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REVIEW ARTICLE **RENEWABLE ENERGY**

Geothermal Energy Expansion in Non-Volcanic Regions: A Review of Enhanced Geothermal Systems (EGS)

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ABSTRACT

Enhanced Geothermal Systems (EGS) is a game changer to utilizing geothermal energy in areas that do not have traditional hydrothermal resources. This literature review presents the existing developments in EGS technology including reservoir stimulation, thermal-hydraulic-mechanical-chemical (THMC) modeling, drilling innovations, power conversion systems, and seismic risk management. We discuss EGS projects around the world, such as Soultz-sous-Forêts (France), Cooper Basin (Australia), Pohang (South Korea), Project Cape (by Fervo Energy) (United States), and FORGE (Utah, USA) to draw the conclusions which can be used in the large-scale application. The article measures the theoretical resource base of EGS (over 10,000 EJ can be recovered in the United States alone), model levelized cost of energy (LCOE), and assesses key technical constraints such as well productivity, reservoir life, and induced seismicity. New technologies such as superhot rock (SHR) geothermal, machine-learning-controlled drilling, and distributed acoustic sensing (DAS) are examined in terms of how they can speed up the commercialization process. We find that EGS might be able to deliver 8.5 percent of world electricity by 2050 in favorable learning-rate conditions, but it will take long-term R&D, permit streamlining, and innovative financing systems. The review serves as an excellent resource to researchers, engineers, and policymakers moving about in the new EGS terrain.

التوسع في استخدام الطاقة الحرارية الأرضية في المناطق غير البركانية: مراجعة لأنظمة الطاقة الحرارية الأرضية المحسنة (EGS)

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الكلمات المفتاحية

أنظمة الطاقة الحرارية الأرضية المحسّنة
التحفيز الهيدروليكي
الطاقة الحرارية الأرضية العميقة
الزلازل المستحثة
الصخور فائقة السخونة

الملخص

تُعدّ أنظمة الطاقة الحرارية الأرضية المُحسّنة (EGS) نقلة نوعية في استغلال الطاقة الحرارية الأرضية في المناطق التي تفتقر إلى موارد الطاقة الحرارية المائية التقليدية. يستعرض هذا البحث الأدبي التطورات الحالية في تقنية أنظمة الطاقة الحرارية الأرضية المُحسّنة، بما في ذلك تحفيز المكامن، والنمذجة الحرارية-الهيدروليكية-الميكانيكية-الكيميائية (THMC)، وابتكارات الحفر، وأنظمة تحويل الطاقة، وإدارة المخاطر الزلزالية. نناقش مشاريع أنظمة الطاقة الحرارية الأرضية المُحسّنة حول العالم، مثل مشروع سولتز-سو-فوريه (فرنسا)، وحوض كوبر (أستراليا)، وبوهانغ (كوريا الجنوبية)، ومشروع كيب (من شركة فيرفو إنرجي) (الولايات المتحدة)، ومشروع فورج (يوتا، الولايات المتحدة الأمريكية)، لاستخلاص النتائج التي يُمكن تطبيقها على نطاق واسع. يقيس المقال قاعدة الموارد النظرية لأنظمة الطاقة الحرارية الأرضية المُحسّنة (حيث يُمكن استخراج أكثر من 10,000 إكساجول في الولايات المتحدة وحدها)، ويُنمذج التكلفة المُستوية للطاقة (LCOE)، ويُقيّم القيود التقنية الرئيسية مثل إنتاجية الآبار، وعمر المكمن، والزلازل المُستحثة. تُدرس التقنيات الحديثة، مثل الطاقة الحرارية الأرضية باستخدام الصخور فائقة السخونة، والحفر المُتحكم فيه بواسطة التعلم الآلي، والاستشعار الصوتي الموزع، من حيث قدرتها على تسريع عملية التسويق التجاري. وقد توصلنا إلى أن أنظمة الطاقة الحرارية الأرضية المُحسّنة (EGS) قد تُساهم في توفير 8.5% من الكهرباء العالمية بحلول عام 2050 في ظل ظروف التعلم

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المُواتية، ولكن ذلك يتطلب بحثًا وتطويرًا طويل الأجل، وتبسيطًا لإجراءات الترخيص، وأنظمة تمويل مبتكرة. ويُعدّ هذا التقرير مرجعًا قيّمًا للباحثين والمهندسين وصانعي السياسات العاملين في مجال أنظمة الطاقة الحرارية الأرضية المُحسّنة.

Introduction

The energy shift in the world requires a low-carbon, dispatchable, and firm power generation that would fill the natural gaps between the intermittent nature of solar and wind power. Geothermal energy, which is a form of energy derived from the internal heat of the earth, fulfills the following needs: it is renewable on human time, it is not affected by weather, and it does not need a lot of land use compared to the amount of energy it produces. Nonetheless, traditional hydrothermal geothermal power, based on naturally found hot water or steam fields, is limited in geographical scope to tectonically active areas like Iceland, the Western United States, New Zealand, the Philippines, Indonesia, Kenya, and Iceland.

Enhanced Geothermal Systems (EGS) also seek to eliminate this geographic constraint by developing artificial reservoirs in hot and low-permeability rock by hydraulic stimulation to open up geothermal resources effectively anywhere on Earth. The original MIT work by Tester et al. [1] approximated the base of the EGS-accessible geothermal resources in the United States alone to be over 13,000 EJ—about 130,000 times the United States' yearly electric use. In the entire world, Aghahosseini and Breyer [2] estimated the technical EGS capacity to be about 7,500 EJ/year, which was estimated to be enough to provide the world's projected 2050 electricity requirement several times over.

In spite of this vast theoretical promise, EGS has not so far realized a wide commercial adoption. The technology has several interrelated issues: the cost of drilling deep into crystalline basement rock; the challenge of producing and maintaining networks of permeable fractures at high pressure and temperature; the risk of induced seismicity that can cause community damage or prompt regulatory shutdown of the project; deep-temperature corrosion and scaling of well materials; and the unpredictability of the economics of an early-stage technology competing with quickly falling solar and wind costs. More recent discoveries, however, especially the successful commercial horizontal EGS wells of Fervo Energy in Nevada and the DOE-funded Frontier Observatory for Research in Geothermal Energy (FORGE) project in Utah, have brought a vital boost of renewed industry and investor confidence.

This review gives a thorough evaluation of EGS technology throughout the lifecycle of the project, beginning with the geological site characterization and continuing with the reservoir creation, power generation, and environmental management. We use exemplar projects across the globe [3], [4], [5], [6] to generalize experience and uncover long-standing technical challenges and assess the prospects of large-scale EGS implementation across a range of technological and policy conditions. The paper is structured in the following way: Section 2 discusses the basics of geothermal resources; Section 3 discusses site characterization procedures; Section 4 discusses reservoir stimulation and engineering. Section 5 discusses the THMC modeling. Section 6 discusses drilling technologies. Section 7 discusses power conversion systems. Section 8 discusses induced seismicity and risk management, and Section 9 discusses economics and deployment trajectory

Geothermal Resource Fundamentals and Classification

Earth's Heat Budget

Having a constant rate of about 44.2 TW of heat released through its surface, the Earth has two main sources of this heat: primordial heat stored during accretion and differentiation (~20 TW) and radiogenic decay of long-lived isotopes (uranium-238, thorium-232, and potassium-40) in the crust and mantle. This diffuse heat flux (with an average of only 87 mW/m² worldwide) is virtually available at a depth at which the temperature is high enough to drive power production (usually, over 150 °C in the case of binary cycle systems, or over 200 °C in the case of flash steam plants).

Geothermal gradient is the change in heat with depth and is on average 25-30 ºC/km in most areas of the world but differs unbelievably depending on the tectonic environment. Volcanic arcs and mid-ocean ridges can have steepens of more than 100 °C/km, and old Precambrian cratons can have steepens of less than 15 °C/km. Moeck [7] established a systematic geothermal play type classification, based on the tectonic environment, the type of heat source, the route of the fluid, and the geometry of the cap rock. This model is especially useful in determining EGS targets in sedimentary basins, fault-controlled areas and orogenic belts where high levels of heat flow are present but natural permeability is too low to be exploited conventionally.

EGS Resource Classification

The level of natural permeability and the kind of stimulation necessary can be generalized into three categories of EGS resources:

1. Hot Dry Rock (HDR): The original concept of EGS was first used at Fenton Hill, New Mexico during the 1970s-1990s. Rock is essentially not permeable; fracture networks have to be nearly carved out through stimulation. The stimulation challenge is compensated by high gradient temperatures (>200 °C).
2. Deep Sedimentary Aquifer EGS: These are naturally porous and permeable sedimentary rocks at depths of 3-7 km and are moderately permeable, stimulated to improve permeability. This is e.g. Cooper Basin (Australia) and part of the Pannonian Basin (Central Europe).
3. Naturally Fractured Basement EGS: Crystalline basement rock that has naturally occurring fractures and faults that can be re-opened and magnified. An example is that of Soultz-sous-Forets (France) where natural fractures are a significant source of permeability.

The U.S. Department of Energy GeoVision study [8] projected a baseline 60 GWe of installed capacity in the United States of EGS in a base-case scenario, with a peak of 120 GWe under optimistic assumptions of rapid cost reduction of drilling. The global outlook is also bright: Lu [4] has found huge EGS potential in the Sichuan Basin of China, the Rhinegraben of Germany, the Cooper Basin of Australia, the Cornwall peninsula of the UK, and throughout the Middle East and North Africa-populated areas where electricity demand is high and growing.

