Geothermal Power Output Growth

Greg Leveille

April 29, 2026

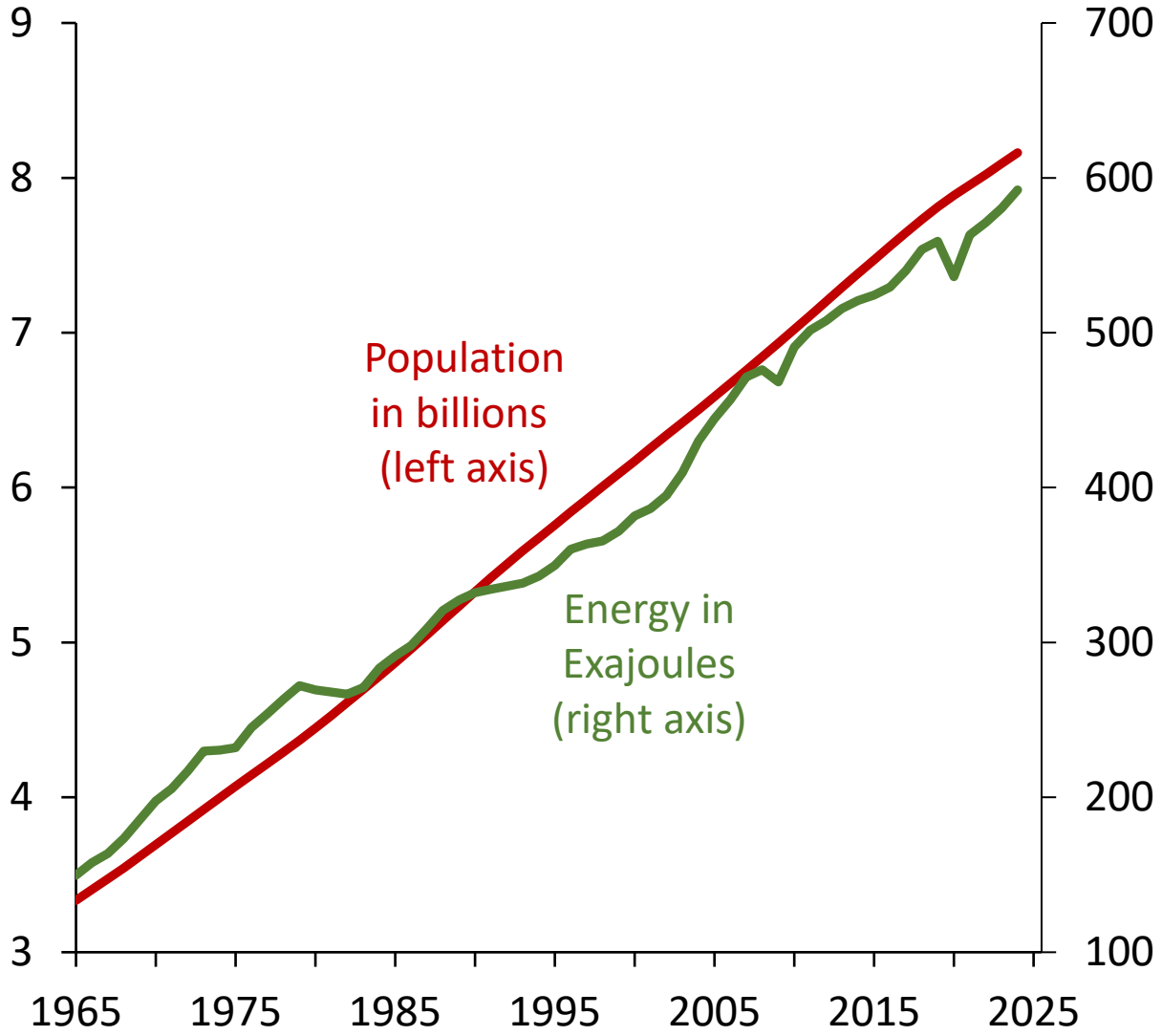
Picture from Fervo Energy's website

Presentation Outline

- Humankind’s insatiable need for energy
- The geothermal power output prize
- Techno-economic challenges
- Innovative solutions
- Achieving liftoff

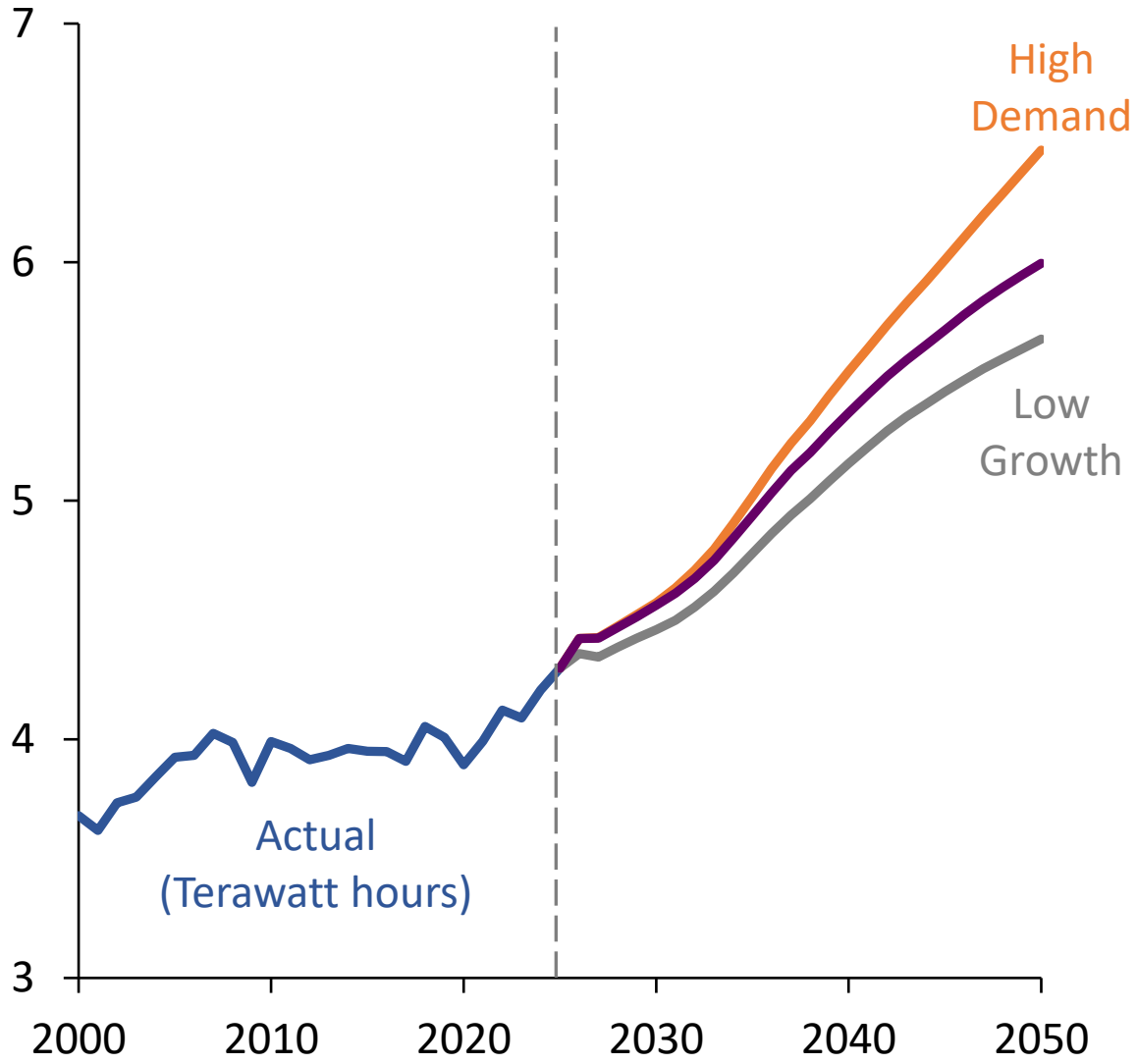
The world needs further sources of abundant, reliable, affordable, firm, dispatchable energy

Growth in global population & energy consumption



Sources: Population = World Bank; Energy consumption = Energy Institute

Projected growth in U.S. electricity consumption



Sources U.S. Energy Information Administration

Geothermal energy can provide a sixth important attribute: Low GHG emissions

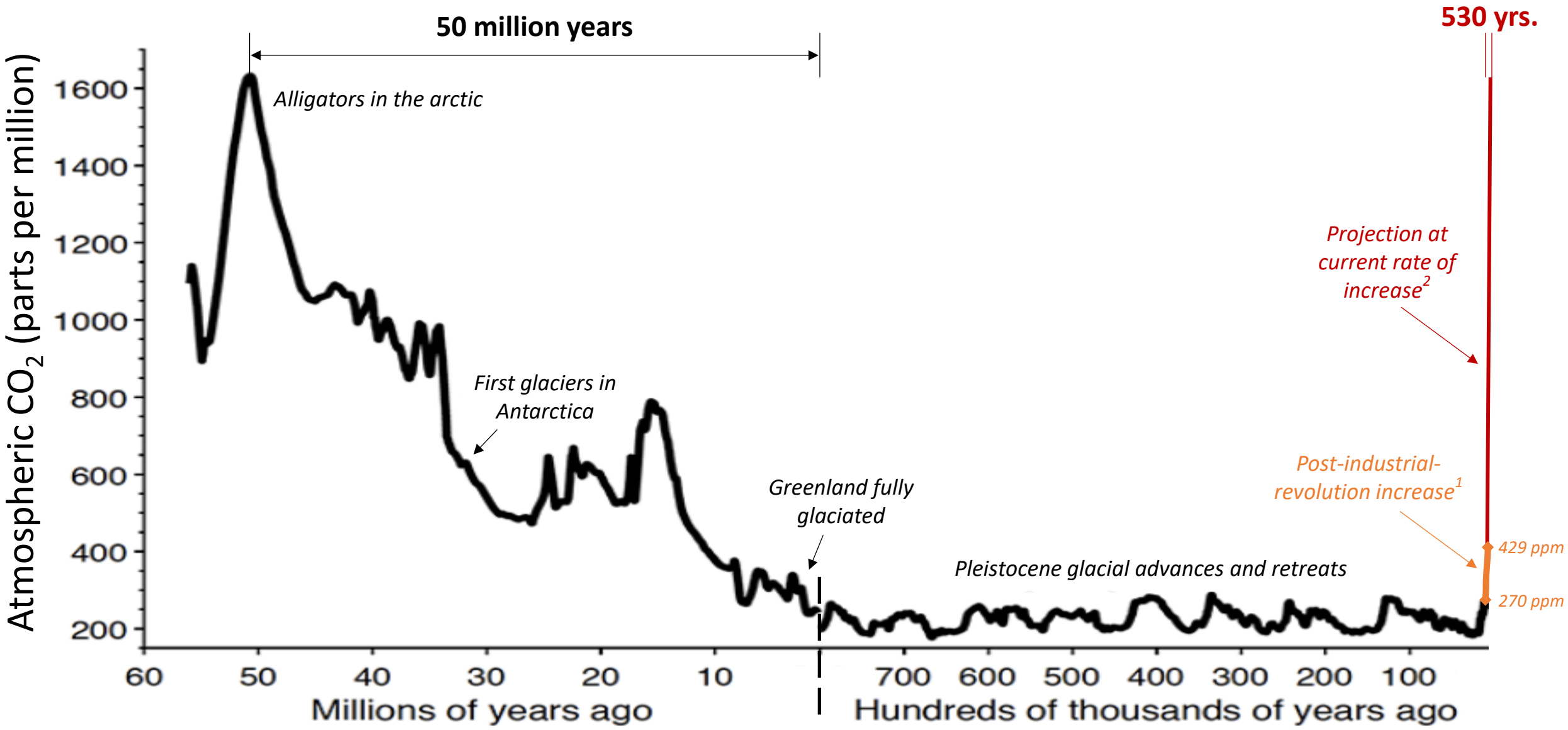
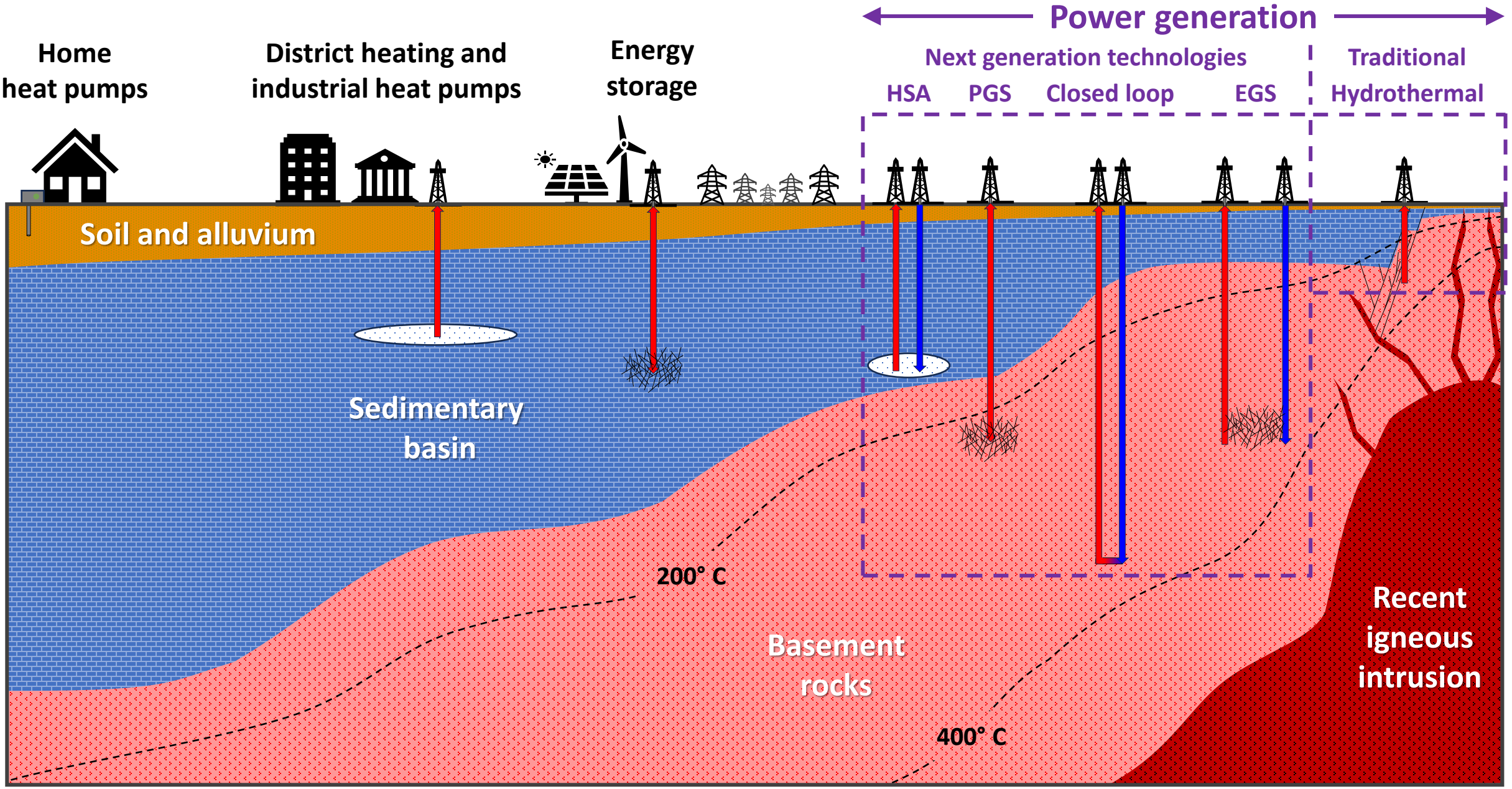


Diagram modified after Zhang, Y. and Liu, X., 2021. [1] From 270 ppm pre-industrial revolution to 429 ppm as of February 2026. [2] Rate of increase over the past 25 years has been 2.2 ppm per annum. PPM = Parts per million.

