern Nevada, USA, using the plug and perf stimulation approach and proppant. The Project Red system (adjacent to the Blue Mountain conventional geothermal field) was commissioned in the summer of 2023 and began supplying power to the grid by October. The reported well-to-well flow rate was 63 kg/s. At Project Cape in southern Utah, by September 2024, 15 horizontal wells had been drilled. A three-well pad was stimulated by the plug and perf approach, with 80 treatment stages, all with proppant. During a 30-day test, the first production well reached a peak flow output equivalent to 12 MW electrical generation capacity and sustained 8–10 MW. The maximum well-to-well flow rate was 121 kg/s, stabilizing at 93 kg/s.

2.5.3. EGS-induced seismicity

EGS can cause earthquakes during stimulation and operation. Although most are usually small and only detectable on sensitive instruments, some are large enough to create nuisance shaking and a few have been strong enough to cause structural damage and human injury, leading to the delay, scaling back or cancellation of the industrial activity.

Seismicity occurs when fluids are either injected into or extracted from faults, which can tip the balance between applied stress and fault strength. In many settings, such a fault is brought to failure by transmission of increased pore pressure to the fault.

For both natural and engineered geothermal energy projects, long-term circulation of fluids has the potential to destabilize faults through contractional strains caused by cooling of the rock mass or disturbance of geochemical equilibrium of faults and fractures from fluid–rock interactions.

2.5.4. Managing EGS-induced Seismicity

When combined with the exposure of people or the built environment and their vulnerability, the resulting risk or chance of suffering loss or harm from induced seismicity can be quantified. This risk — to the project, nearby populations and infrastructure — needs to be considered when developing mitigation strategies for induced seismicity. A serious risk to the project itself is loss of the license to operate, some cases of which have resulted from earthquake shaking levels well below the structural damage threshold. Nuisance shaking from earthquakes no larger than M3–4 has led to the cancellation of EGS, unconventional hydrocarbon and natural gas production and storage projects worldwide.

Experiences with hydraulic fracturing have shown the benefits of well-planned operational controls for addressing seismicity. In practice, these controls often take the form of a traffic light protocol that is informed by high-sensitivity local seismic monitoring and that defines actions to be taken at the well site if certain earthquake magnitudes are exceeded. The protocol is commonly set as green for normal operations, yellow to trigger a defined response and red to stop operations, either temporarily or permanently. Such traffic light systems are most successful when they have been developed with input from all stakeholders, including the public, and operate in a transparent and open environment. Critical elements of a comprehensive seismicity mitigation plan begin with preliminary site screening, development of hazard models for both natural and induced events, evaluation of the risk posed by induced events to people and property and ongoing public ongoing communication with all findings, among other steps.

In an analysis of approaches to mitigate induced seismicity at a Swiss-project, it was proposed that the multistage stimulation approach, such as that used at FORGE, would reduce the risk of triggering seismicity compared with a single massive stimulation.

Final author's comment: As I suggested above, the best approach in limiting public outcry due to EGS-induced earthquakes, is to keep these projects well away from any general population-settlements. I would also guess that areas like mine (SF Bay Area), where we are accustomed to minor quakes, would be less sensitive to EGS-quakes.

Also, our area has been naturally fracked by Mother Nature over millennia, limiting the propagation distances for small quakes. Newer homes are built to seismic standards, and older-homes have been already tested with decades of small quakes. The strongest earthquake Livermore, my home-city, has experienced in several decades was a 5.8 M quake in1980, and yes, my wife and I lived here then, but we were at work in San Jose (still felt it there), and when we got home, there was no damage.[7]

Contrasted with my area, I would guess the greatest out-cry would come from EGS projects in areas that are mostly unused to small quakes.

[7] https://en.wikipedia.org/wiki/1980_Livermore_earthquake