Site Characterization Methods

Geological Mapping and Structural Analysis

The creation of the EGS successfully starts with the thorough geological characterization of the candidate site. Understanding of lithology, stratigraphy and structural

geology is based on surface mapping coupled with interpretation of available petroleum and mining well logs. Importantly, the orientation, density and connectivity of already existing fault and fracture systems play a key role in determining the success or failure of hydraulic stimulation campaigns [9]. Sites whose natural fractures are well oriented, i.e., the poles of the site lie on the failure envelope of the principal stress space, need lower stimulation pressures and have larger stimulated reservoir volumes (SRV).

In non-volcanic areas, regional stress fields are to be mapped in detail. The database of World Stress Map, along with the measures of locality in borehole breakouts, drilling-induced fractures, and hydraulic fracturing experiments in slim exploration wells, limits the orientation and magnitude of the three main stresses ($S_1 \geq S_2 \geq S_3$). This data directly guides well design (azimuth and inclination), stimulation strategy (target fracture sets) and seismic hazard assessment.

Geophysical Survey Methods

A combination of geophysical techniques is generally used to image underground structure without drilling. Natural microseismicity can be monitored passively by seismic observations which give fault geometries and tectonic stress patterns. Magnetotelluric (MT) and controlled-source electromagnetic (CSEM) surveys visualize subsurface resistivity that is temperature sensitive, fluid content, and clay alteration [10]. Three-dimensional reflection seismic surveys - which are becoming more borrowed in the petroleum industry - give high-resolution images of reflective horizons, fault geometries, and basement depth.

An intensive pre-drilling characterization program was carried out at the FORGE Utah site that comprised of 3D seismic reflection surveys, gravity and magnetic surveys, magnetotelluric profiles and examination of temperature logs of 46 existing shallow wells. This multi-physics method made possible the creation of a three-dimensional geological model which constrained temperature, lithology and in-situ stress conditions before the first deep test well was drilled [11]. Dobson et al. [11] showed that by combining these heterogeneous datasets, the uncertainty in estimating the reservoir temperature was lowered by 15% as compared to using the thermal gradient.

Exploration Drilling and Well Testing

Thin exploratory wells (usually 100-150 mm) offer ground-truth on temperature gradients, lithology, fluid chemistry, natural fractures and in-situ stress unavailable to surface surveys alone. The latest logging-while-drilling (LWD) and measurement-while-drilling (MWD) equipment relay real-time information about rock properties, porosity, and image the borehole wall to locate fractures. The formation micro-imager (FMI) logs indicate fracture orientation, aperture and fill material at a sub-centimeter resolution.

Well testing Techniques, such as injection tests at various flow rates, step-rate tests to measure parting pressure in the formation, and analysis of the decay of shut-in pressure, are used to measure natural permeability and to put limits on the critical pressure necessary to cause fracture opening or shear slip. Fracture connectivity, residence time distribution and risk of thermal breakthrough Tracer tests between wells can be used once a multi-well arrangement has been completed and characterizes the connectivity of the fractures, distributions of residence time and the risk of thermal breakthrough.

Reservoir Stimulation and Engineering

Hydraulic Stimulation Mechanisms

The key activity in EGS development is hydraulic stimulation, a process controlled by injecting fluid through rates and pressures that are adequate to form or expand fracture permeability. Two different processes work concurrently: hydroshearing (shear stimulation) where the effective normal stress on preexisting fractures is lowered by increasing pore pressure to the point of slipping the fractures permanently, dilating and propping them open; and hydrofracturing (tensile fracturing), where injection pressure is increased above the minimum principal stress combined with the tensile strength of the rock, developing new tensile fractures. Zoback et al. [12] have shown that in crystalline rocks where pre-existing fractures are well oriented, hydroshearing is normally the prevailing mechanism whereas in tight and fracture-poor formations, hydrofracturing is the predominant mechanism.

The desired stimulation result is a fracture network that is complex, interconnected, and covers a large rock volume- the Stimulated Reservoir Volume (SRV)- which is permeable enough ($>10^{-14}$ m²) to support economic rates of fluid flow (>10 kg/s per well pair) throughout the life of the project (>25 years). This has to be achieved through a delicate balance; the injection pressure should be sufficient to trigger distal fractures but at the same time not exceed the threshold where large-magnitude fault reactivation will occur; the amount of fluid injected must be adequate to propagate the fracture network laterally; and the proppants used must be careful not to close the fractures aperture under stress.

Stimulation Fluids and Additives

Water is most likely to be used as an EGS stimulation fluid because of its low cost, accessibility and low ecological effects relative to hydrocarbon-based fracturing fluids. Yet, in high temperature reservoirs (above 200 ºC), viscous gel and foam additives applied to the oil and gas industry fall out of favour due to quick degradation. The use of CO_2 as an alternative stimulation and working fluid has been studied with potential benefits such as lower viscosity (increased penetration into narrow fractures), increased buoyancy-driven circulation and decreased water usage (important in arid areas). The concepts of CO_2 EGS are theoretical and not proven to work on an actual scale.

Stimulation fluids include chemical additives that have a variety of purposes: scale inhibitors diminish carbonate and silica deposition; corrosion inhibitors guard against downhole metal; and biocides hinder microbial proliferation in reservoirs. The interaction of injected fluid with host rock can increase permeability (dissolution of calcite and feldspar) or decrease it (swelling of clay and formation of silica), depending on geochemical processes. Thermodynamic models of fluid-rock reactions coupled with multiphase flow were developed by Spycher and Pruess [13] and discovered that small variations in injection temperature can cause the silica saturation index to vary sufficiently to induce permeability-weakening precipitation around injection wellbores.

Multi-Well Configurations

The initial EGS thought of a basic doublet - one injection well and one production well - linked by a fracture formed hydraulically. Triplet, quartet and more complicated multi-well configurations are increasingly used in modern EGS projects to spread the extraction of the heat source over a larger volume of the reservoir, mitigate the risk of thermal breakthrough, and provide the flexibility to control induced seismicity. In the Soultz-sous-Forêts project, there is a triplet

(one injection, two production wells) and the Cape project by Fervo Energy implements several pairs of horizontal wells similar to unconventional shale gas operations.

Horizontal and deviated wells are drilled perpendicular to the least principal stress, and intersect more natural fractures and offer more surface to heat exchange compared with vertical wells. One of the most notable recent discoveries in the sector is the use of the technology of horizontal drilling, which has been developed over several decades in the shale gas sector, to EGS. The possibility of drilling laterally at 2,600 m depth in granitic rock at temperatures of over 200 °C was demonstrated in horizontal wells drilled at FORGE (2022-2023), and the first successful multi-zone stimulation data were obtained in a horizontal EGS well in the United States. *The EGS well configuration and hydraulically stimulated reservoir are illustrated in Figure 1.*

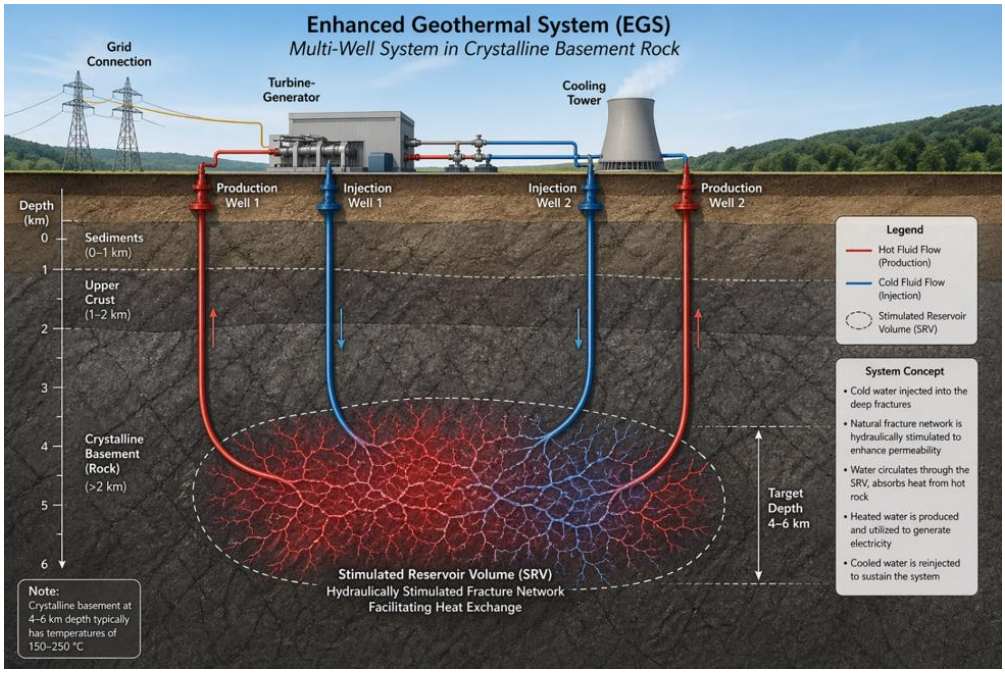


Figure 1: Conceptual cross-section of an EGS installation showing injection and production wells penetrating to 4–6 km depth in crystalline basement, with the hydraulically stimulated fracture network (SRV) facilitating heat exchange. Surface infrastructure includes turbine-generator, cooling tower, and grid connection.