There are many ways to harvest energy from heat within the Earth: Power is the biggest prize



Cross section view; not to scale; depictions of geothermal systems are greatly simplified; HSA = Hot Sedimentary Aquifers; PGS = Pressure Geothermal Systems; EGS = Enhanced Geothermal Systems

Heat within the Earth is sufficient to provide an inexhaustible supply of power

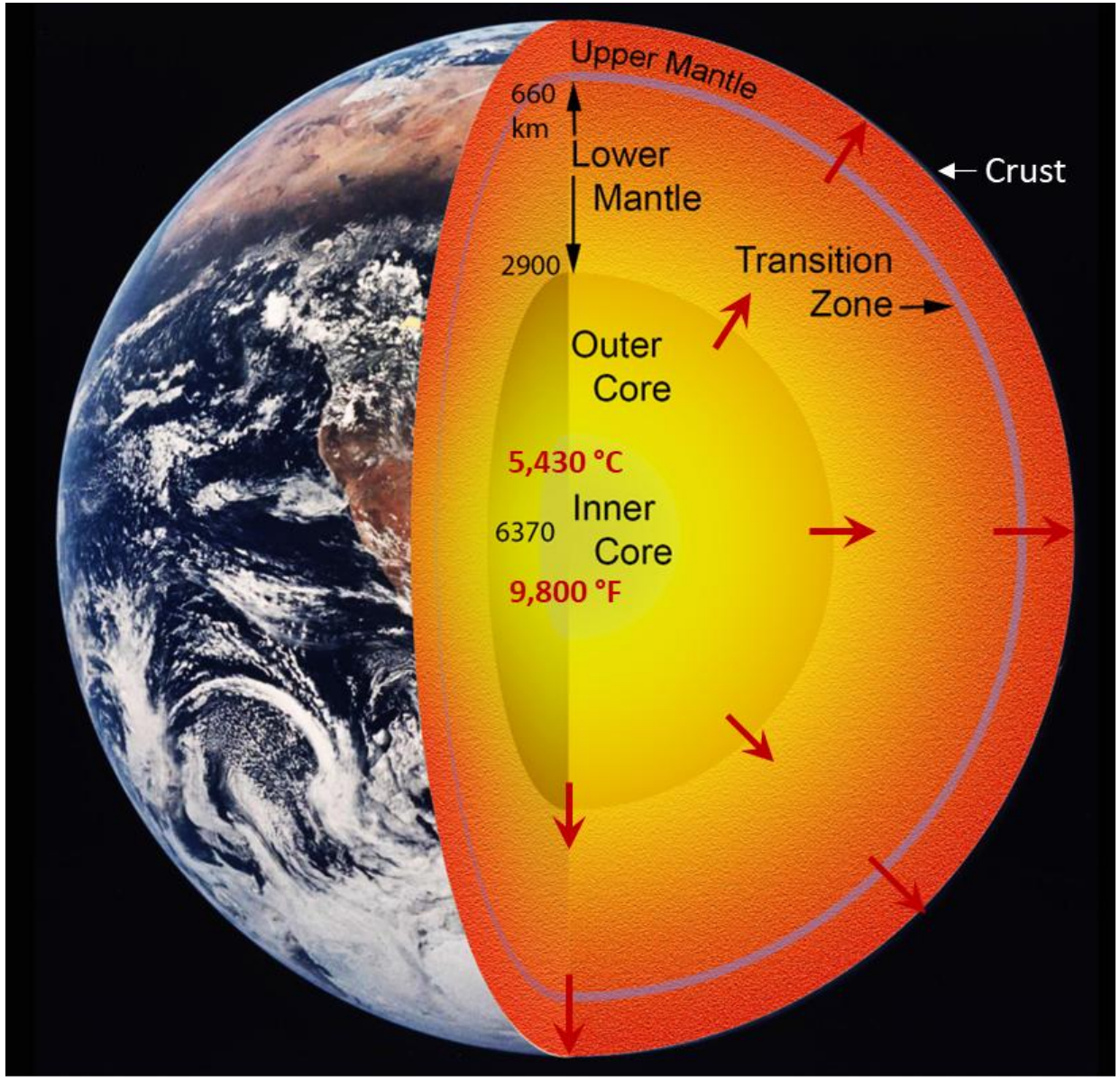
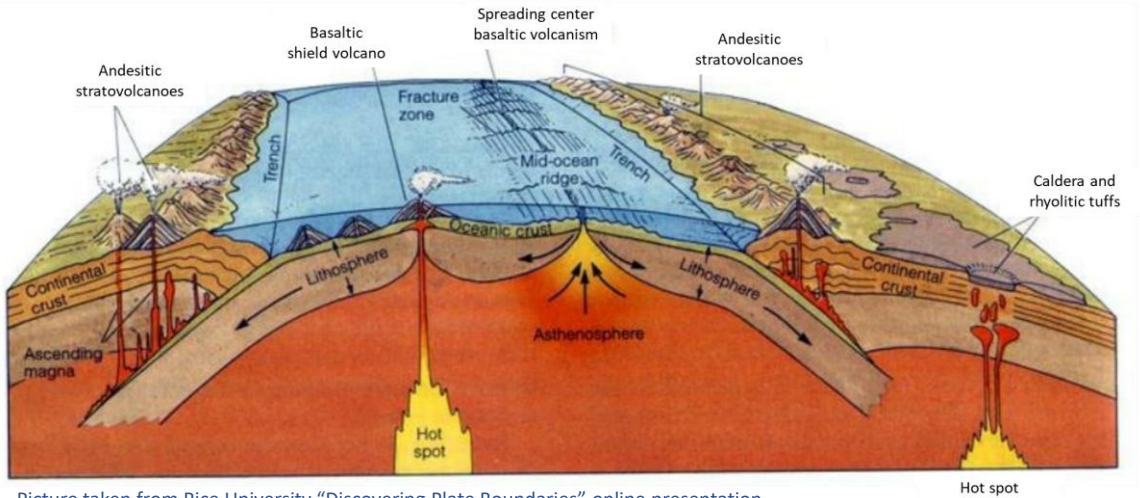
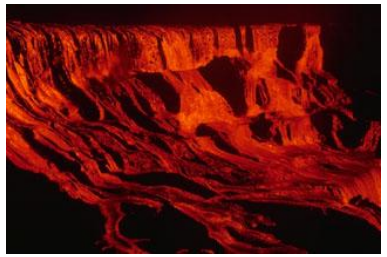


Diagram modified after Steve Jacobsen, Department of Earth, Environmental, and Planetary Sciences, Northwestern University



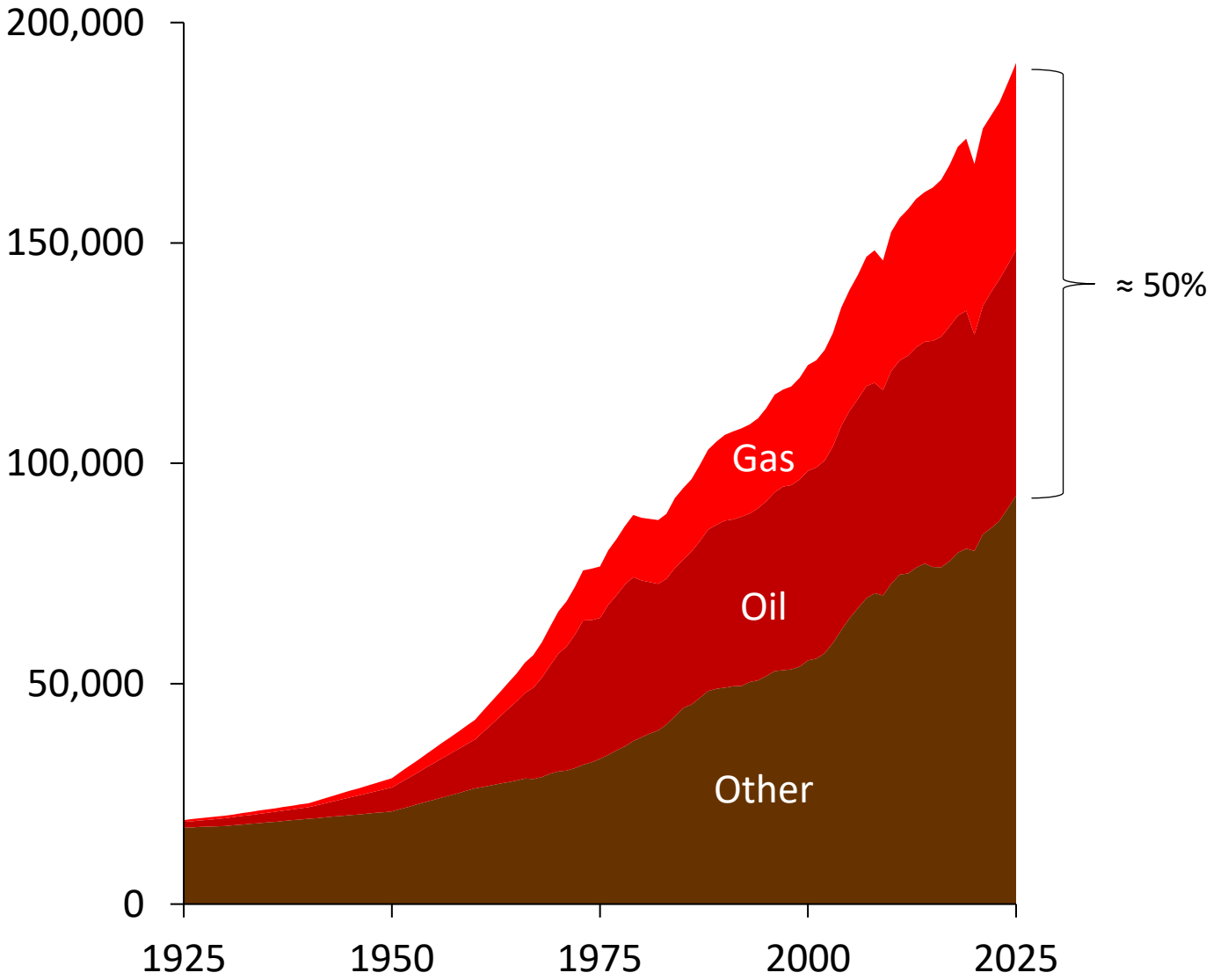
Picture taken from Rice University "Discovering Plate Boundaries" online presentation



Pictures taken from Smithsonian Institute Global Volcanism program website

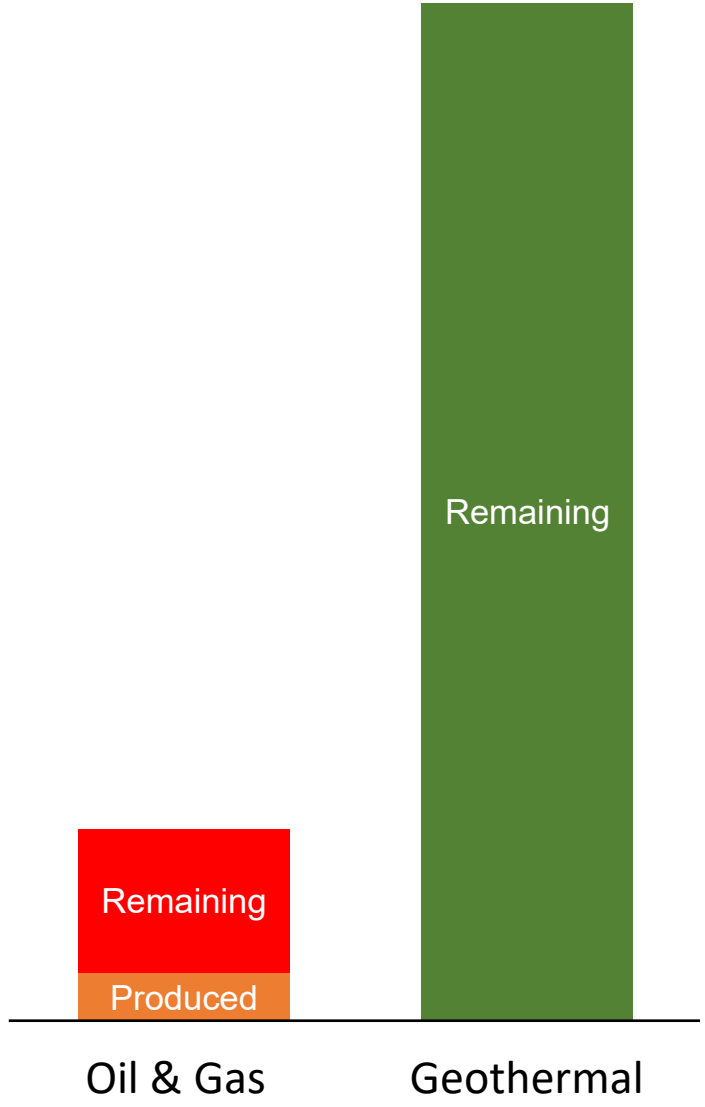
The amount of energy in geothermal resources is many times greater than oil and gas

Global primary energy consumption
(terawatt hours)



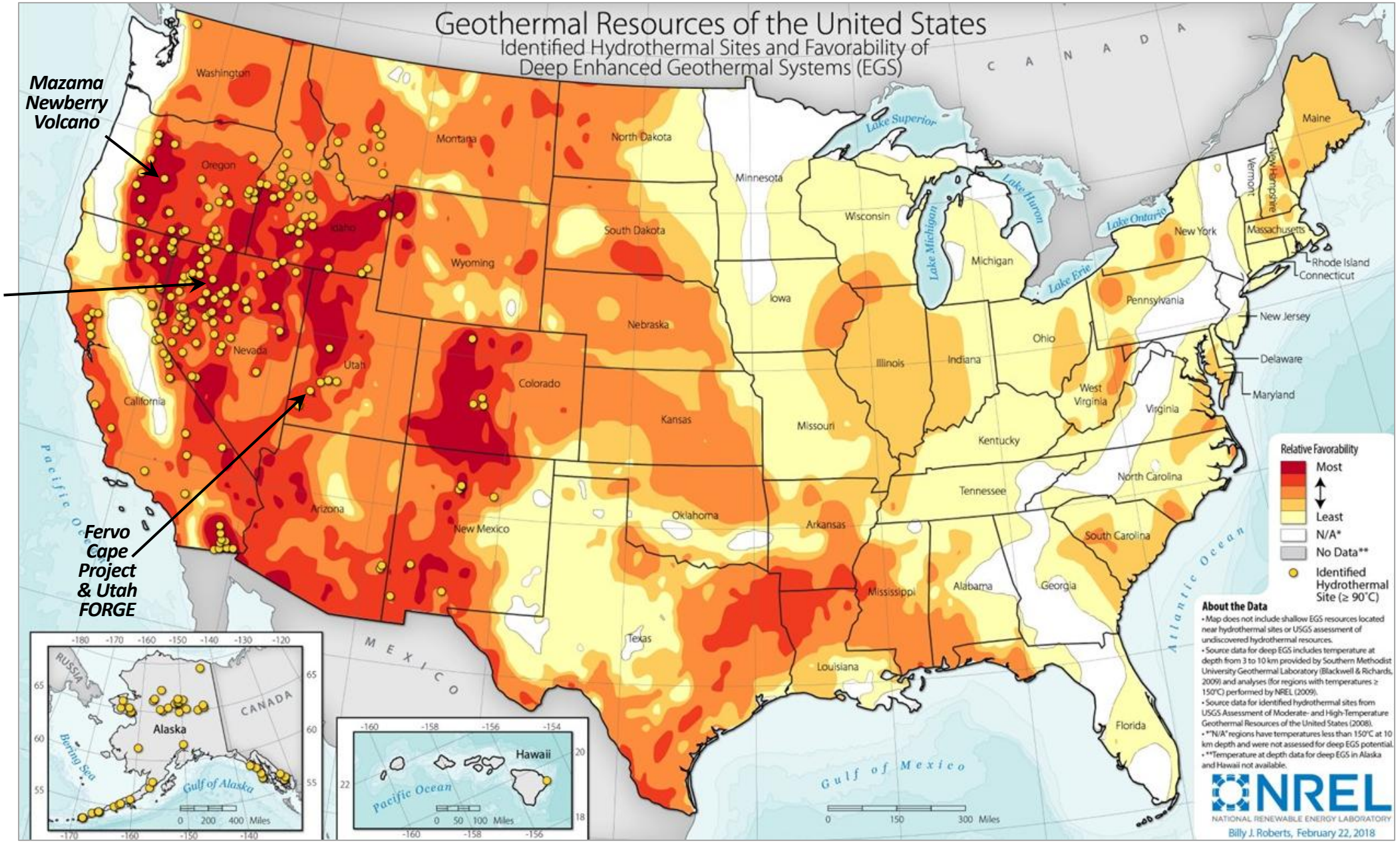
Sources: 1925 to 1964 = Vaclav Smil 2017; 1965 onwards = Energy Institute

Global energy resources
(estimated recoverable volumes)



Sources: Oil & Gas from Energy institute, EIA and other sources; geothermal based on Tester et al. 2006