Table 1: Key THMC Parameters and Monitoring Methods among Thermal (T), Hydraulic (H), Mechanical (M), and Chemical (C) domains in EGS reservoir simulation. Arrows indicate the primary coupling mechanisms; all four domains interact simultaneously during reservoir operation.

Domain	Key Parameter	Typical Range	Monitoring Method
Thermal (T)	Rock thermal conductivity	1.5–5.0 W/m·K	Laboratory core measurements, downhole DTS
Thermal (T)	Specific heat capacity	700–1200 J/kg·K	Calorimetry, empirical correlations
Hydraulic (H)	Matrix permeability	10^{-20}–10^{-15} m²	Pressure transient analysis, core plugs
Hydraulic (H)	Fracture transmissivity	10^{-10}–10^{-7} m²/s	Well test analysis, tracer tests
Mechanical (M)	Uniaxial compressive strength	100–300 MPa	Triaxial core testing
Mechanical (M)	In-situ stress ratio (k_0)	0.5–2.0	Hydraulic fracturing tests, overcoring
Chemical (C)	Brine total dissolved solids	0.5–300 g/L	ICP-MS water sampling
Chemical (C)	Silica saturation index	0–2.5	Geochemical modeling (PHREEQC)
Coupled THM	Thermo-elastic stress change	1–15 MPa/100°C	Microseismic monitoring + FEM
Coupled HMC	Mineral dissolution rate	10^{-13}–10^{-9} mol/m²/s	Lab reactors + reactive transport codes

Thermal-Hydraulic-Mechanical-Chemical (THMC) Reservoir Modelling

Coupled Process Framework

Four coupled physical and chemical processes, including thermal (T), hydraulic (H), mechanical (M), and chemical (C) initially govern the behavior of EGS reservoirs. Any of these couplings neglected will cause serious errors in the forecast of reservoir performance, thermal breakthrough, and induced seismicity hazard [14]. THMC has become the common modeling paradigm to EGS reservoir simulation, and is used in codes like TOUGH2/TOUGH+, OpenGeoSys, FLAC3D and SIERRA. *The principal THMC domains and monitoring approaches are summarized in Table 1, while their bidirectional interactions are illustrated in Figure 2.*

Thermal Evolution and Breakthrough

One of the most critical limiting factors to the longevity and economics of EGS projects is thermal breakthrough: the introduction of cooled fluid to the production wells before it can be replaced by conduction through the rock matrix. Analytical and numerical models of heat extraction in discretely fractured reservoirs were developed by Fox et al. [15] and it was demonstrated that the thermal breakthrough times are proportional to the inverse of the fracture aperture and flow rate, and proportional to the fracture spacing and thermal conductivity of the rock. An effective EGS reservoir

ought to have thermal breakthrough times of more than 25-30 years under design flow conditions.

Distributions of temperatures within EGS reservoirs change on different timescales. The thermoelastic stresses of the cool

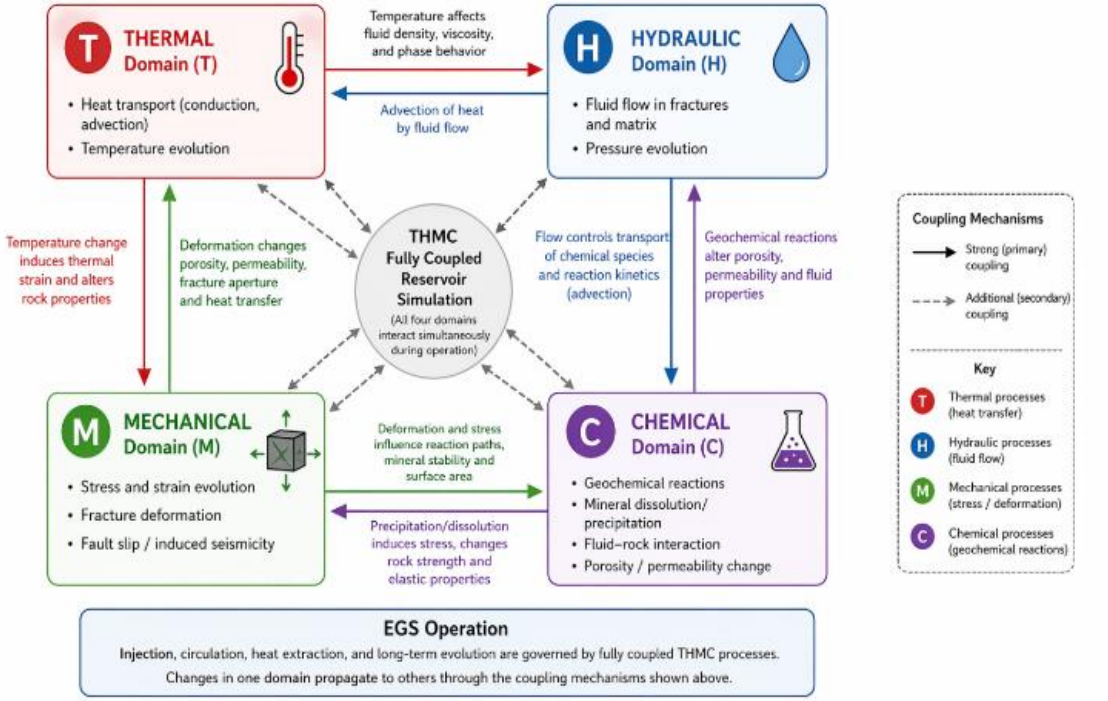


Figure 2: Schematic representation of bidirectional couplings

injection fluid during stimulation (days to weeks) cause the rock to contract, which may create new fractures and change the stress field. In early production (months to years), a thermal halo is formed around the injection wellbore due to heat extraction that exhausts the rock that is immediately available. During the life of the decadional projects, the heat source spreads out through the fracture network into the rock matrix, which serves as a distributed heat exchanger.

Drilling Technologies for EGS

Geomechanically Modeling and Seismic Hazard

Geomechanically modeling measures effective stress variations across the reservoir, which determines the change in fracture aperture, the stability of faults and the hazard of induced seismic. The Mohr-Coulomb failure criterion is a failure criterion that characterizes the conditions under which fractures slide: a fracture fails when the shear stress is greater than the sum of cohesive strength and the product of the friction coefficient and the effective normal stress. An increase in pore pressure during injection reduces the effective normal stress, and pushes critically stressed fractures to failure [16].

In modern THMC codes the reservoir is discretized into millions of finite elements or finite volumes and the coupled governing equations are solved at each time step using an iterative process. Computationally tractable models consist of discrete fracture network (DFN) models, which model individual fractures explicitly, dual-porosity/dual-permeability continuum models, which homogenize fracture and matrix properties, and hybrid methods which combine the two. Surrogates of machine learning trained on the ensembles of THMC simulation are becoming more common in reducing the cost of computation in the quantification of uncertainty and optimization problems.

Drilling Cost as the Primary Economic Barrier

The biggest single capital investment in EGS development is the cost of drilling that usually constitutes 40-60 percent of the project costs. According to a cost-benefit analysis of geothermal well drilling carried out by Lukawski et al. [17], the cost of drilling a well is non-linearly dependent on depth: a 5 km well would be 5-8 times more expensive than a 3 km well, due to increased drill times, additional casing strings, higher pressure management expenses, and increased prevalence of drilling issues (stuck pipe, lost circulation, wellbore instability) in deep, hot crystalline rock.

In contrast to the oil and gas industry, decades of learning-by-doing have also made drilling costs 50-70% cheaper since the 1970s, whereas EGS drilling does not offer the high-volume repetition that leads to efficiency improvements. A 2010 report by the GeoVision study of the DOE [8] predicted that a 50 per cent decrease in the cost of wells (due to faster well penetration rates, longer bit life, and a lower non-productive time) would enable EGS to become economically competitive with natural gas in most of the U.S. markets by 2035. To achieve this decrease, it is necessary to enhance the current rotary drilling technology as well as to make radical innovations on the new drilling technologies.

Novel Drilling Concepts

A number of novel drilling technologies are in different stages of development, each having the potential to make EGS wells dramatically cheaper, by enhancing the rate of penetration (ROP) in hard crystalline rock: *The main drilling technologies, operating-temperature constraints, and EGS applications are compared in Table 2.*

Millimeter-wave (gyrotron) drilling, developed by researchers at MIT (now being commercialised by Quaise Energy), involves high-power microwave beam (gyrotron sources at 95 GHz producing about 1 MW) drilled down the borehole to ablate rock in front of the bit. Laboratory tests

have reached ROP of about 1 m/min in granite-10-100 times faster than PDC bits in the same rock-and Quaise intends to demonstrate in a geothermal well in 2025. The technology also avoids mechanical contact with the rock and it may avoid the wear and failure modes that shorten the conventional life of the bits in abrasive crystalline formations [18].

Table 2: Drilling Technologies Applicable to EGS Development — Capabilities and Limitations

Technology	Principle	Temperature Limit	EGS Advantage
PDC Bits	Polycrystalline diamond cutters	200°C (standard) / 300°C (high-T)	Fast ROP in moderate-hard rock; most deployed
Roller Cone (TCI)	Tri-cone tungsten carbide	260°C	Robust in fractured/abrasive formations
Percussion / DTH	Compressed air hammer	150°C	Effective in crystalline basement rock
Plasma / RF Drilling	Plasma arc or microwave energy	No mechanical limit	Contactless; potential 10× ROP; pre-commercial
Millimeter-Wave Drilling	Gyrotron beam ablation	No mechanical limit	MIT/Quaise Energy; vaporizes rock; 2025 demo
Rotary Steerable System	Near-bit steering while rotating	175°C (standard)	Enables horizontal/multilateral EGS wells
Casing While Drilling	Drill & case simultaneously	175°C	Reduces NPT; stabilizes swelling/fractured zones
Fiber-Optic DAS/DTS	Distributed acoustic/temperature sensing	300°C+ (specialty)	Real-time wellbore diagnostics; replaces discrete gauges

Plasma drilling involves electrical discharge between electrodes of high voltages to spall rock by means of electrohydraulic shock. Similar to millimeter-wave drilling, it does not use mechanical contact, and can achieve high ROP in hard formations. GreenFire Energy has shown concepts of closed-loop thermosiphons that circulate working fluid in closed coaxial tubes without hydraulic fracturing or creation of an open hole reservoir, which eliminates the use of water and eliminates the risk of induced seismicity, but also limits the efficiency of heat extraction.

High-Temperature Downhole Tools

The temperatures that are experienced in the EGS targets (150-400 ^{o}C) are higher than the operating range of most standard oilfield downhole tools that are used in petroleum reservoir (which are usually less than 175 ^{o}C). Silicon carbide (SiC) semiconductor based high-temperature electronics, silicon-on-insulator (SOI) transistors, and gallium nitride (GaN) electronics can be used up to 300 ^{o}C and can be used to deploy measurement-while-drilling (MWD) tools, logging-while-drilling (LWD) sensors, and downhole pumps in deeper and higher-

Distributed temperature sensing (DTS) and distributed acoustic sensing (DAS) with fiber-optic cables permanently installed in the EGS wells continuously and in real-time measure temperature profiles, fluid flow distribution and microseismic activity throughout the length of the wellbore. These types of technology were first developed in the petroleum sector but adapted to geothermal have allowed Fervo Energy to discover that individual clusters of perforation in their horizontal wells were not contributing equally to production, a discovery that directly influenced re-stimulation targeting and informed the design of wells subsequently.

Landmark EGS Projects: Case Studies and Lessons Learned

Soultz-sous-Forêts, France: The EGS Pioneer

The Soultz-sous-Forêts project in the Upper Rhine Graben, initiated in 1987 and producing has been commercially operated since 2016, the longest-running EGS operation in the world, and has produced a priceless scientific and engineering literature [3], [19]. Three wells were excavated to a depth of 3,000-5,000 m into granitic basement and a natural fault zone was penetrated at around a depth of 3,500 m. Several experiments showing hydraulic stimulation proved that the main mechanism of enhancing permeability was shear stimulation of the existing natural fractures, with fracture apertures enlarging between micrometers and hundreds of micrometers after stimulation.

The project showed EGS to be technically viable on a commercial scale, with sustainable flow rates of 25 L/s between injection and production wells at wellhead temperatures of ~150 ^{o}C, with enough flow to drive ~1.7 MWe through Organic Rankine Cycle (ORC) turbines. The long-term tracking showed slow thermal depletion at the production wells as predicted by the THMC model, but at a rate that would allow extraction of heat to support economic extraction over a number of decades [19]. The main constraint has been financial: the low size of the plant (planned to be science-oriented, rather than commercially optimized) and the enormous cost of European drilling have led to electricity prices that are far beyond the market average.

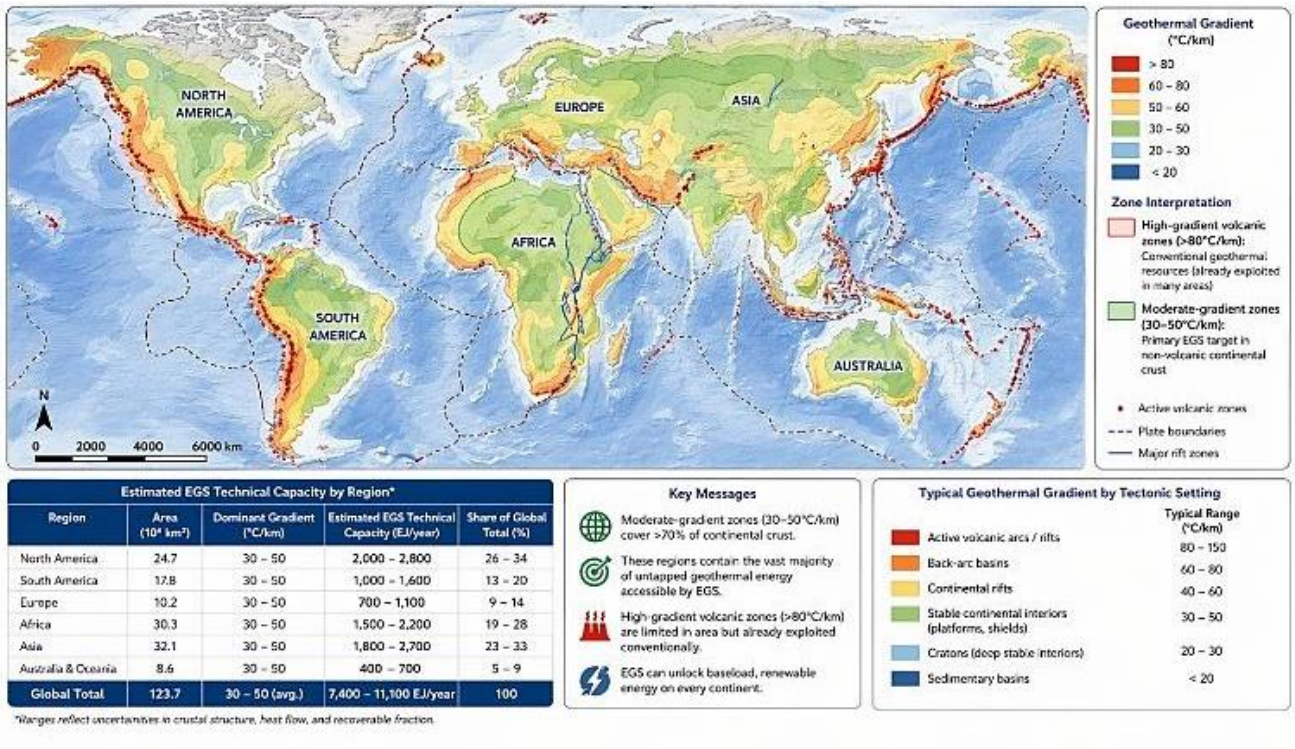
Pohang, South Korea: A Cautionary Tale

Developed in 2010-2017 and located 4,274 m in metasedimentary rock, the Pohang EGS project tragically culminated on November 15, 2017, when a Mw 5.5 earthquake hit the city of Pohang, killing one person, injuring 135 and causing around $52 million dollars in property damage. Follow-up studies by Kim et al. [6] and some later studies by Grigoli et al. [20] concluded that the earthquake had probably been caused by the EGS injection activities, which had increased pore pressures in an undetected fault about 600 m outside of the injection zone.

The disaster at Pohang had far-reaching implications on the global EGS industry: the South Korean government stopped the project immediately; public resistance against EGS in Germany and Switzerland (where such events had already led to the cancellation of projects) grew; and regulators across the globe increased seismic monitoring conditions. The incident highlighted some important lessons: the need to do extensive pre-project fault mapping, including deep seismic reflection surveys; the value of effective Traffic Light Protocols (TLPs) with conservative magnitude thresholds that are actively enforced; and the need to consider pore pressure diffusion over a much greater distance than the direct injection area when evaluating seismic hazard [21].

FORGE Utah, USA: The Science Foundation

In 2016, the Frontier Observatory for Research in Geothermal Energy (FORGE) program, funded by the U.S. Department of Energy was inaugurated as an open scientific field laboratory to conduct EGS research. Milford, Utah site was chosen after a competitive site selection process due to its well-characterized geology (quartz monzonite granite at depths of 2300-2600 m), good infrastructure access, and good in-situ stress state to allow hydro-stimulation [22]. The geographical distribution of geothermal gradients and potential EGS resources is illustrated conceptually in Figure 3.



Estimated EGS Technical Capacity by Region*

Region	Area (10^4 km²)	Dominant Gradient (°C/km)	Estimated EGS Technical Capacity (EJ/year)	Share of Global Total (%)
North America	24.7	30 – 50	2,000 – 2,800	26 – 34
South America	17.8	30 – 50	1,000 – 1,600	13 – 20
Europe	10.2	30 – 50	700 – 1,100	9 – 14
Africa	30.3	30 – 50	1,500 – 2,200	19 – 28
Asia	32.1	30 – 50	1,800 – 2,700	23 – 33
Australia & Oceania	8.6	30 – 50	400 – 700	5 – 9
Global Total	123.7	30 – 50 (avg.)	7,400 – 11,100 EJ/year	100

*Ranges reflect uncertainties in crustal structure, heat flow, and recoverable fraction.