America possesses abundant geothermal resources that could be converted to power

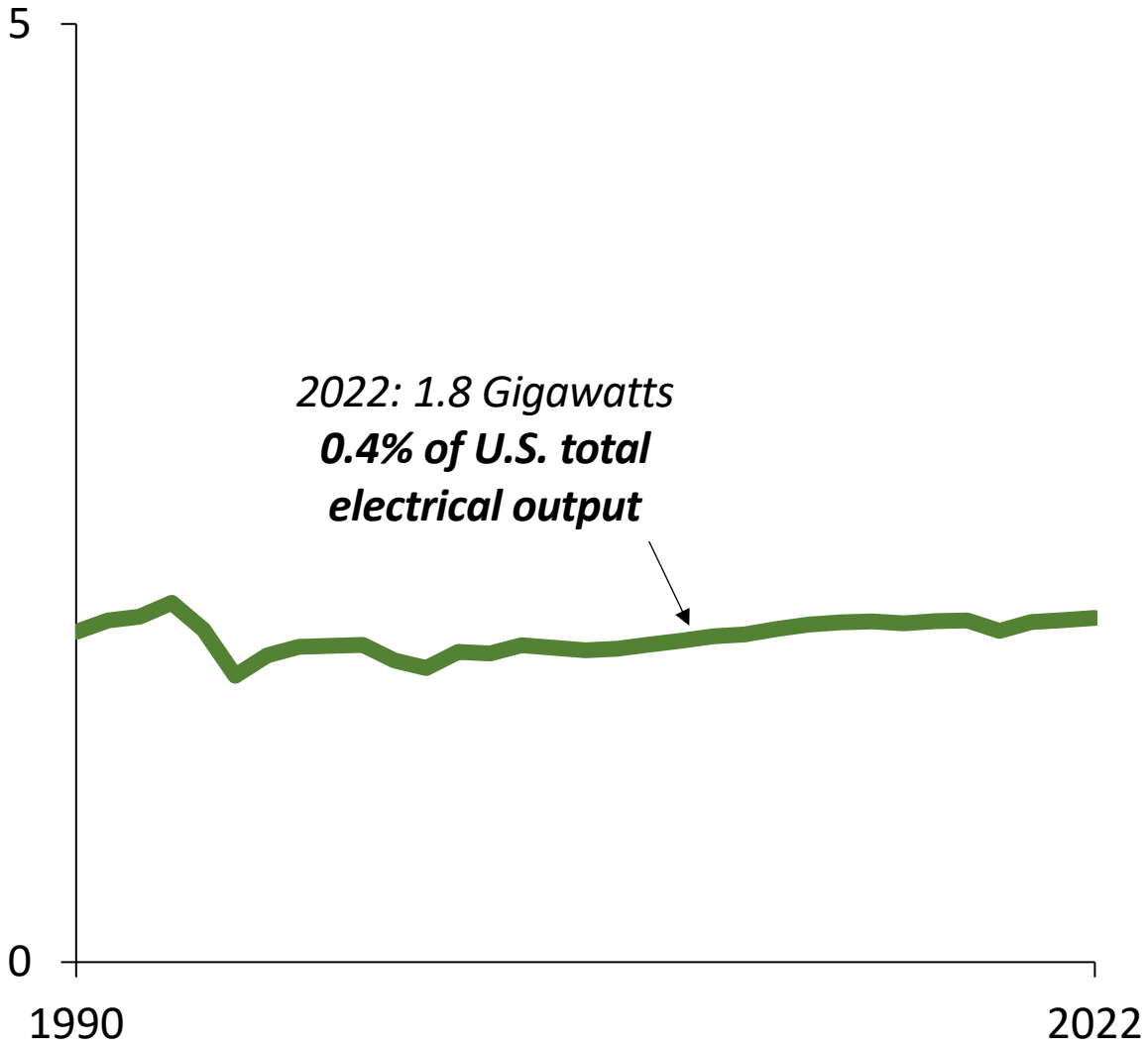


Map taken from U.S. National Laboratory of the Rockies website

But U.S. geothermal power output is trivial

U.S. average instantaneous power generation

(Gigawatts of geothermal power)



Source: U.S. EIA; curve shown is the average instantaneous output from geothermal power plants on an annual basis

Geothermal power economic scorecard

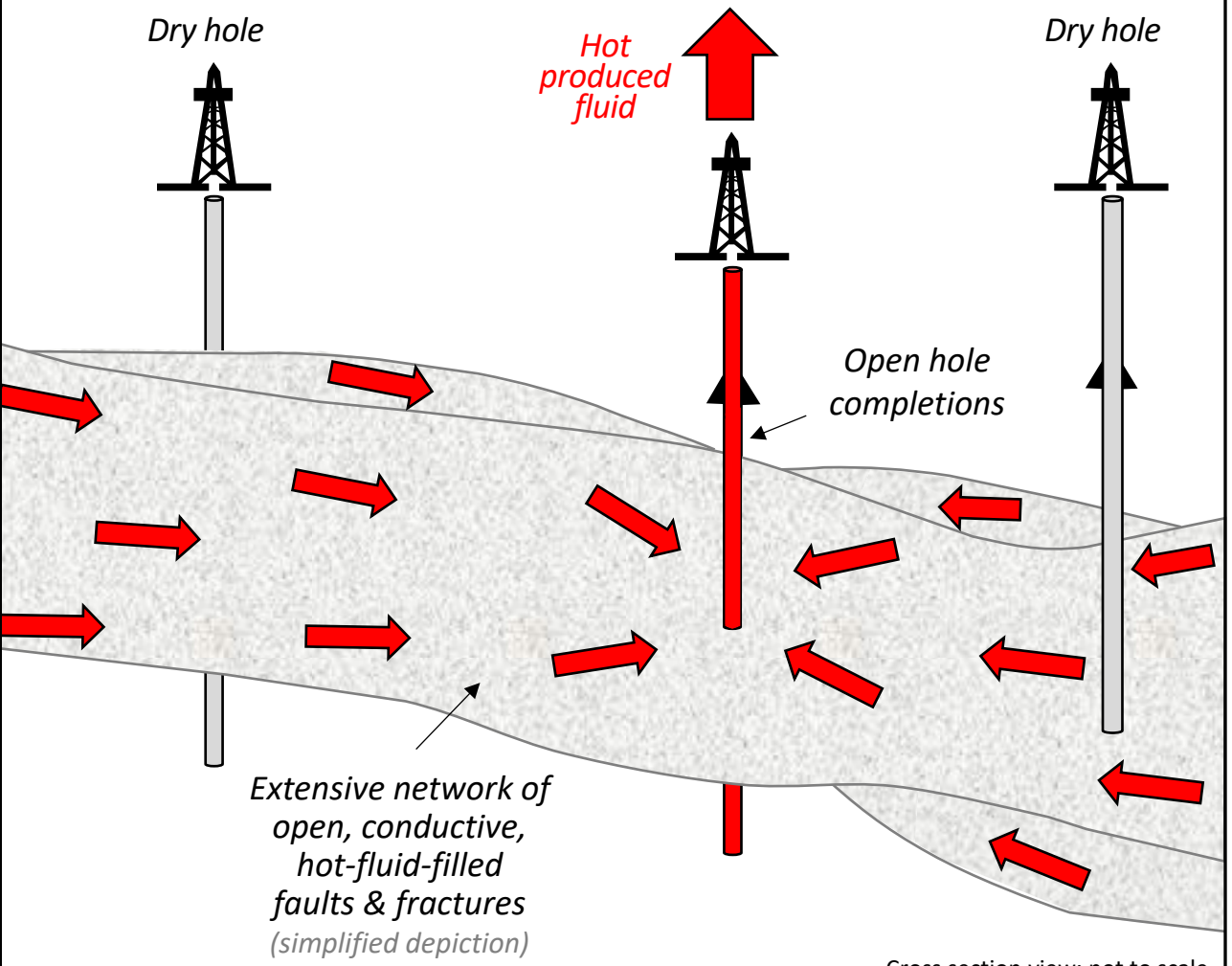
(Historical record; pre-2024)

Abundant:	☑
Reliable:	☑
Firm:	☑
Dispatchable:	☑
Low GHGs:	☑
Affordable:	X

Reliable refers to plant uptime after first several months of production; firm = 24/7/365 output

Past approaches to extracting heat for power production have met with limited success

Hydrothermal (naturally occurring) systems

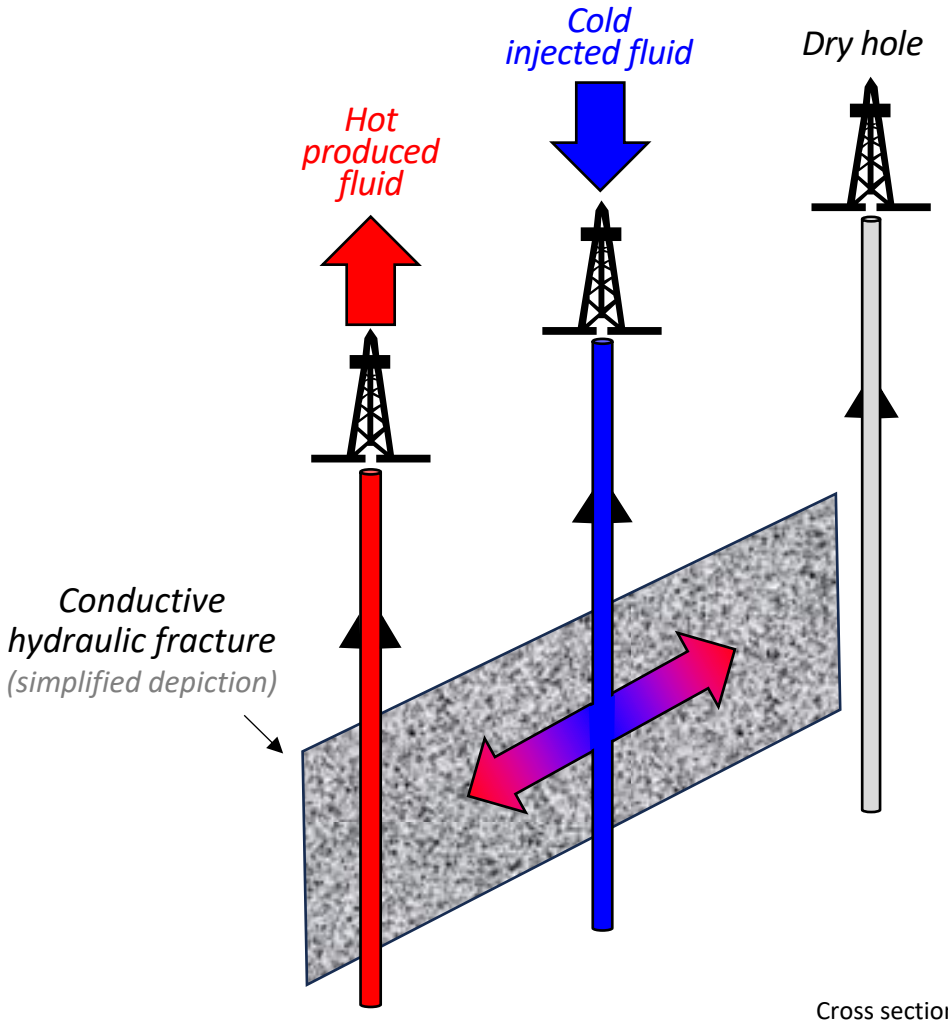


Cross section view; not to scale

HARD TO FIND; PERCEIVED TO BE RARE

Examples: The Geysers, California; McGinnis Hills, Nevada

Enhanced geothermal systems with vertical wells



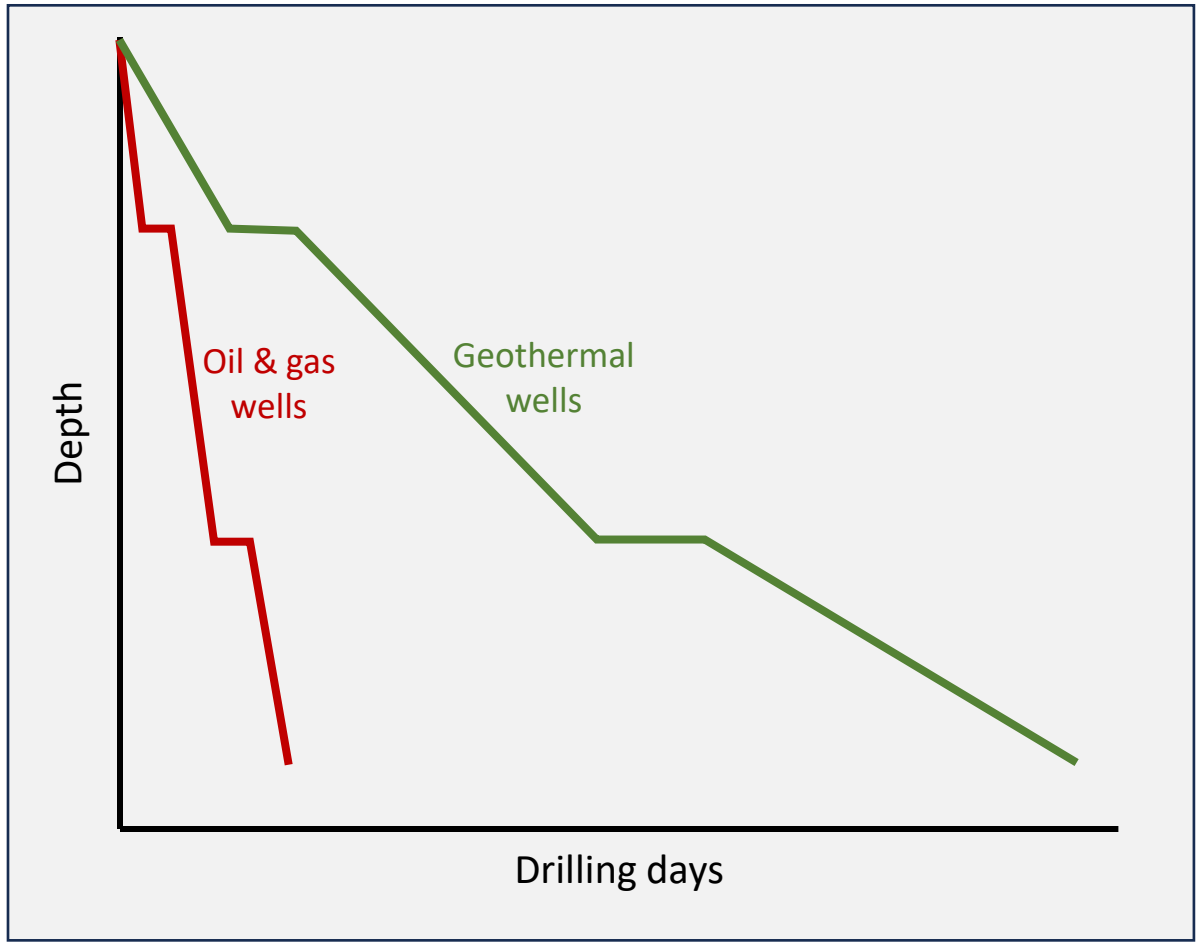
Cross section view; not to scale

EXCEEDINGLY DISAPPOINTING

Examples: Most EGS projects between 1970-2023

Historical performance was also hampered by high well costs and low energy density

Geothermal wells historically took far longer to drill



Drilling time comparisons are schematic representation of performance

Great Basin geothermal wells: Temperature & flow rate

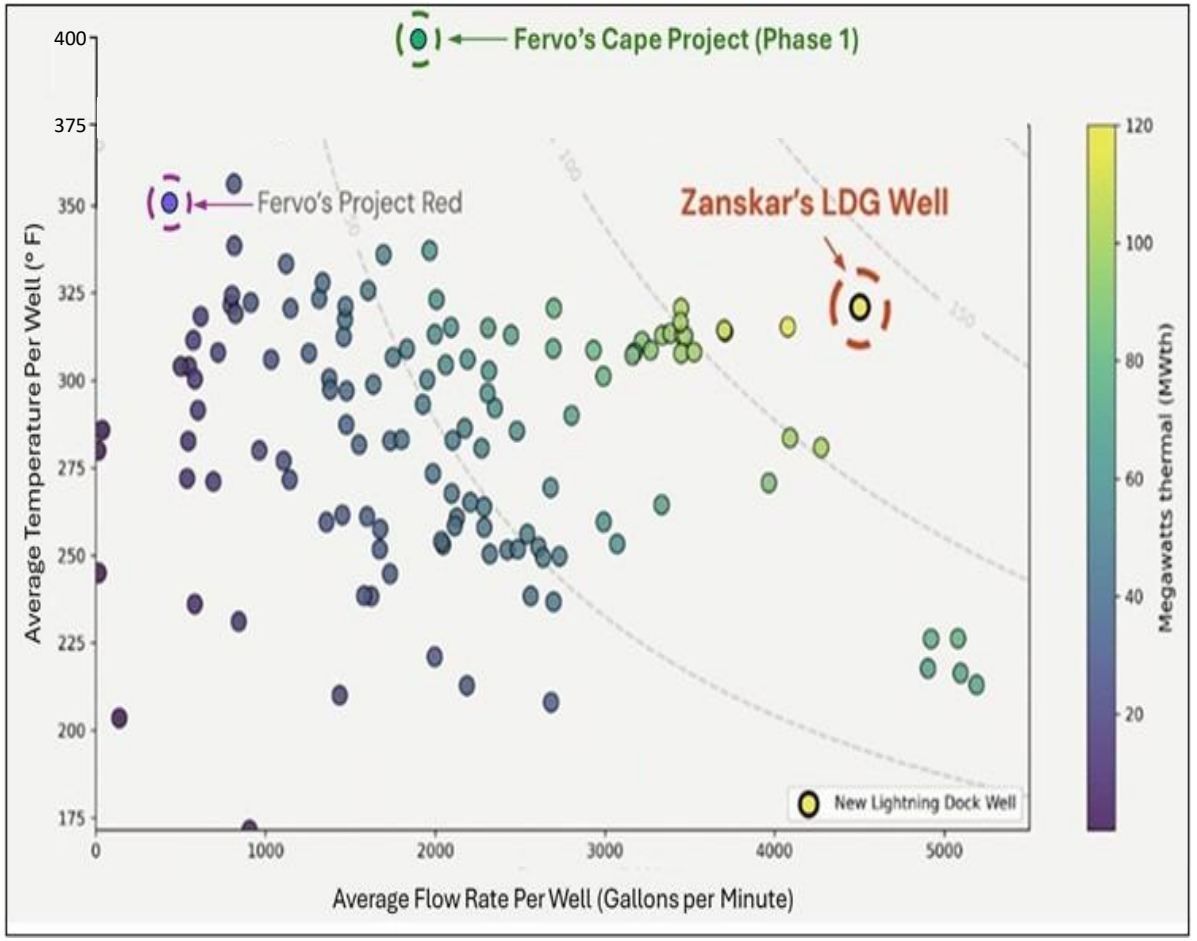
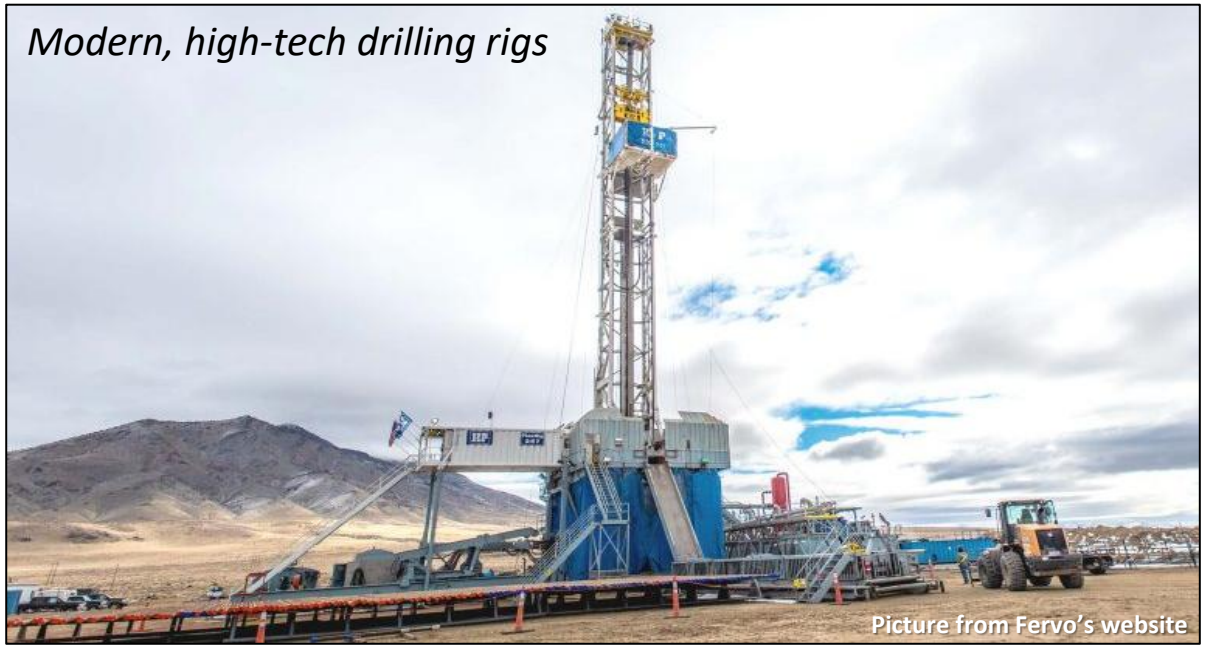