Figure 3: Conceptual map of global geothermal gradient zones and estimated EGS technical capacity by region. High-gradient volcanic zones (>80°C/km) are already exploited conventionally; EGS targets the vast moderate-gradient zones (30–50°C/km) covering most non-volcanic continental crust

The FORGE team drilled two multilateral horizontal (16A(78)-32 and 16B(78)-32) wells in granite at a depth of about 2,600 m at a temperature of about 225 °C between 2020 and 2023. In 2023, FORGE became the first U.S. EGS project to have closed-loop fluid circulation between a pair of horizontal wells. According to Cladouhos et al. [22], distributed fiber-optic sensing showed that the profiles of fluid intake in the horizontal laterals were highly heterogeneous, with 70-80 percent of the flow entering the formation through a few discrete fracture intersections. This result has the direct implications to the design of the stimulations: the following campaigns can focus on the areas that perform poorly and aim at re-stimulation.

Fervo Energy, Nevada: Commercial Breakthrough

Project Cape in Nevada is the most commercial EGS project developed so far by Fervo Energy. The project took the horizontal drilling and completion methods developed in shale gas industry and applied them to geothermal, where two horizontal wells (~400 m lateral length) were drilled into a naturally fractured zone at a depth of about 2,500 m, with reservoir temperatures of about 190 °C [5]. *A schematic representation of the stimulated reservoir volume and well arrangement is provided in Figure 4.*

Norbeck and Latimer [5] reported a sustained flow rate of about 63 kg/s at wellhead temperatures of 176 °C and was sustained in Project Cape in response to hydraulic stimulation, which was enough to generate about 3.5 MWe with only a single well pair. The fiber-optic distributed sensing used in the project offered unprecedented real-time insight into the behavior of the reservoir such as flow profiling, fracture characterization, and pressure monitoring. Google LLC entered into an agreement with Fervo to buy power on its expanded 400 MWe development (Cape 2), which would come online by 2028, the first utility-scale EGS power purchase contract.

Power Conversion Systems and Plant Design

Organic Rankine Cycle (ORC) Systems

The Organic Rankine Cycle (ORC) is the predominant type of power conversion technology used in EGS-based applications that run below about 200 °C at which point traditional steam turbines are not feasible because of low steam enthalpies and high specific volumes. The evaporator with ORC system relies on a low-boiling-point organic working fluid (isobutane, isopentane, n-pentane, R245fa or supercritical CO_2) that vaporizes in geothermal brine temperatures, expands via a turbine, condenses and is recirculated to the evaporator. DiPippo [23] gives a thorough treatment of the thermodynamics of the ORC cycle, choice of working fluid, and design of components to be used in geothermal systems.

Current binary ORC systems have thermal efficiencies of 8-14% at brine temperatures of 150-200 °C, and the unit capacity is 200 kWe to 7.5 MWe. The units are skid-mounted and can be stacked together with a desired plant capacity and

offer redundancy. The closed-loop ORC system is especially well-adapted to EGS since geothermal brine (which is

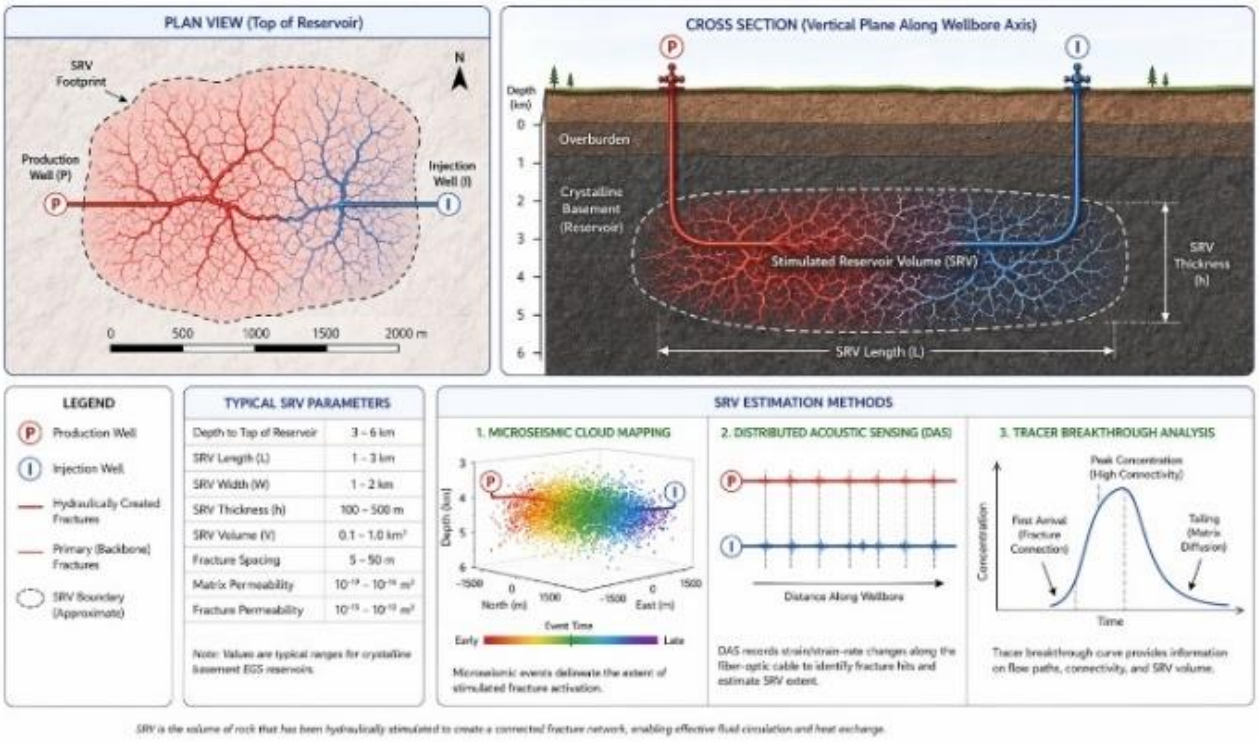


Figure 4: Schematic representation of a Stimulated Reservoir Volume (SRV) in plain view and cross-section, showing production (P) and injection (I) wells, the hydraulically created fracture network, and typical reservoir parameters. SRV estimation methods include microseismic cloud mapping, distributed acoustic sensing, and tracer breakthrough analysis.

typically saline and scaling) never comes in contact with the power conversion equipment; heat exchange is achieved by plate heat exchangers which can be cleaned or replaced without stopping the power cycle.

Flash Steam Systems

Single-flash or double-flash steam power plants have a greater thermodynamic performance compared to binary ORC cycles when the EGS reservoirs generate fluids at temperatures exceeding about 180 ºC. This is a one-pass plant where high-pressure geothermal brine is throttled with a flash separator to produce steam, which powering a standard steam turbine; the brine and condensate are separated and reinjected. In double-flash plants, a second, lower pressure flash stage is used to extract more power, enhancing efficiency by 15-25% compared to single-flash.

The mechanism of flash systems is less complex than ORC plants, but more sensitive to brine chemistry: silica scaling, carbonate deposition, and hydrogen sulfide corrosion must be carefully handled by maintaining pH, adding scale inhibitors, and selecting corrosion resistant materials. To operate superhot (>300°C) EGS, supercritical steam conditions are close to those of conventional power plant performance, and may allow thermal efficiencies of 20-30%.

Direct Use and Cascaded Applications

Not all EGS heat need be converted to electricity. Geothermal heat can be used more efficiently in direct-use applications (district heating, industrial process heat, greenhouse agriculture, aquaculture and mineral extraction) than in electricity generation (so-called utilization efficiencies of 50-70% vs. 10-15% in power generation) and can be economically viable at lower temperatures. Cascaded systems harness the heat to the point of space heating, then to low-temperature agricultural use, then as a high-temperature steam or ORC unit, which generates electricity, and then the remaining brine is used to heat space.

Mechanisms and Magnitude Scales

The greatest social, regulatory, and reputational risk to EGS development is induced seismicity. The first systematic review of induced seismicity in connection with EGS was by Majer et al. [24] who considered 11 projects and found that felt seismicity is a frequent result of hydraulic stimulation in crystalline rock, especially where injection pressures are comparable or greater than the pre-existing faults in a critically stressed condition. This analysis was generalized worldwide by Foulger et al. [21], who discovered that the maximum induced earthquake magnitude is linked to injected fluid volume (the 'McGarr relationship'), but with a large amount of scatter that restricts predictive capabilities.

Pre-Project Hazard Assessment

Probabilistic seismic hazard analysis (PSHA) scaled to induced seismicity is a quantitative system that is used to determine risk prior to project initiation. The evaluation combines the characterization of already existing fault networks (seismic reflection and potential field data and borehole images), the prevailing in-situ stress field with respect to fault orientations (Coulomb failure function analysis), historical seismicity, site specific ground motion attenuation relationships and building vulnerability models of local population [16].