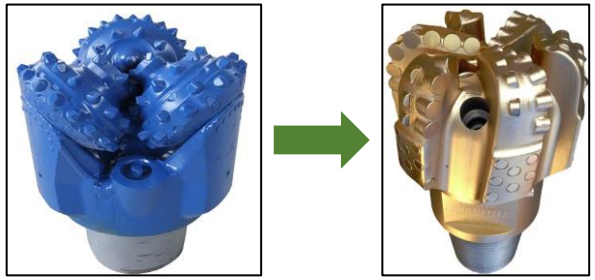
Figure modified after diagram in Zanskar February 3, 2025, Substack post (LINK)

Technology transfer from the O&G industry has transformed geothermal economics

Latest oil and gas drilling technologies



Drill bit design



Roller Cone → PDC

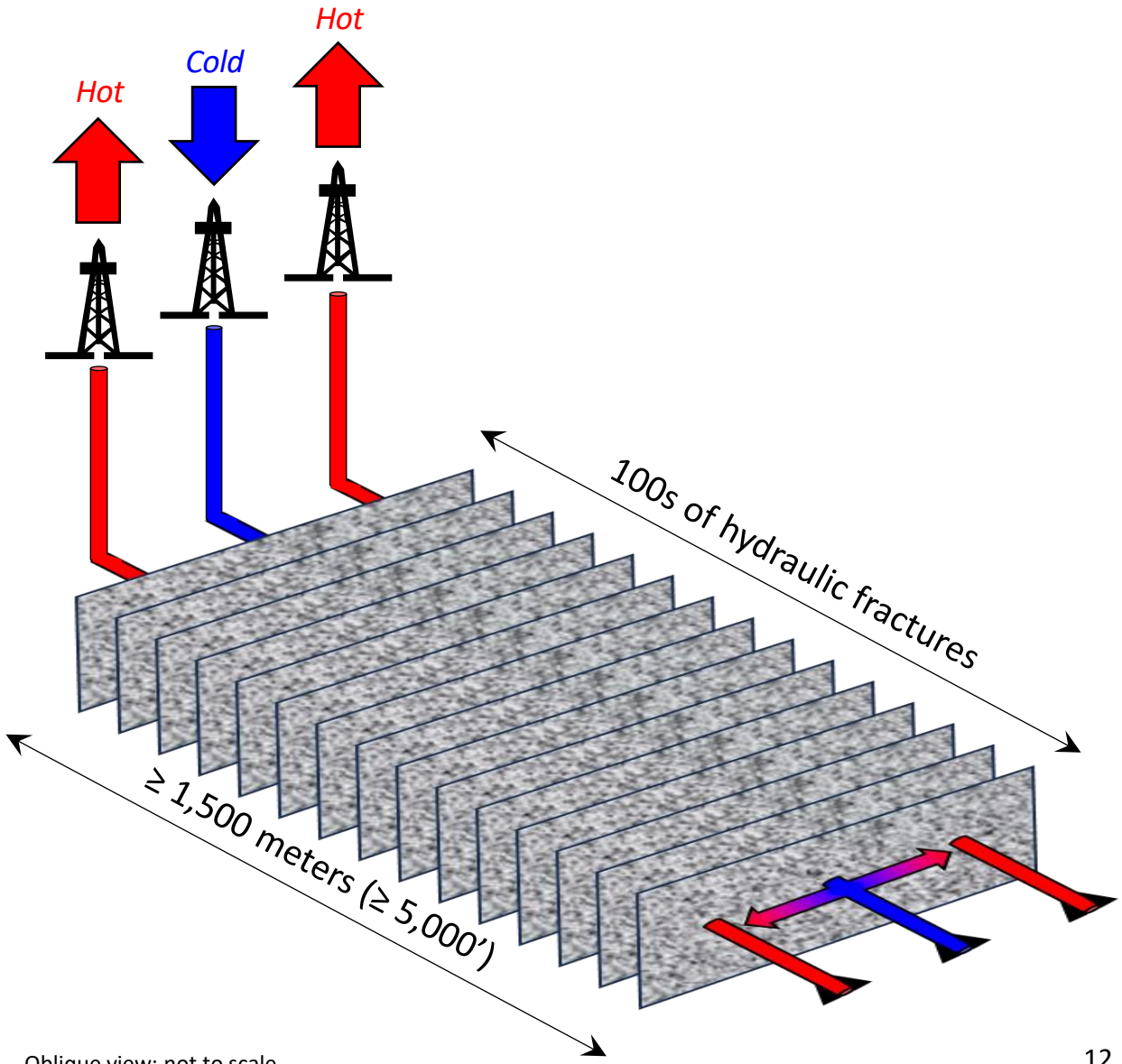
Physics-based drilling

Fred Dupriest
& Sam Noynaert

Texas A&M University

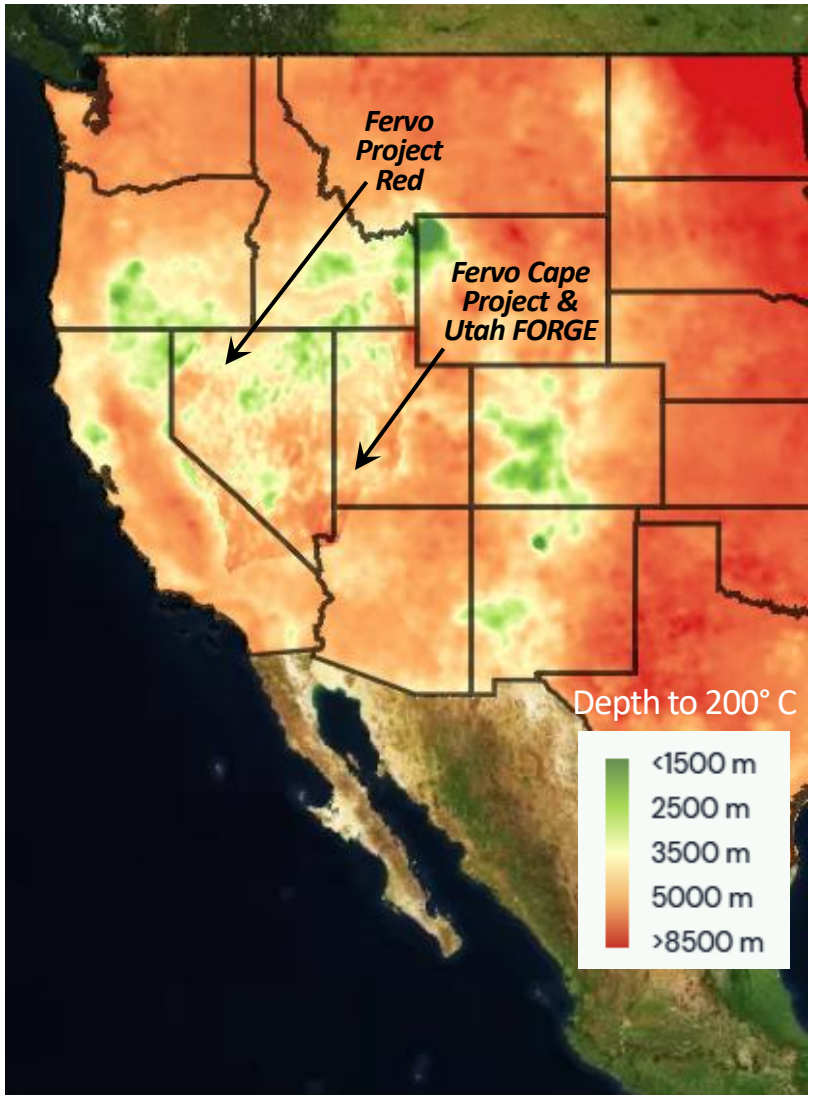
EGS = Enhanced geothermal systems; PDC = Polycrystalline diamond compact (bits)

Hydraulically fractured horizontal wells

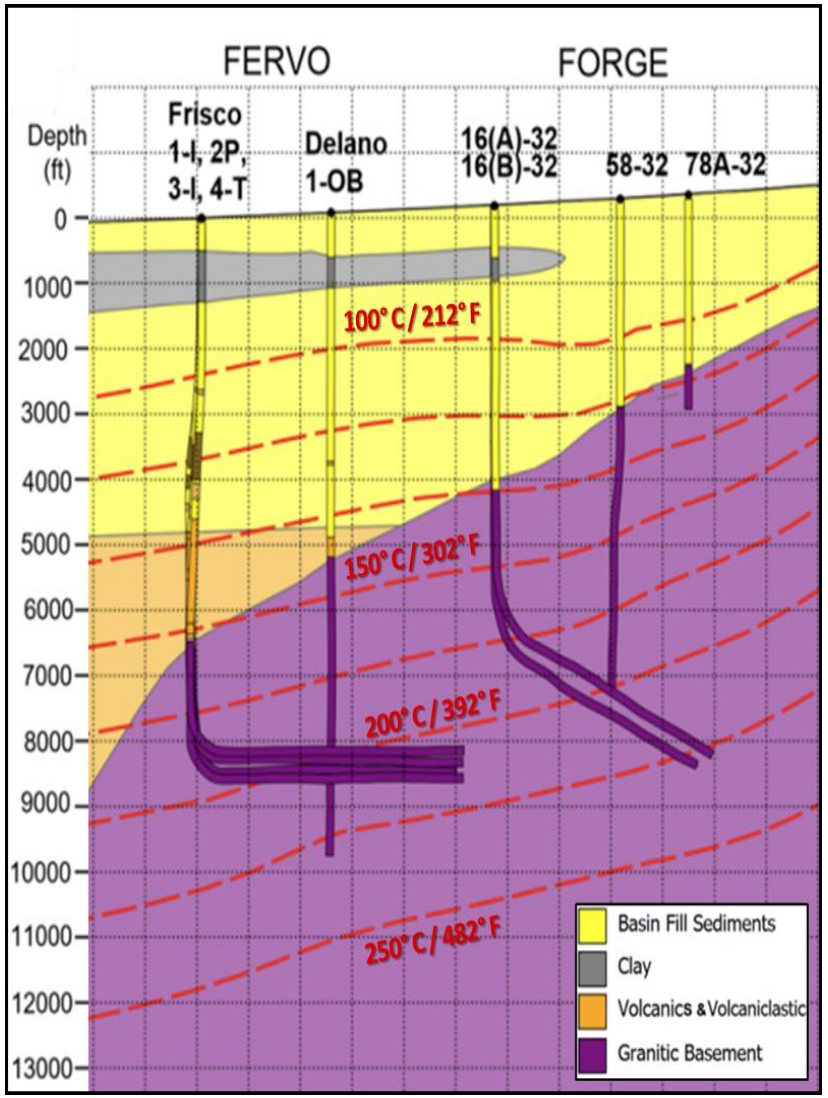


Oblique view; not to scale

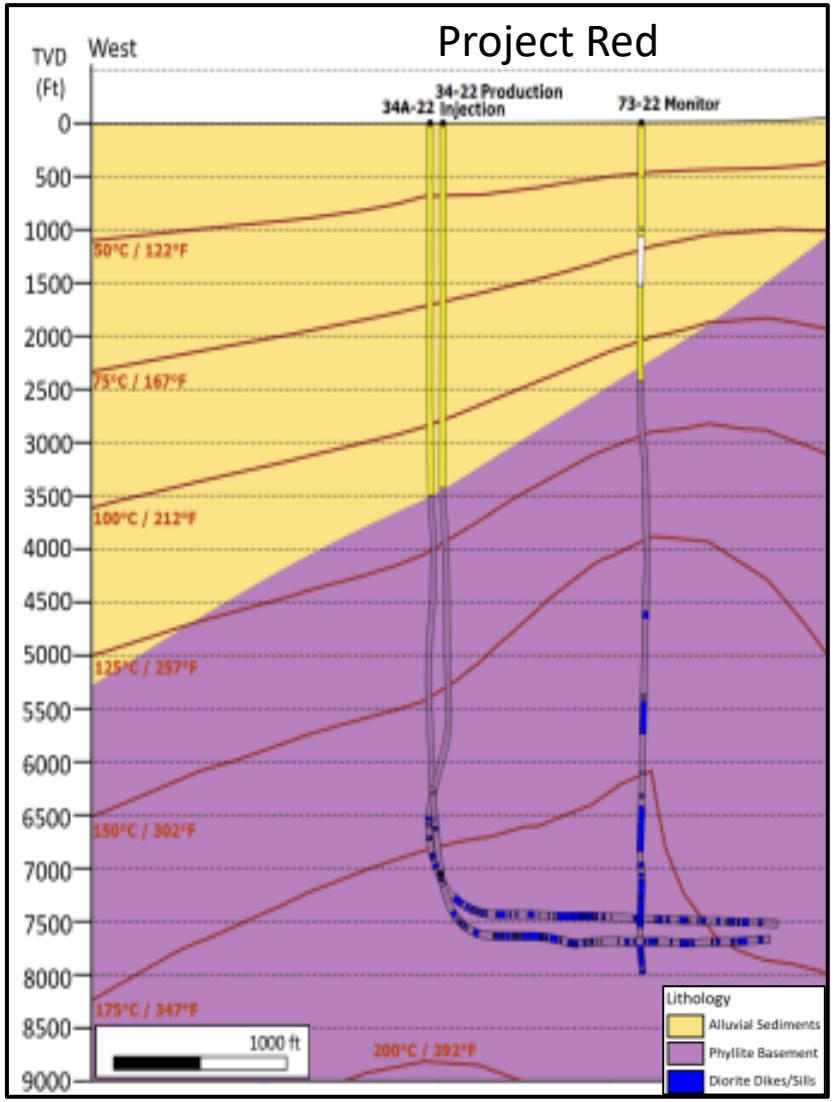
Cutting edge oil and gas industry technologies were first deployed at the U.S. DOE funded Utah FORGE project and Fervo Energy's Red and Cape projects



Map copied from Project Innerspace's website, February 2025



Cross section view parallel to horizontal lateral direction taken from 2024 paper presented at the 49th Stanford Geothermal Workshop by Fercho et al.

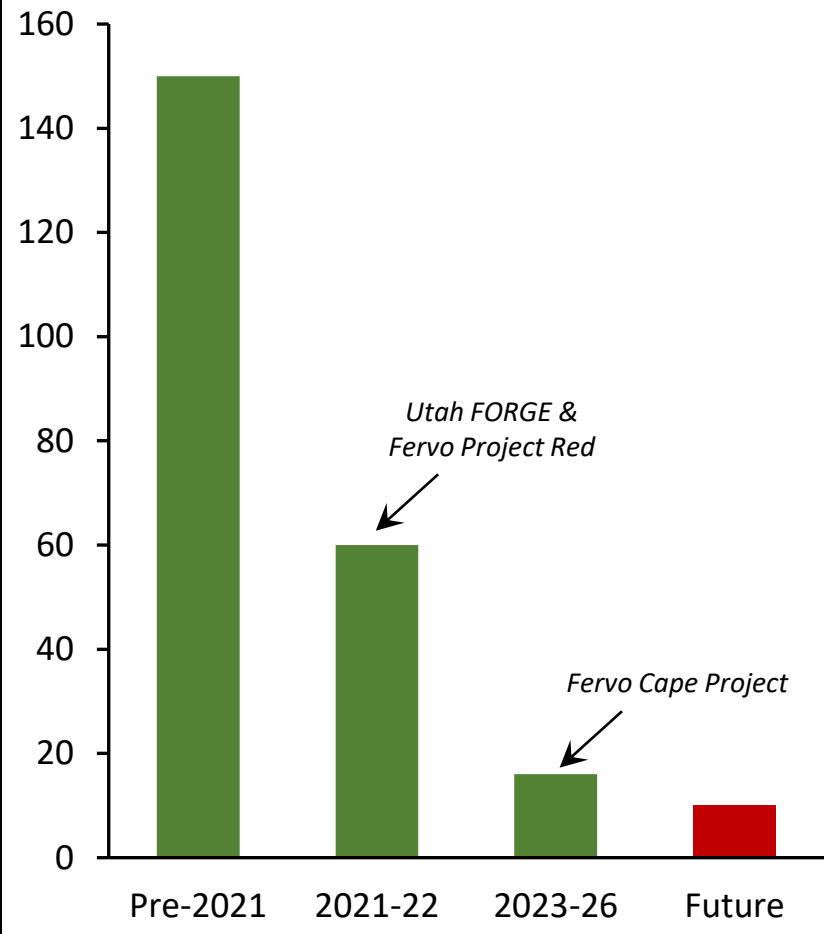


Cross section view parallel to horizontal lateral direction taken from 2023 by Jack Norbeck and Tim Latimer

O&G technologies have allowed Utah FORGE and Fervo Energy to shatter long-held geothermal industry paradigms much like Mitchell Energy did in the Barnett Shale

Spectacular drilling performance improvements

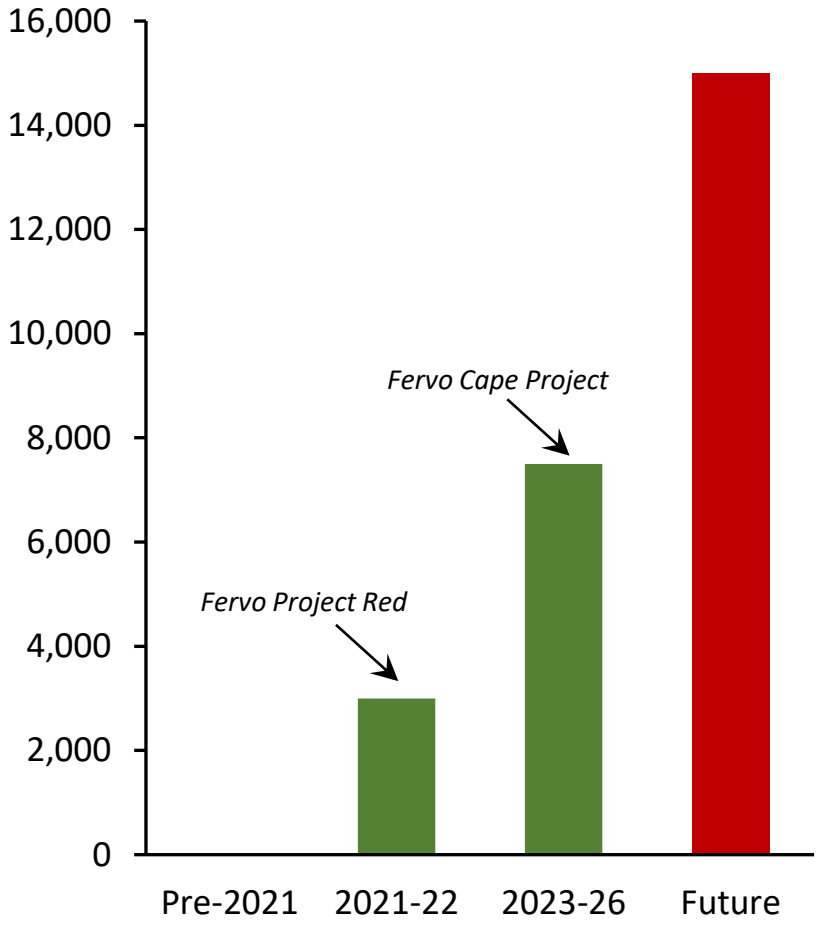
Drilling days to 12,000' MD (≈ 3,600 m)



Sources: El-Sadi et al, 2024, Review Of Drilling Performance In A Horizontal EGS Development; Winkler & Swearingen, 2021, Summary of Drilling Activities, Utah FORGE; MD = Measured depth

Ability to D&C horizontal EGS wells in basement rocks

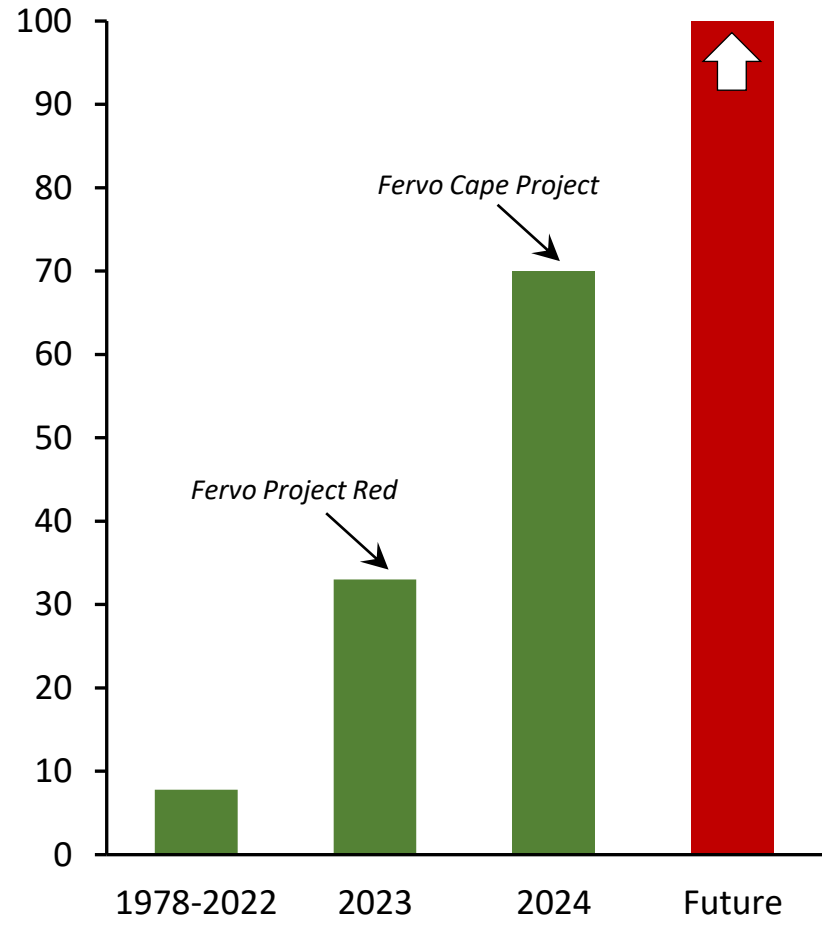
Lateral length (feet)



Note: The first fully horizontal EGS wells drilled were those drilled by Fervo at their Project Red demonstration project in 2022. D&C = drill and complete

Near order-of-magnitude increase in per well production

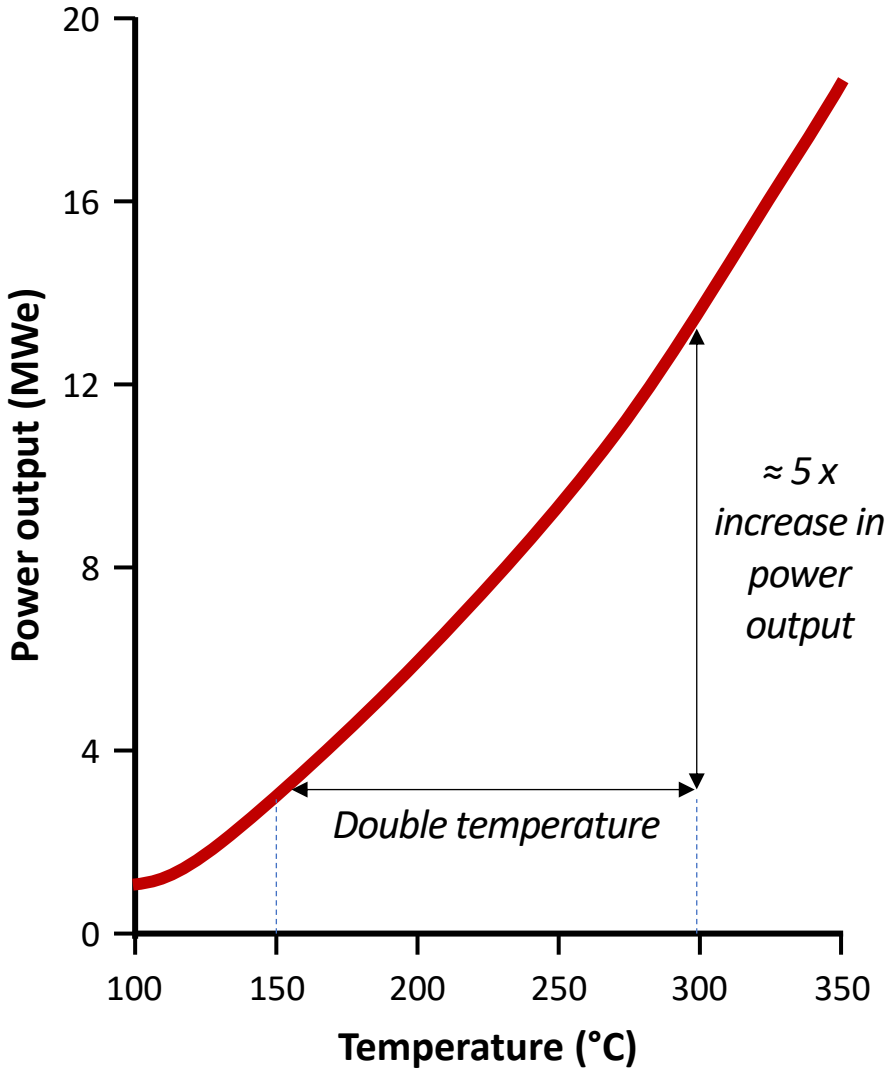
Peak EGS production flow rate (MBFPD)



Note: 1978 – 2020 data from 11 projects; average peak flow rate shown (7,800 bfpd); range was from 2,700 to 16,300; MBFPD = thousands of barrels of fluid per day

Super hot temperatures – greater energy density, much higher power output

Power generation vs. temperature[1]

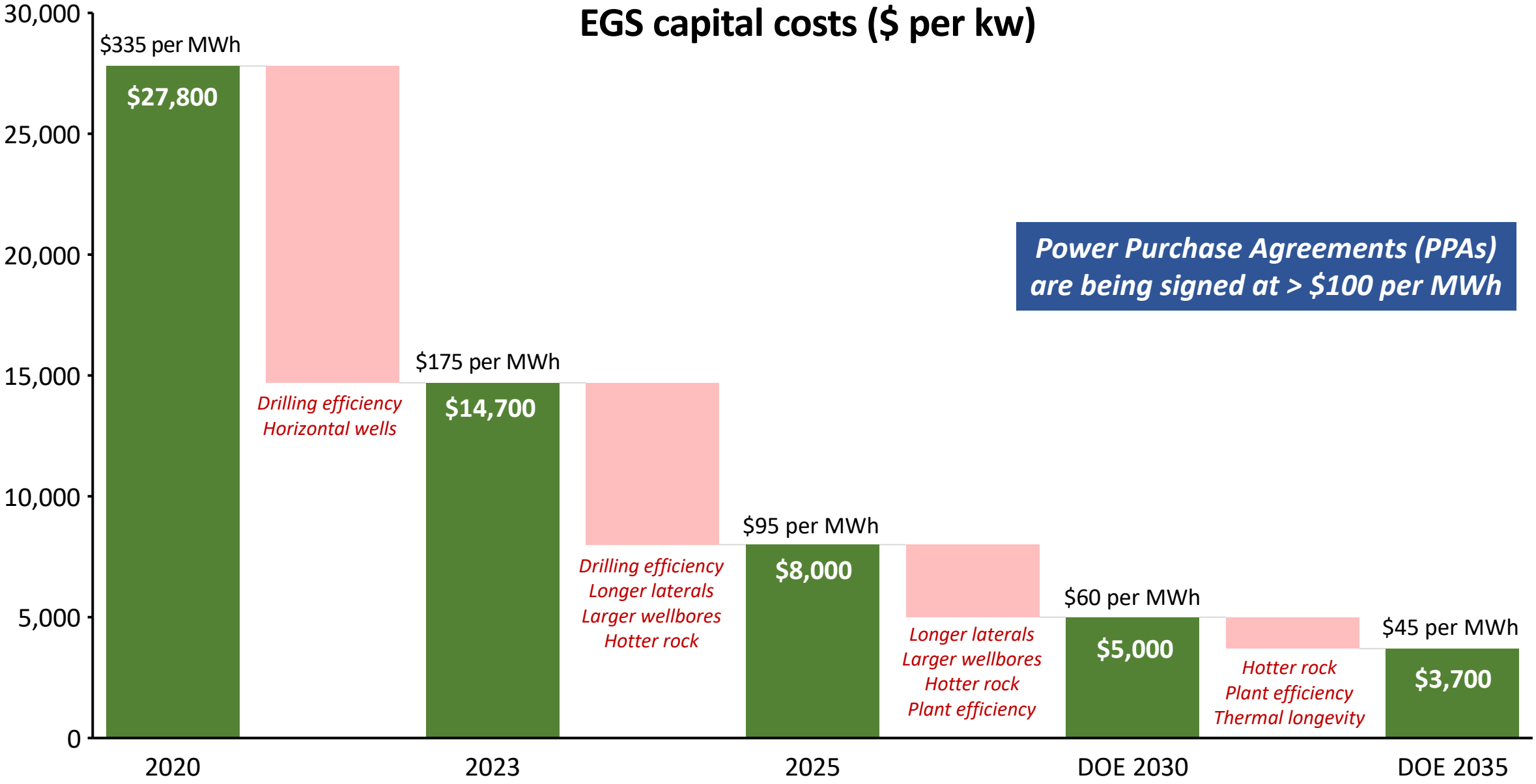


[1]Calculations generated by Mark McClure; graph is for 50,000 barrels per day of produced fluids

Mazama Energy have achieved EGS production at 331° C / 629° F

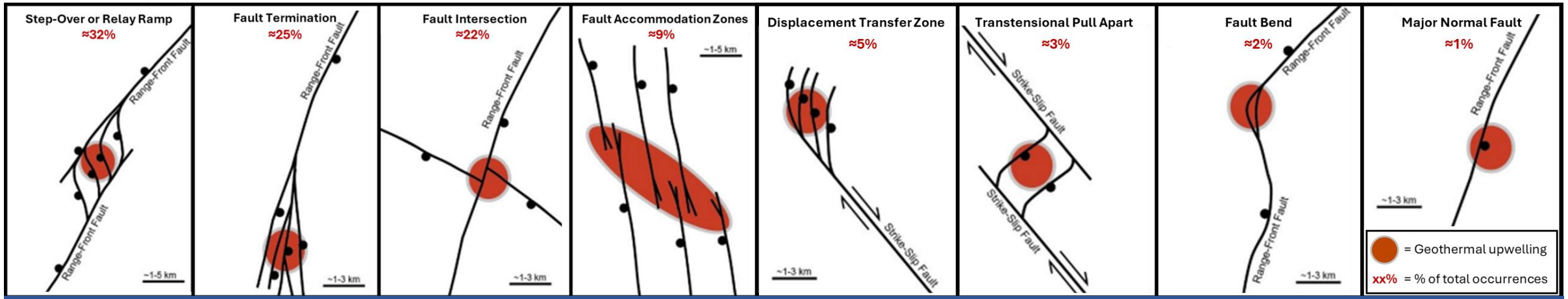
Picture from Mazama Energy's website

EGS capital costs have fallen precipitously over the past five years



All $ per kw numbers from US DOE Next Generation Geothermal Liftoff report except 2025 number, which is estimated. All numbers are unsubsidized. $ per MWh numbers from DOE report or scaled therefrom.