A defensible pre-project induced seismicity hazard evaluation requires minimum data requirements that include: high-resolution 3D seismic reflection data of no less than a radius of 5 km around the intended injection zone; at least 6-12 months of background seismicity monitoring data with a network that is capable of detecting earthquakes of magnitude Mw≥0.5 and above; borehole stress measurements

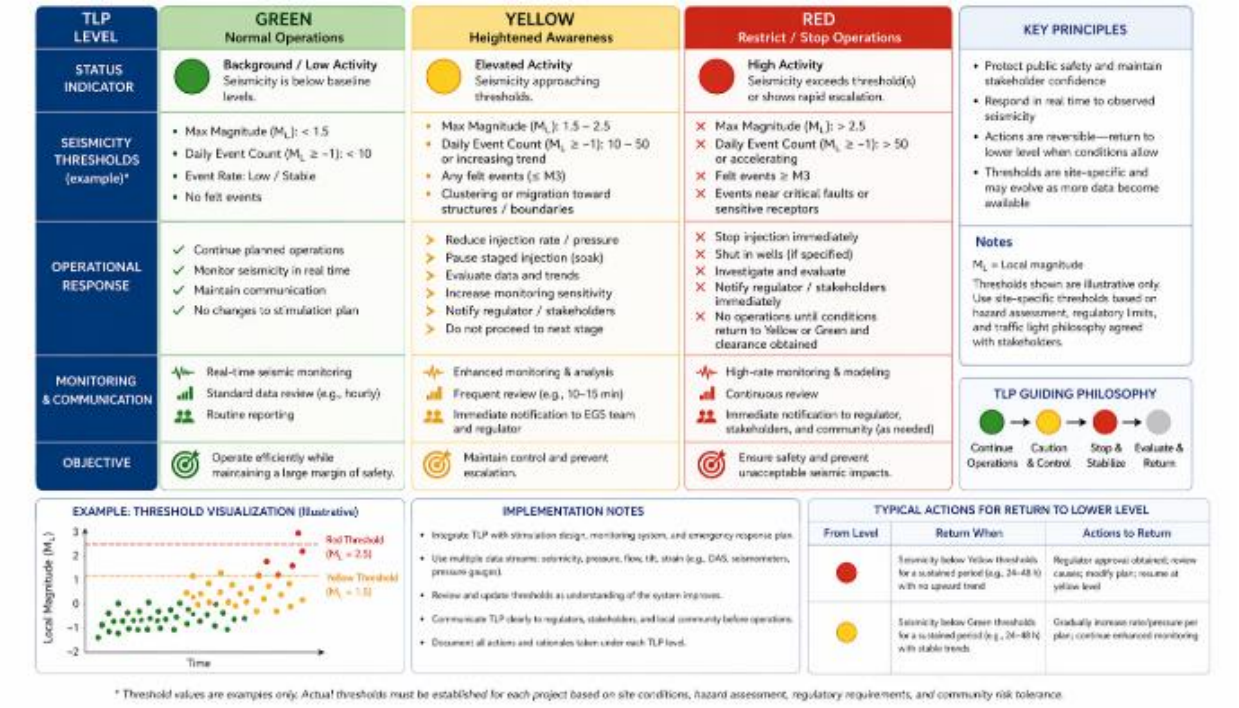


Figure 5: Tiered Traffic Light Protocol for managing induced seismicity during EGS hydraulic stimulation. Green, yellow, and red thresholds trigger progressively more restrictive operational responses. Thresholds are determined site-specifically based on pre-project hazard assessment and regulatory requirements.

of at least one well within 2 km of the injection target; and geomechanical modeling of pore pressure diffusion and associated Coulomb stress changes on identified faults.

Operational Risk Mitigation

During stimulation operations, real-time seismic monitoring combined with adaptive injection The main operational tool to manage induced seismicity risk is protocols (Traffic Light Protocols, or TLPs). A strong TLP establishes operational responses, such as continue, throttle or halt injection, based on real-time seismic parameters such as maximum magnitude, event rate and b-value changes. Importantly, the TLP should be binding: Basel (Switzerland) gives the warning example of a project that disregarded the initial seismic warning signals, and went ahead with injection until a Mw 3.4 earthquake had to cancel the project and cost the developers CHF 9 million in damage claims. *The operational thresholds and responses of a tiered seismic traffic-light protocol are illustrated in Figure 5.*

Monitoring after stimulation is also critical: diffusion of pore pressure goes on even when the injection process is stopped, seismicity can persist or even accelerate later on as the pressure fronts enter remote faults (so-called post-injection seismicity). Although the final stimulation campaign took place about 2 months ago, the Pohang earthquake demonstrated the necessity of further monitoring and flexibility of operations (with the controlled pressure bleed-off) in the post-injection period.

Economics, Deployment Trajectories, and Policy Context

Current LCOE and Cost Structure

The cost of energy (LCOE) in EGS projects is quite wide-ranged, with the best-in-class projects like the Cape project by Fervo being priced at around $80/MWh, and first-of-its-kind deep drilling campaigns being priced at over 200/MWh. This variation indicates that EGS economics is highly sensitive to the well productivity (flow rate and temperature), the number of wells needed, and the cost of drilling per meter [25]. In comparison, utility-scale solar PV can now be competitive at LCOE of 24-45/MWh in most markets and onshore wind can be competitive at 28-55/MWh [25] with current EGS cost-uncompetitive unless supported by policy or acknowleding its firm, dispatchable contribution.

Value of Dispatchability

The key weakness of straightforward LCOE comparisons is that they fail to reflect the incremental value of dispatchable, firm capacity in electricity systems where variable renewable energy has a significant portion. The marginal value of additional solar and wind drops and the value of controllable, always-on generation increases as solar and wind generation increases. EGS, as nearly-100% capacity factor and it can increase and decrease with demand, would have the potential to fetch a large premium over its LCOE in markets with large seasonal and diurnal imbalances [26]. According to the International Energy Agency [27], the world will require firm low-carbon capacity in the future to meet an expected demand of over 8,000 GW of capacity in 2050 in the conditions of net-zero.

Policy and Investment Landscape

The U.S. Bipartisan Infrastructure Law (2021) and Inflation Reduction Act (2022) jointly provided up to about 84 million towards enhanced geothermal systems, and wider clean energy tax credits (such as the Investment Tax Credit and Production Tax Credit) on geothermal projects. In 2022, the DOE announced its Enhanced Geothermal Shot program, which aims to achieve a cost of EGS LCOE of $45/MWh by 2035, a 90% reduction over 2021 levels, by combining drilling innovation, better reservoir engineering, and scale-up of deployment [8]. The assumed reductions in EGS electricity costs under technology-learning scenarios are illustrated in Figure 6.

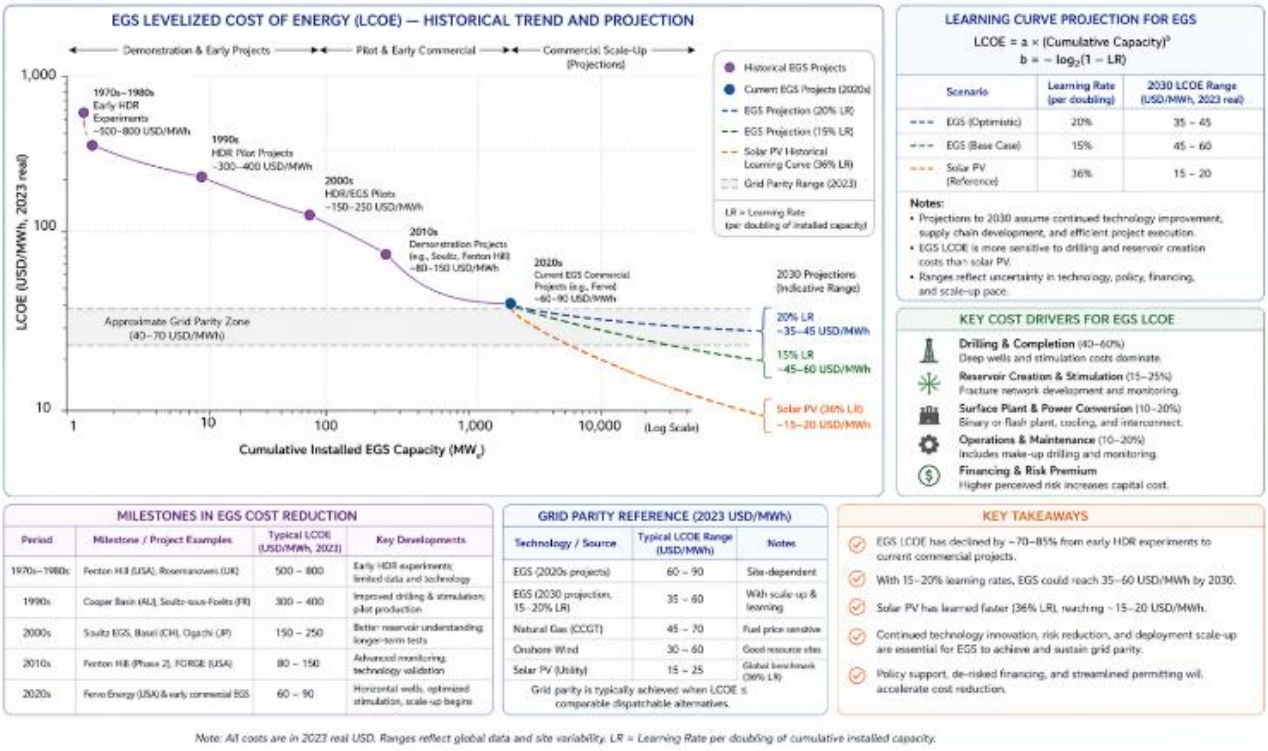


Figure 6: Learning curve for EGS LCOE showing historical cost reduction from early HDR experiments to current EGS commercial projects. Projections to 2030 assume learning rates of 15–20% per doubling of installed capacity, compared to 36% achieved by solar PV. Grid parity requires continued technology development and scale-up

Investment environments across the world differ widely. In Germany, more than 40 deep geothermal projects (mostly district heating) have been implemented but have been opposed by the public due to induced seismicity. The ADEME agency in France has been assisting Soultz and the new deep geothermal projects in the Paris Basin. In Australia, the federal government has re-invested in geothermal research funding, after a 10-year absence after the commercial failure of the Cooper Basin. The ARIA (Advanced Research and Invention Agency) of the UK has funded Cornwall Hot Rocks as a pilot project. The largest electricity consumer in the world and having vast hot rock deposits, China has initiated several EGS pilot projects in its southwest highlands.