Hydrothermal exploration and production has been revitalized



Key uncertainties: Location of faults, dilation tendency, recency of fault movement, degree of mineralization

Diagram showing the geologic setting for fault-system-related hydrothermal upwellings in The Great Basin, western USA in map view. Diagram modified after Faulds and Hinz (2015)

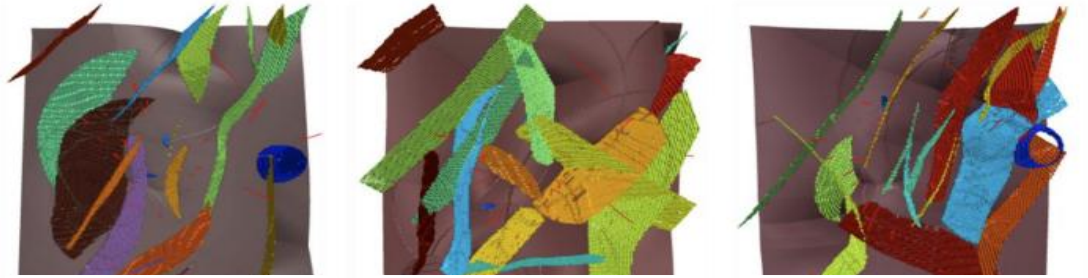
Remote sensing / Seismic imaging

Quaternary fault mapping from LIDAR data using deep learning

Diagram from Hermant et al. (2025)

Machine learning / AI

Model 1 (map view) Model 2 (map view) Model 3 (map view)



Model 1 (side view) Model 2 (side view) Model 3 (side view)

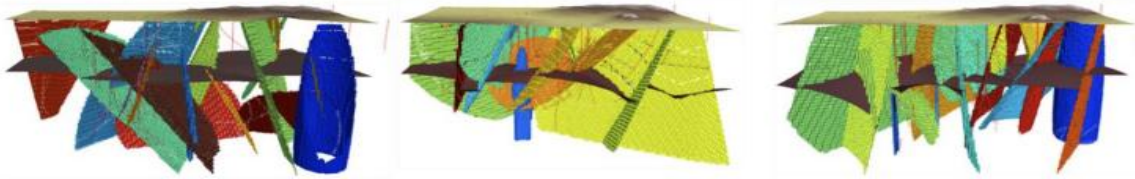


Diagram from Pollock (2020)

Horizontal wells could also greatly enhance hydrothermal power economics

Identifying faults in basement rocks is difficult

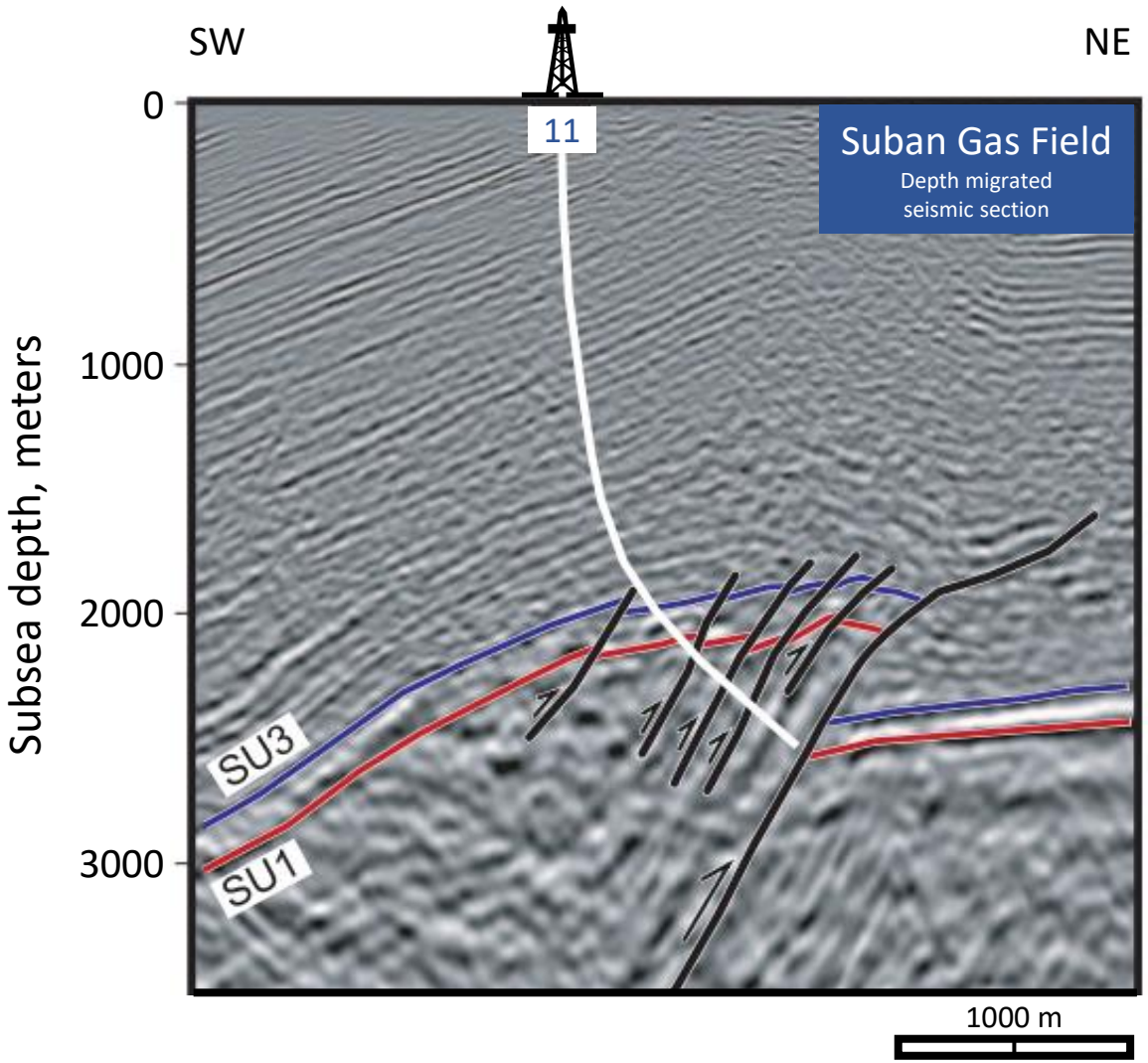


Figure after Hennings et al. (2012). Suban field estimated ultimate recovery = 6 TCFG from fractured basement rocks

To increase flow rates, intersect more fractures

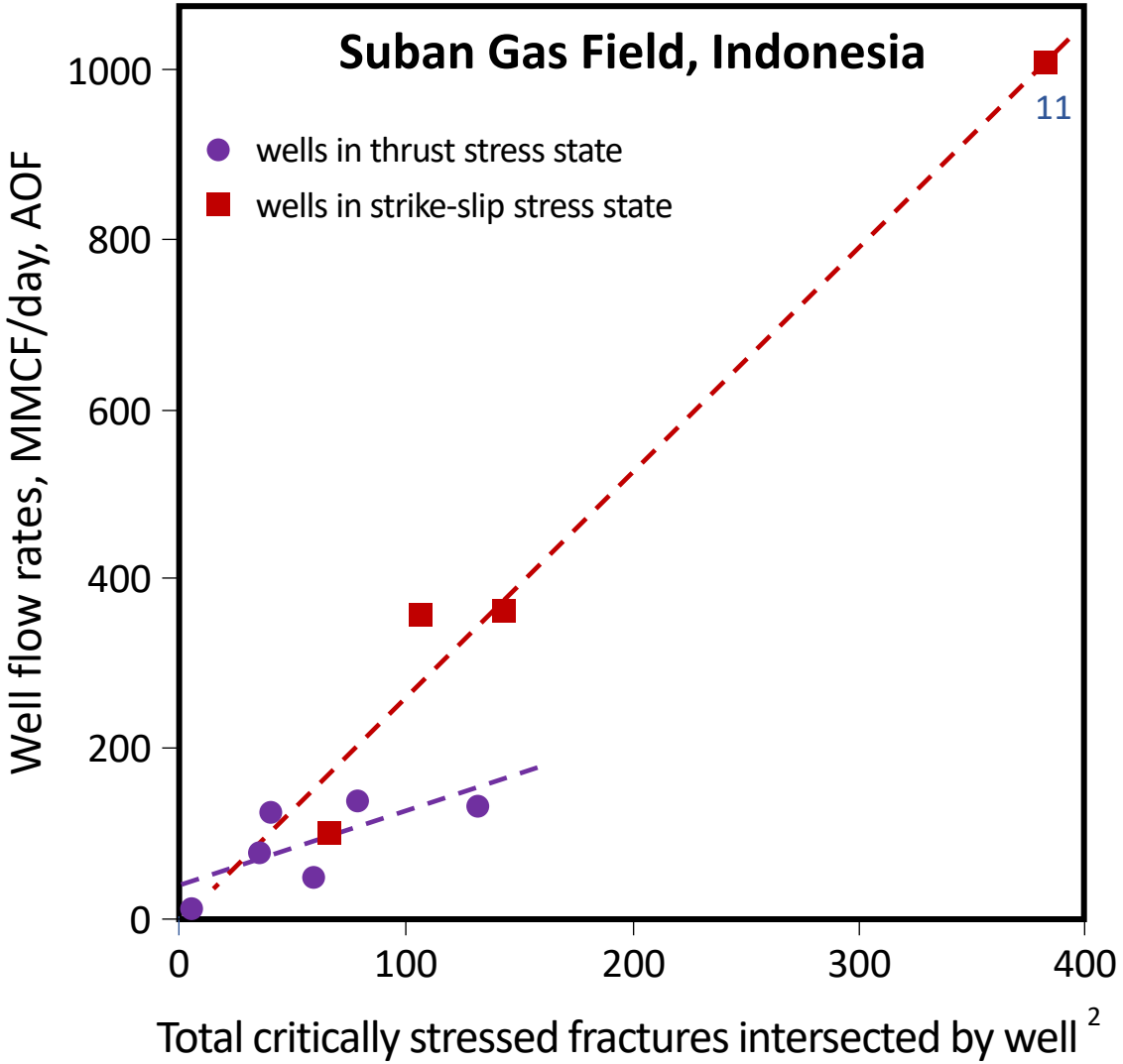


Figure after Hennings et al. (2012). MMCF = million cubic feet; AOF = absolute open flow; [1] critically stressed fractures; [2] from image logs.

Pressure geothermal systems can both store and generate power

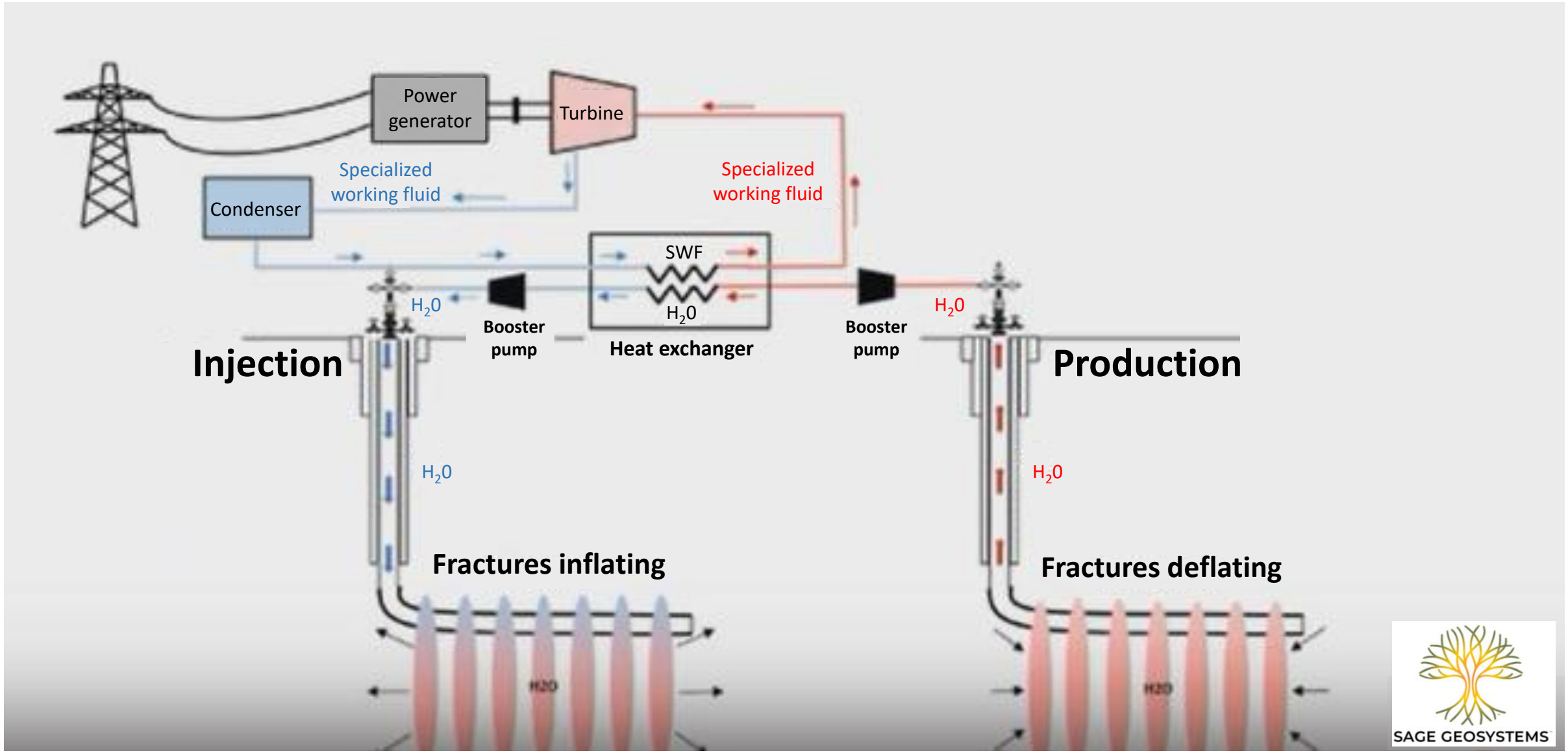
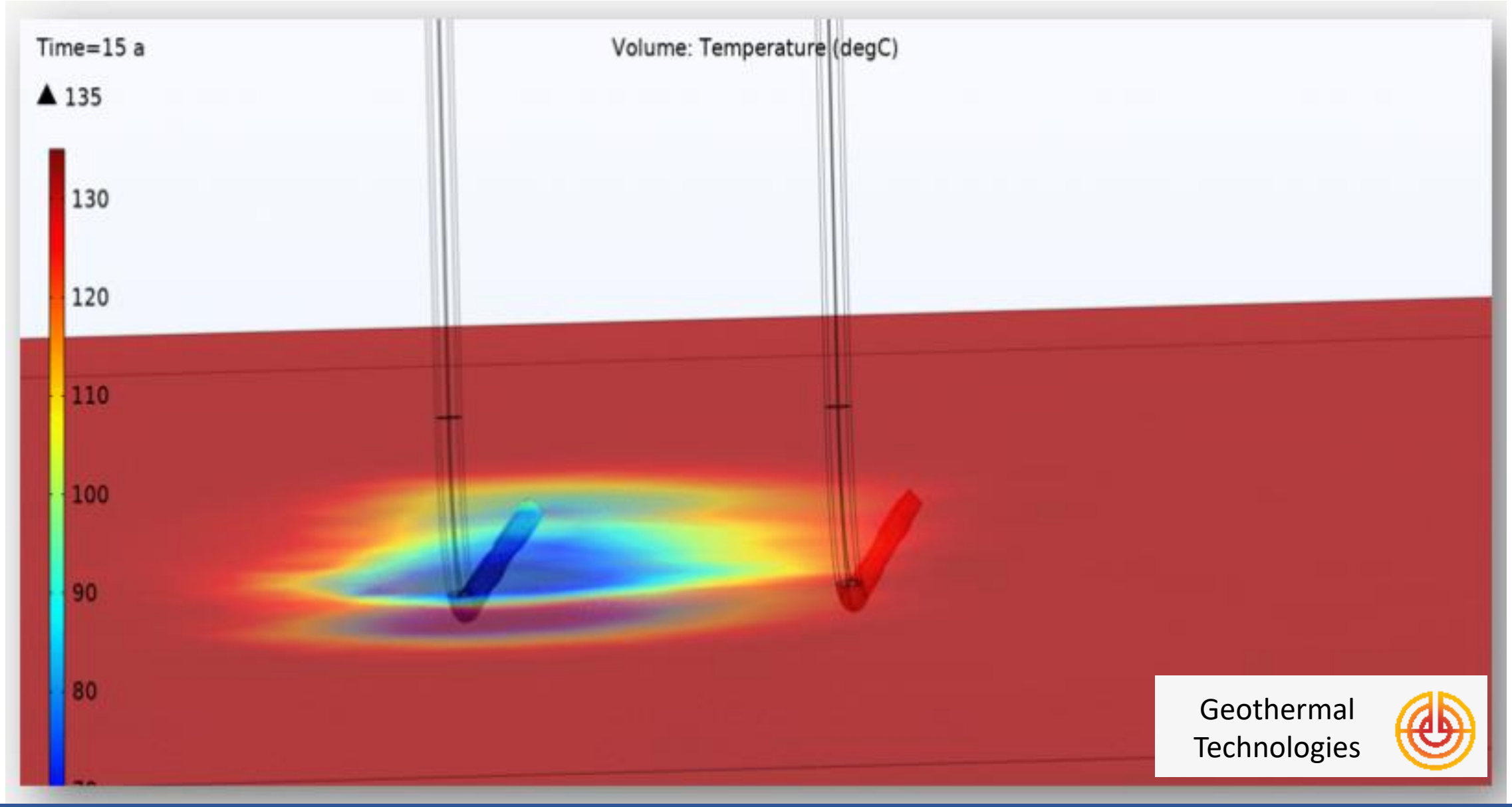


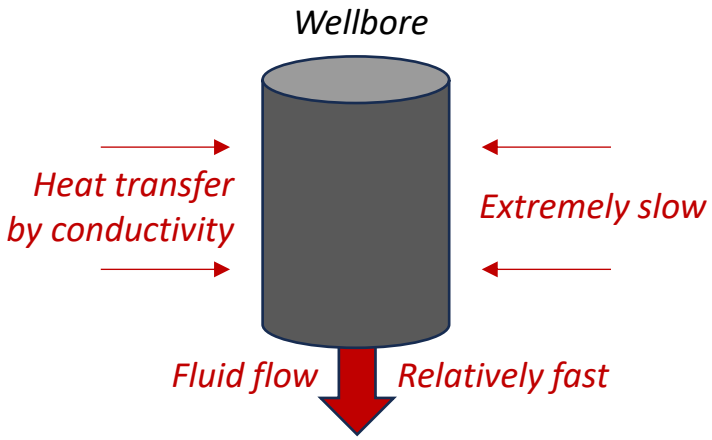
Figure modified after one presented by Sage Geosystems at Petrobras sponsored 1st Brazilian Workshop on Geothermal Energy, November 2024

Sedimentary geothermal systems flow fluids through pore space in permeable formations



Occlusion of porosity and permeability at temperatures conducive for large scale power production is largest challenge

Solving the closed loop thermal longevity challenge



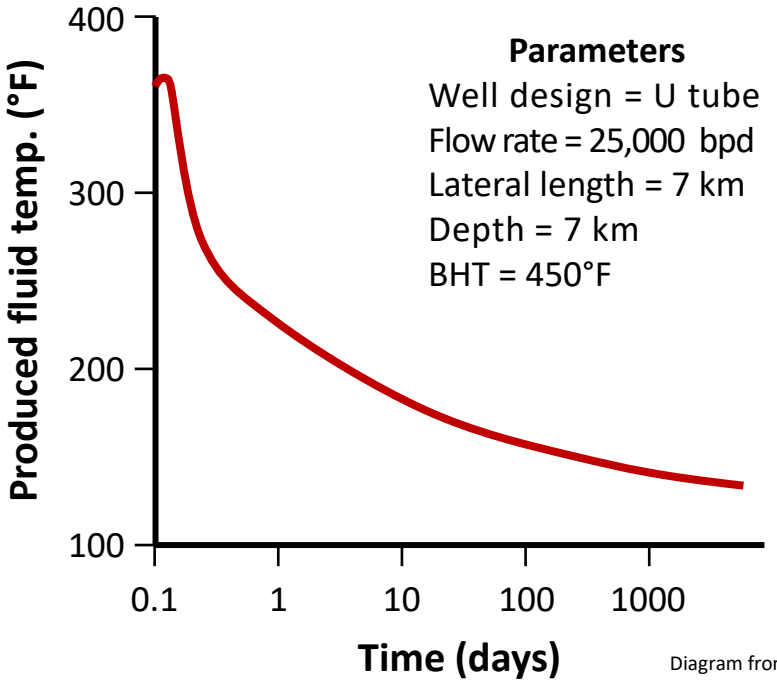
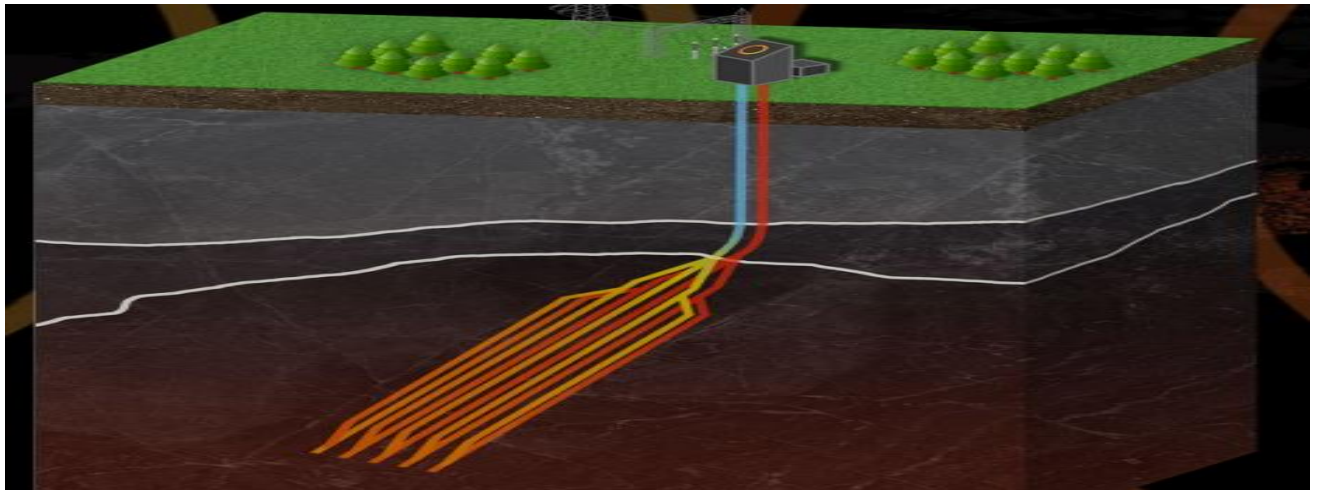
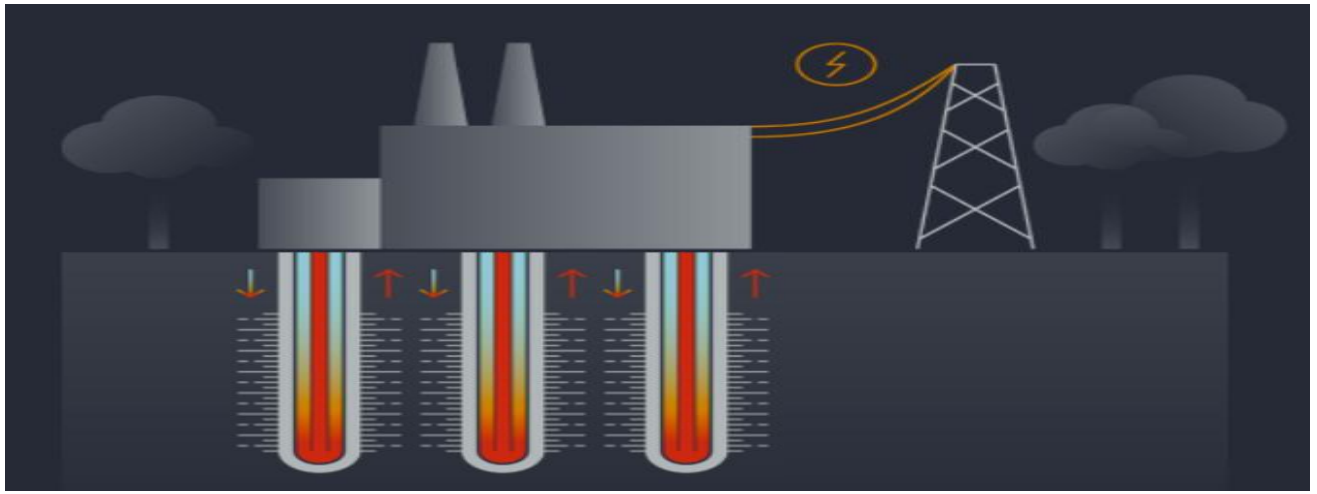


Diagram from McClure 2021

Eavor multi-lateral closed loop "radiator" design



XGS enhanced-conductivity combined inj./prod. well



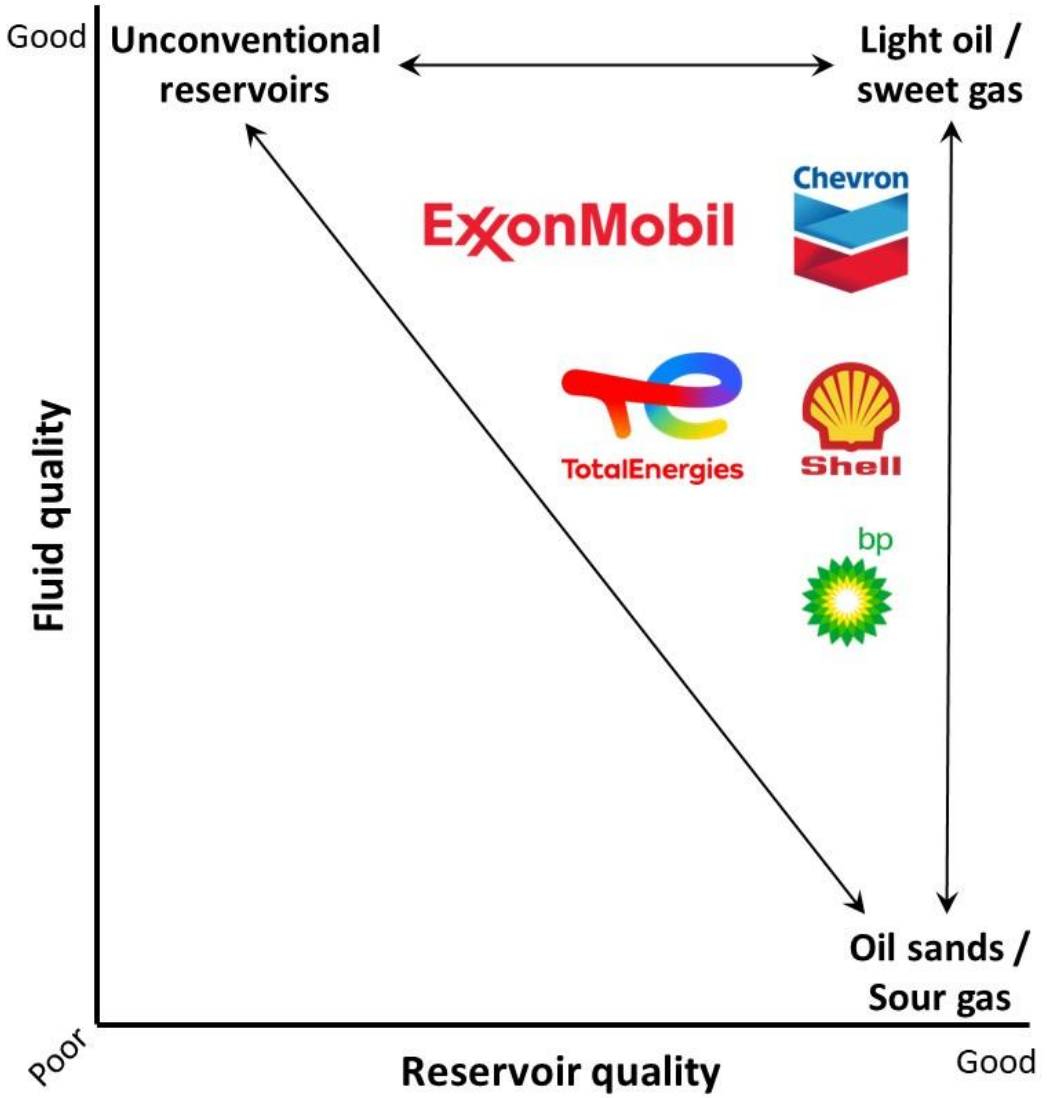
Potential solutions: increase flow loop surface area at depth; insulate upper portion of flow loop; target higher temperatures

As the geothermal industry matures, operators are likely to become technology integrators

Geothermal – Technology specialists

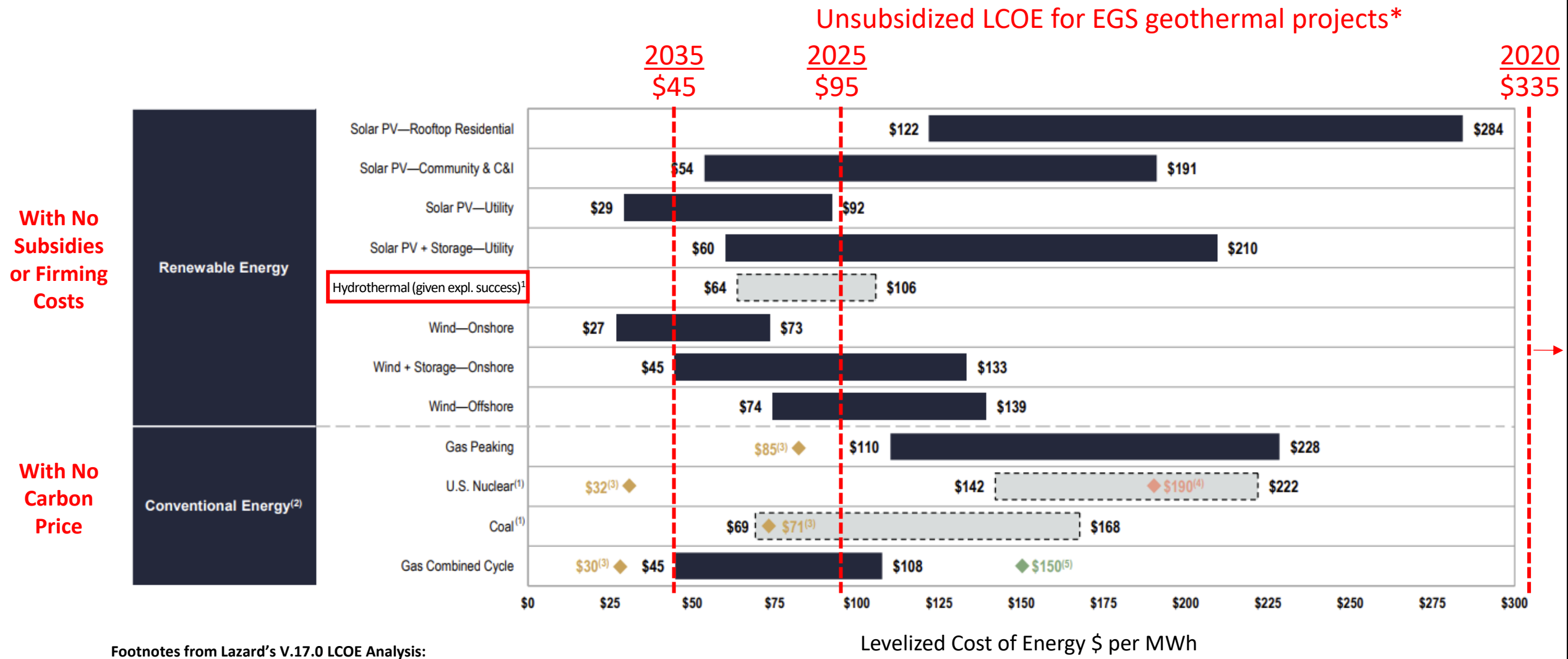
Hydrothermal	EGS
ORMAT zanskar	FERVO ENERGY MAZAMA ENERGY
Closed loop	**Pressure geothermal**
Eavor XGS ENERGY	SAGE GEOSYSTEMS

Oil majors – Technology integrators



See slide 31 for an example of degree of technology integration capabilities that exists within oil and gas operating companies

The world needs abundant, reliable, affordable, firm, low-GHG energy like what geothermal will be able to provide given further technology advancements



Footnotes from Lazard's V.17.0 LCOE Analysis:

All LCOE assessments assume 60% debt at an 8% interest rate and 40% equity at a 12% cost of capital.

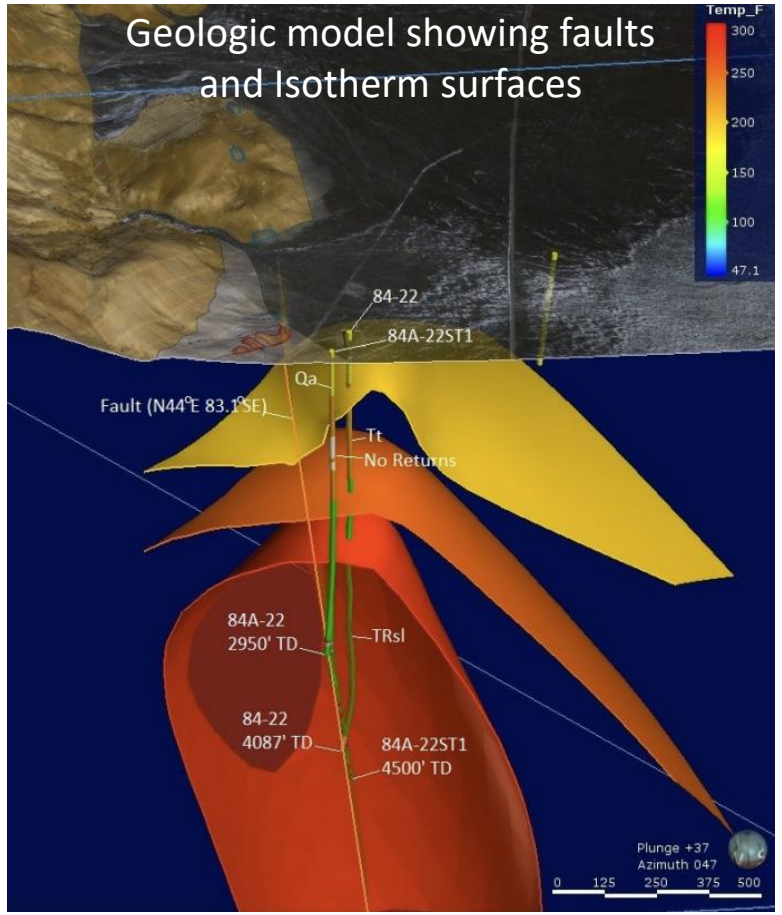
[1] Given the limited public or observable data available for new build geothermal, coal, and nuclear projects, the LCOE presented herein reflects Lazard's LCOE V.14.0 results adjusted for inflation. Coal LCOE does not include the cost for transportation & storage.