Emerging Frontiers in EGS Technology

Superhot Rock (SHR) Geothermal

Water turns into a supercritical state with no difference between a liquid and vapor at temperatures over about 374 °C and pressures over about 22 MPa. Supercritical fluids in the geothermal can have enthalpy levels that are significantly higher than subcritical steam (by 3-5 times), which could allow wells with power outputs of 50-100 MWe (10 times greater than a typical geothermal well) to be produced out of a single wellbore [28]. In 1963, the Iceland Deep Drilling Project (IDDP-2) drilled 4500 m down the Reykjanes peninsula and found fluids at 427 °C -indicating the availability of supercritical conditions, but found that well control and materials were problematic and prevented sustained production [29].

Superhot Rock (SHR) geothermal, capable of reaching even higher temperatures (400-700 °C), in areas of highly anomalous heat flow or in areas of shallow magma intrusion, has seen considerable private investment in recent years. Companies such as Quaise Energy (Massachusetts), Eavor Technologies (Canada) and GA Drilling (Slovakia) are already designing drilling technology that is specifically tailored to these extreme conditions. The major technical issues are brittle-ductile transition of rock beyond about 300 °C (which can seal fractures by itself), the corrosive chemistry of supercritical fluids and the requirement of high-temperature materials in downhole tools and surface equipment.

Closed-Loop Geothermal Systems

Geothermal Cyclic closed-loop geothermal systems, where the working fluid is circulated in a closed system through sealed wellbores or perforated pipes in the hot rock, and there is no direct interaction with the formation, are a paradigm shift to conventional open-loop EGS. The closed-loop systems eliminate the risk of induced seismicity, do not use any water, eliminate scaling and corrosion of production equipment, and do not require permeable fracture networks. Eavor Technologies (Eavor-Loop), GreenFire Energy, and Sage Geosystems are companies that are working on commercial closed loop products.

The main drawback of closed-loop systems is the heat transfer efficiency: with no convective heat exchange between the formation fluid and the rock, the only way that power can be transferred is through conductive heat transfer through the surrounding rock matrix, which constrains the power output per unit borehole length. Analytical modeling indicates that a single closed-loop well-pair at 3 km depth, and 2 km lateral length would generate 13 MWth, or 3 MWth, of power, versus 5-20 MWth of power in an equivalent open-loop EGS with good permeability. This limitation is partially compensated by multi-lateral drilling patterns that make maximum contact with the rock of the boreholes.

Machine Learning and Digital Twins

EGS development workflow is increasingly using machine learning (ML) methods. ML models predicting the optimal drilling parameters in real time using historical drilling data (weight on bit, RPM, flow rate, vibration and ROP) are used in drilling optimization to minimize bit wear and nonproductive time [30]. Convolutional neural networks on seismic reflections are used in reservoir characterization to enhance detection of faults and fractures. ML surrogate models trained using THMC simulation ensembles can be used in stimulation design to quickly optimize injection strategies in hundreds of candidate scenarios that would be computationally infeasible with full physics simulations.

The concept of digital twins, which is real-time computational models in line with sensor measurements of running EGS wells, is becoming a revolutionary operational decision-making tool. A digital twin combines wellbore flow models, reservoir THMC simulations, surface plant thermodynamic models, and seismic monitoring data into a single platform, which can be queried by operators to predict production, detect anomalies, and experiment with changes in operations without actually implementing them. The fiber-optic-heavy monitoring strategy implemented by Fervo Energy at Cape offers the density of data needed to maintain a meaningful digital twin, and other strategies of this type are being standardized as commercial EGS projects.

Carbon Capture Integration

The brine that is produced under high pressure and high temperature in the EGS reservoirs can potentially be used to carry dissolved CO_2 and thus geothermal power production and geological carbon storage can be attained in the same wellfield. The CarbFix technology was demonstrated in Iceland which injects CO_2 saturated water into basaltic rocks where it mineralizes in 2 years—much faster than conventional supercritical CO_2 injection in sedimentary rocks [13]. Early research indicates that mafic and ultramafic basement rock geothermal systems (EGS) might be used as CO_2 sinks and at the same time as a source of geothermal heat, which is a synergistic carbon-negative energy source.

Environmental Considerations and Life Cycle Assessment

EGS has the lowest life cycle greenhouse gas (GHG) emission intensity of any electricity generation technology with an estimated value of 15-55 gCO_2eq/kWh by Rybach [31]- comparable to nuclear power and much lower than natural gas combined cycle (490 gCO_2eq/kWh) or coal (820-1050 gCO_2eq/kWh). Not operational fuel combustion is the dominant source of life-cycle emissions, which are steel and concrete used to construct the well. With the decarbonisation of grid electricity, the life-cycle footprint of EGS will decrease further.

Water usage in open-loop EGS should be carefully managed especially in water-deficient areas. During stimulation, 10,000-50,000 m^3 injection volumes are common; during long-term operation, the net water loss through reservoir retention and surface evaporation is usually 1-3 m^3/MWh, more than solar PV and wind (which use insignificant quantities of water) but similar to nuclear and less than coal with cooling towers. EGS designs that are closed loop do not use any water that is in operation.

The land use needs of EGS are very low by power generation standards: a 100 MWe EGS facility covers around 1-2 km^2 on the surface and all facilities, versus 5-10 km^2 of a similar sized solar PV farm (excluding transmission). The stimulated reservoir footprint (1-10 km^3) is located deeper in the ground than farming activities and does not interfere with surface land uses directly over the plant as is the case with wind and solar.

Conclusions and Recommendations

This review has provided a synthesis of the body of knowledge in Enhanced Geothermal Systems at both ends of the spectrum between the geological principles and commercial implementation. The evidence brings to the following main conclusions:

1. EGS is a technically feasible route to bringing geothermal energy to the expansive non-volcanic portions of the planet. Theoretical resource base is fundamentally inexhaustible; the economic and operational challenge poses a problem rather than a geological one.
2. New commercial scale demonstrations- especially the Cape project by Fervo Energy- have confirmed horizontal EGS concepts and provided evidence that the technology used in the petroleum industry to drill and complete wells can be effectively applied to geothermal. The initial EGS power purchase agreement of utility scale is an indication of investor confidence.
3. The top-most leverage opportunity of cost reduction of EGS is drilling cost reduction. EGS would be widely cost-competitive with a reduction in the cost of wells—which could be achieved through a combination of better performance of PDC bits in crystalline rock, rotary steerable systems to reduce nonproductive time, and the eventual implementation of new energy-beam drilling systems—by half.
4. Management of induced seismicity should be a part of the design of EGS projects even at the preliminary planning stages. The Pohang disaster proved that an insufficient pre-project fault mapping and lack of Traffic Light Protocols can turn a technically successful EGS stimulation into a community disaster. National regulations should identify minimum required characterization standards and compulsory implementation of TLP.
5. THMC coupled modeling has come of age to deliver credible thermal breakthrough, evolution of reservoir impedance, and induced seismicity hazard prediction, when adequate site characterizations data exist. The use of machine learning techniques is enhancing the speed with which these models are being applied practically in the field.
6. Emerging technologies, such as superhot rock drilling, closed-loop systems, supercritical geothermal fluids, and CO_2 as a working fluid, are potentially transformative, but will need ongoing investment in research and field tests before commercial application.
7. The support of the policies through production tax credits, exploration drilling risk insurance, simplified environmental permitting, and long-term power purchase contracts are necessary to bridge the valley of death between demonstration and commercial scale.

The Sixth Assessment Report by the IPCC has identified geothermal energy as a mitigation measure that has been underutilized, and the implementation of such energy has been constrained by resource awareness and economic factors, as opposed to technical factors. EGS, with the extension of geothermal resources across the world, could turn this untapped resource into a significant pillar of the clean energy transition. To realize this potential, a systems-wide approach has been required through the basic rock physics research, innovation in drilling and reservoir

management, enabling regulatory frameworks, and new financing structures that reflect the distinct risk profile of subsurface energy development.

The next decade will be crucial: as several commercial EGS projects are currently being developed globally and the new generation of drilling technologies is nearing a field demonstration, the technology and economic path of EGS will be significantly elucidated by 2030. Scientific and engineering community can play a crucial role in speeding up this trend with rigorous open-access research, transparent data sharing by field projects and candid interaction with the community about the potential and the dangers of Enhanced Geothermal Systems.

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References

[1] J. Tester, et al. "The future of geothermal energy: Impact of enhanced geothermal systems (EGS) on the United States in the 21st century." Massachusetts Institute of Technology, Cambridge, MA, USA, 2006. https://doi.org/10.2172/1220063

[2] A. Aghahosseini, and C. Breyer. "From hot rock to useful energy: *A global estimate of enhanced geothermal systems potential*." Applied Energy, vol. 279, art. no. 115769, 2020. 10.1016/j.apenergy.2020.115769

[3] A. Genter, et al. "Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS)." *Comptes Rendus Geoscience*, vol. 342, nos. 7–8, pp. 502–516, 2010. https://doi.org/10.1016/j.crte.2010.01.006

[4] S. Lu. "A global review of enhanced geothermal system (EGS)." *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 2902–2921, 2018. https://doi.org/10.1016/j.rser.2017.06.097

[5] J. Norbeck and T. Latimer. "Commercial-scale demonstration of a first-of-a-kind enhanced geothermal system." *EarthArXiv preprint*, 2023. https://doi.org/10.31223/X52X0B

[6] M. Mohammed, S. Boghandora, and A. Belkhair, "Techno-economic analysis of wind and geothermal energy for reverse osmosis desalination: a case study of Tripoli." *Journal of Power and Energy Engineering*, vol. 13, no. 11, pp. 86-109, 2025. https://www.scirp.net/pdf/jpee_1771303.pdf

[7] I. S. Moeck. "Catalog of geothermal play types based on geologic controls." Renewable and Sustainable Energy Reviews, vol. 37, pp. 867–882, 2014. 10.1016/j.rser.2014.05.032

[8] U.S. Department of Energy. "GeoVision: Harnessing the Heat Beneath Our Feet." *Office of Energy Efficiency and Renewable Energy*, Washington, DC, USA, report no. DOE/EE-1306, 2019.

[9] S. E. Laubach, et al. "The role of chemistry in fracture pattern development and opportunities to advance interpretations of geological materials." *Reviews of Geophysics*, vol. 57, no. 3, pp. 1065–1111, 2019. https://doi.org/10.1029/2019RG000671

[10] V. Spichak and A. Manzella. "Electromagnetic sounding of geothermal zones." *Journal of Applied Geophysics*, vol. 68, no. 4, pp. 459–478, 2009. 10.1016/j.jappgeo.2008.05.007

[11] A. Mahgoub, M. Mohammed, N. Ahmed, Y. Ajibade, and H. Mohammed. "Techno-economic analysis of a hybrid solar-wind-geothermal power system for RO desalination in Jizan, Saudi Arabia." *International Journal of Ambient Energy*, vol. 47, no. 1, p. 2755389, 2026. https://doi.org/10.1080/01430750.2026.2755389

[12] M. Zoback, et al. "The importance of slow slip on faults during hydraulic fracturing stimulation of shale gas reservoirs." *Proceedings of the SPE Americas Unconventional Resources Conference*, Pittsburgh, PA, USA, 2012. https://doi.org/10.2118/155476-MS

[13] Y. Nassar, A. ElNoaman, A. Abutaima, S. Yousif, and A. Salem. "Evaluation of the underground soil thermal storage properties in Libya." *Renewable energy*, vol. 31, no. 5, pp. 593-598, 2006. https://doi.org/10.1016/j.renene.2005.08.001

[14] N. Fathi, and S. Alsadi. "Economical and environmental feasibility of the renewable energy as a sustainable solution for the electricity crisis in the Gaza Strip." *International Journal of Engineering Research and Develop*, vol. 12, no. 3, pp. 35-44, 2016. https://www.researchgate.net/publication/301328870

[15] D. ox, et al. "Sustainable heat farming: Modeling extraction and recovery in discretely fractured geothermal reservoirs." *Geothermics*, vol. 46, pp. 42–54, 2013. https://doi.org/10.1016/j.geothermics.2012.09.001

[16] S. Alburki, and A. Elkais. "Reservoir Characterization of Low-Permeability FACHA Formation in Hakim Field Using ECRIN Well Test Analysis." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 258-264, 2026. https://doi.org/10.63318/waujpasv4i2_29

[17] M. Z. Lukawski, et al. "Cost analysis of oil, gas, and geothermal well drilling." *Journal of Petroleum Science and Engineering*, vol. 118, pp. 1–14, 2014. 10.1016/j.petrol.2014.03.012

[18] D. Duchane and D. Brown. "Hot dry rock (HDR) geothermal energy research and development at Fenton Hill, New Mexico." *Geo-Heat Center Quarterly Bulletin*, vol. 23, no. 4, pp. 13–19, 2002.

[19] A. Genter, et al. "Overview of the current activities of the European EGS Soultz project: From exploration to electricity production." *Proceedings of the World Geothermal Congress* 2015, Melbourne, Australia, 2015.

[20] F. Grigoli, et al. "The November 2017 Mw 5.5 Pohang earthquake: A possible case of induced seismicity in South Korea." *Science*, vol. 360, no. 6392, pp. 1003–1006, 2018. https://doi.org/10.1126/science.aat2010

[21] G. R. Foulger, et al. "Global review of human-induced earthquakes." *Earth-Science Reviews*, vol. 178, pp. 438–514, 2018. 10.1016/j.earscirev.2017.07.008

[22] O. Shaltami, et al. "Seismic Geochemistry: A Sustainable Approach to Hydrocarbon Exploration in Libya." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 194-199, 2026. https://doi.org/10.63318/waujpasv4i2_23.

[23] R. DiPippo. "Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact." 3rd ed., Butterworth-Heinemann, Oxford, UK, 2012. https://doi.org/10.1016/C2014-0-02885-7.

[24] E. Majer, et al. "Induced seismicity associated with Enhanced Geothermal Systems." *Geothermics*, vol. 36, no. 3, pp. 185–222, 2007. https://doi.org/10.1016/j.geothermics.2007.03.003

[25] M. Abuhelwa, M. Elnaggar, W. Salah, Y. Nassar, and M. Bashir. "Exploring the Prevalence of Renewable Energy Practices and Awareness Levels in Palestine." *Energy Science & Engineering*, vol. 13, no. 3, p. 1292-1305, 2025. https://doi.org/10.1002/ese3.2070

[26] C. Augustine, et al. "GeoVision Analysis Supporting Task Force Report: Electric Sector Potential to Penetration." *National Renewable Energy Laboratory*, technical report no. NREL/TP-6A20-71833, 2019. https://www.nrel.gov/docs/fy19osti/71833.pdf.

[27] N. Fathi, K. Aissa, and S. Alsadi. "Estimation of Environmental Damage Costs from CO2e Emissions in Libya and the Revenue from Carbon Tax Implementation." *Low Carbon Economy*, vol. 8, pp. 118-132, 2017. https://doi.org/10.4236/lce.2017.84010

[28] T. Reinsch, et al. "Utilizing supercritical geothermal systems: A review of past ventures and ongoing research activities." *Geothermal Energy*, vol. 5, no. 1, pp. 1–25, 2017. https://doi.org/10.1186/s40517-017-0075-y

[29] G. O. Fridleifsson, et al. "The Iceland Deep Drilling Project 4.5 km deep well, IDDP-2, in the seawater-recharged Reykjanes geothermal field in SW Iceland has successfully reached its supercritical target." *Scientific Drilling*, vol. 23, pp. 1–12, 2020. https://doi.org/10.1029/2021GC009747

[30] Z. Hasan. "AI-Enhanced Reservoir Storage Assessment and Depletion Forecasting Using Multispectral Satellite Imagery and Hydrological Modeling." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 316-322, 2026. https://doi.org/10.63318/waujpasv4i2_36

[31] L. Rybach. "'The future of geothermal energy' and its challenges." *Proceedings of the World Geothermal Congress* 2010, Bali, Indonesia, 2010.

[32] K. Breede, et al. "A systematic review of enhanced (or engineered) geothermal systems: Past, present and future." *Geothermal Energy*, vol. 1, art. no. 4, 2013. https://doi.org/10.1186/2195-9706-1-4

[33] J. Ziagos, et al. "A technology roadmap for strategic development of Enhanced Geothermal Systems." *Proceedings of the 38th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, USA, 2013.

[34] T. Cladouhos, et al. "Improving geothermal project economics with multi-zone stimulation: Results from the Newberry Volcano EGS demonstration." *Proceedings of the 38th Workshop on Geothermal Reservoir Engineering*, Stanford, CA, USA, 2013.

[35] P. Olasolo, et al. "Enhanced geothermal systems (EGS): A review." *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 133–144, 2016. 10.1016/j.rser.2015.11.031

[36] L. Xie, et al. "Observations of hydraulic stimulations in seven enhanced geothermal system projects." *Renewable Energy*, vol. 79, pp. 56–65, 2015. 10.1016/j.renene.2014.07.044

[37] J. W. Tester, et al. "Impact of enhanced geothermal systems on US energy supply in the 21st century." *Philosophical Transactions of the Royal Society A*, vol. 365, no. 1853, pp. 1057–1094, 2007. https://doi.org/10.1098/rsta.2006.1964

[38] O. Shaltami, et al. "Geological Framework and Exploration Potential of Manganese Mineralization in Libya: A Comparative Study of Nalut–Jabal Nafusa, Wadi Urari and Shati Valley." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 4, no. 2, pp. 281-286, 2026. https://doi.org/10.63318/waujpasv4i2_32

[39] IPCC. "Climate Change 2022: Mitigation of Climate Change." *Contribution of Working Group III to the Sixth Assessment Report*, Cambridge University Press, 2022. [https://escholarship.org/uc/item/23n103jv]