[2] The fuel cost assumptions for Lazard's LCOE analysis for natural gas generation, coal generation, and nuclear generation are $3.45 per MMBTU, $1.87 per MMBTU, and $0.85 per MMBTU, respectively

* See slide nine for path to $45 per MWh LCOE. It is reasonable to expect at this early stage of technology deployment a considerable range of uncertainty in both current and 2035 LCOE due to both uncertainty in the ultimate level of performance achieved and local variations that impact LCOE.

Just as with unconventional reservoirs, there will be unexpected & underappreciated challenges to overcome

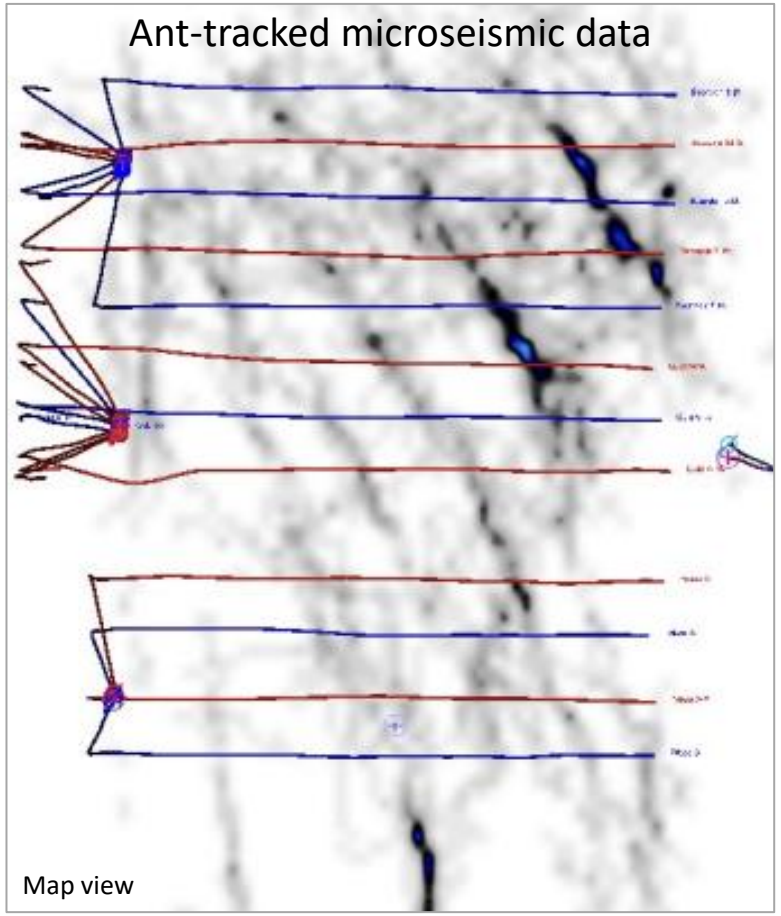
Hydrothermal systems



- Determining fault geometries and characterizing fluid flow pathways
- Challenges: placing injectors to provide pressure support but avoid breakthrough

Source: Successful Deployment of a Multi-Crossing Directional Drilling Method at Ormat's New Tungsten Mountain Geothermal Field in Churchill County, Nevada, Delwiche (2018)

Enhanced geothermal systems (EGS)



- Managing challenges created by pre-existing faults and fractures
- Challenges: thermal degradation, water losses, casing deformation

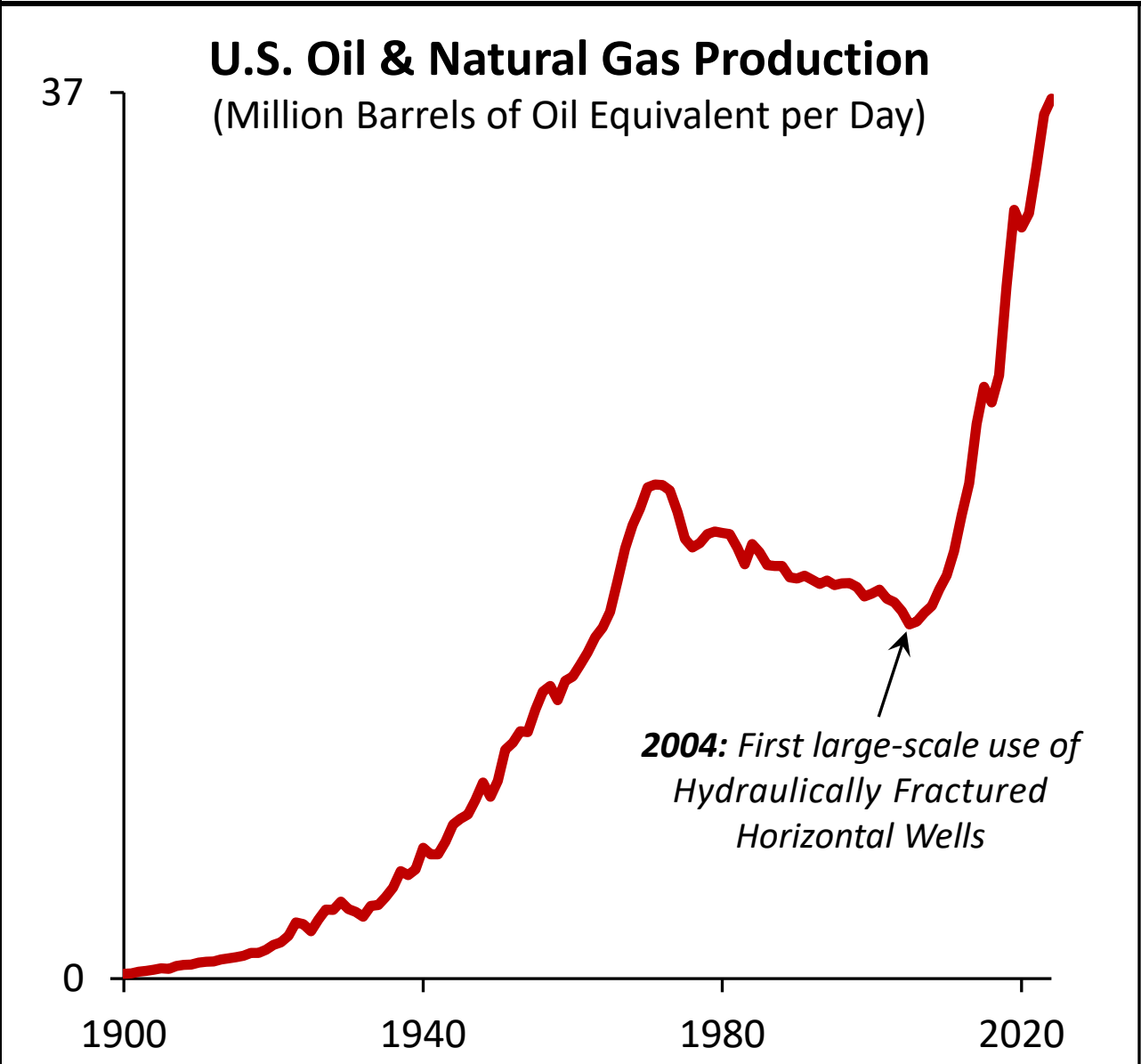
Source: Insights from Microseismic Monitoring of Enhanced Geothermal Systems: Case Study from Cape Modern, Utah, USA, Dadi (2025)

Super hot production

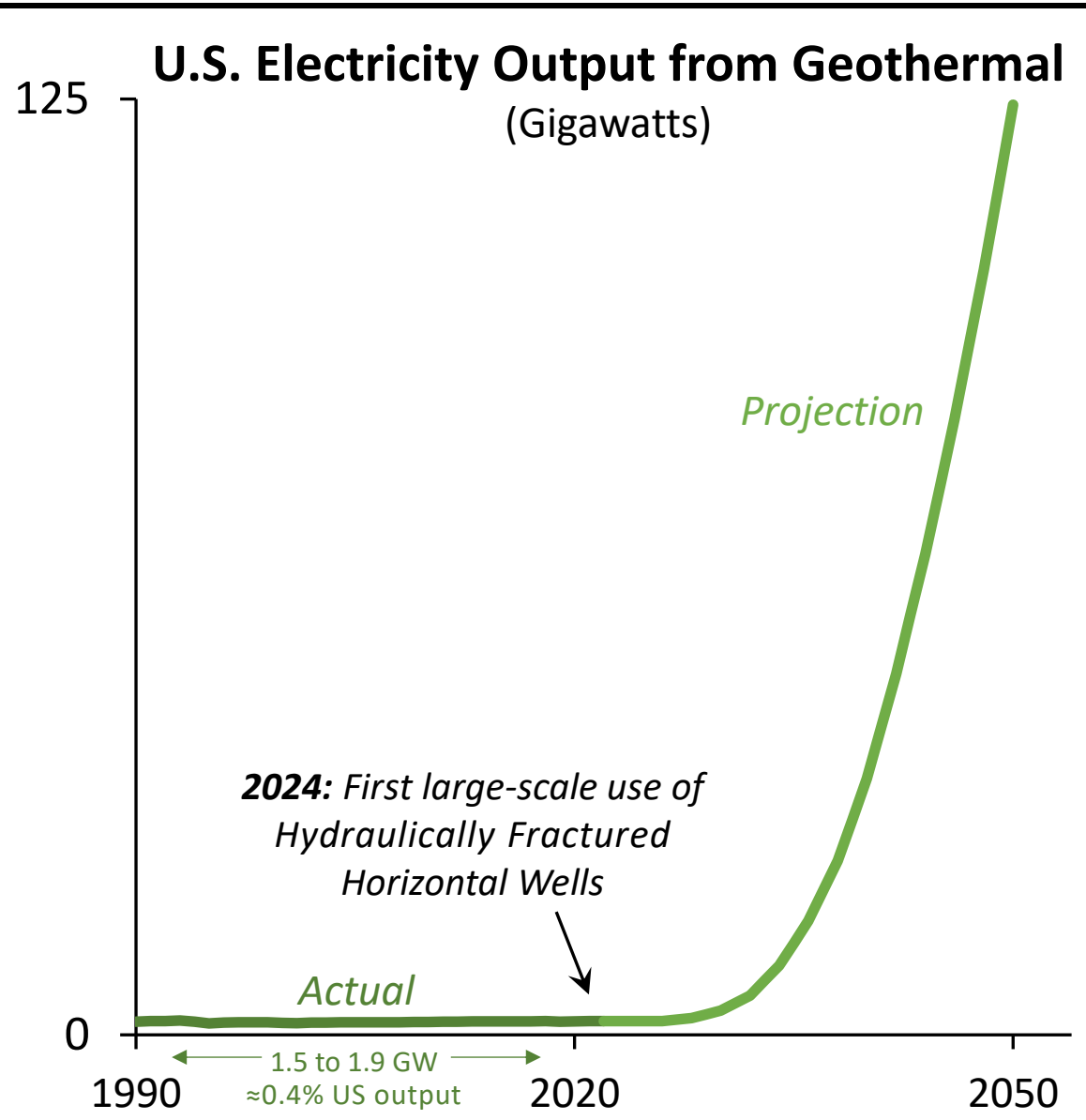
- Managing challenges created by high temperatures and reactive fluids
- Challenges: proppant dissolution, equipment failures, scaling, corrosion

Source: CATF website (LINK)

Geothermal power production is poised to achieve a breakthrough like that achieved in U.S. unconventional O&G reservoirs



Sources: U.S. EIA and Energy Institute websites



Sources: U.S. EIA for 1990 to 2022; 2022 average output = 1.8 GW (0.4% of U.S. total); Author projection from 2023 to 2050

Fervo's Cape Project will increase U.S. geothermal power output by > 25%

0.5 GW of power output
Phase 1 start-up in 2026
Phase 2 start-up in 2028

Areal photo of Fervo Cape Phase 1 project; April 2025. Picture from Fervo Energy's website

Geothermal Power Output Growth

Greg Leveille

April 29, 2026

A copy of this slide deck can be downloaded at:
https://tidalwavetechnologies.com/

From IFP website

Key papers and publications (Hydrothermal systems)

- Faulds et al., 2026, **Favorable Structural Settings for Geothermal Systems in the Great Basin Region, Western USA: A Critical Regional Dataset and Harbinger for Hidden Geothermal Resources** (LINK)
- Leveille, 2025, **Horizontal Hydrothermal Wells: An Idea Whose Time Has Come** (LINK)
- Leveille, 2025, Slide deck accompanying paper "**Horizontal Hydrothermal Wells: An Idea Whose Time Has Come**" (LINK)
- Dadi, 2025, **Insights from Microseismic Monitoring of Enhanced Geothermal Systems: Case Study from Cape Modern, Utah, USA** (LINK)
- Kim et al., 2026, **Evidence of Direct Fluid Connections between Hydraulic Fractures and Pre-existing Faults at the Cape Station EGS Project** (LINK)
- Pollack, 2020, **Quantifying Geological Uncertainty and Optimizing Technoeconomic Decisions for Geothermal Reservoirs** (LINK) – see especially sections four and five of this document (pages 71 – 154)
- Macrossie Smith, 2021, **Machine Learning Techniques Applied to the Nevada Geothermal Play Fairway Analysis** (LINK)
- Hart-Wagoner et al., 2024, **Preliminary regional play fairway workflow for the Great Basin region, USA** (LINK)
- Hermantet al., 2025, ***Using Deep Learning to Map Quaternary Faults in Western USA*** (LINK)
- Edwards et al., 2025, **A Look Into Geothermal Discoveries Across the Western United States** (LINK)
- Grujic et al., 2025, **GeoCore: An Efficient and Scalable Framework to Optimize Geospatial Machine Learning** (LINK)
- Zheng et al., 2026, **Thermal Gradient Signatures of Fault-Controlled Hydrothermal Systems: Insights from Conceptual Models and Field Data** (LINK)

Key papers, posts and presentations (Enhanced geothermal systems; 1 of 2)

- Dupriest and Noynaert, 2022, ***Drilling Practices and Workflows for Geothermal Operations*** (LINK)
- Moore, 2024, ***Current Activities at Utah FORGE*** (LINK)
- Norbeck and Latimer, 2023, ***Commercial-Scale Demonstration of a First-of-a-Kind Enhanced Geothermal System*** (LINK)
- McClure, 2023, ***Fervo Energy's 'Project Red' Results are a Historical Breakthrough for Geothermal – What Comes Next*** (LINK)
- Norbeck, Gradl, and Latimer, 2024, ***Deployment of Enhanced Geothermal System technology leads to rapid cost reductions and performance improvements*** (LINK)
- El-Sadi et al., 2024, ***Review Of Drilling Performance In A Horizontal EGS Development*** (LINK)
- Dadi, 2025, **Insights from Microseismic Monitoring of Enhanced Geothermal Systems: Case Study from Cape Modern, Utah, USA** (LINK)
- Kim et al., 2026, **Evidence of Direct Fluid Connections between Hydraulic Fractures and Pre-existing Faults at the Cape Station EGS Project** (LINK)
- Leveille and Zoback, 2025, **Impacts of Shear Zones on Enhanced Geothermal Systems (EGS): Best Practices for Avoiding Induced Seismicity, Premature Thermal Breakthrough, and Excessive Leakoff** (LINK)
- Project Innerspace, 2025, ***The Geothermal Exploration Opportunities Map Beta*** (GeoMap™) (LINK)
- Ertas, 2025, ***EGS Reservoir Characterization Through Injectivity and Steady-State Circulation Tests*** (LINK)
- Fercho et al., 2025, ***Update on the Geology, Temperature, Fracturing, and Resource Potential at the Cape Geothermal Project Informed by Data Acquired from the Drilling of Additional Horizontal EGS Wells*** (LINK)

Key papers, posts and presentations (Enhanced geothermal systems; 2 of 2)

- Fervo, 2026, **Fervo Energy Drills Hottest Well to Date at New Giga-Scale Geothermal Project Site** (LINK)
- Fervo, 2026, **Enhanced Geothermal Has Been Proven at Scale. Here's What Two Years of Production Data Show** (LINK)
- Grubac et al., 2026, **Implementation of the World's First Greater than 300 °C Propped EGS Reservoir** (LINK)
- Bonneville et al., 2026, **A Major Milestone at Newberry, Oregon: Advancing Toward a Superhot Rock EGS Reservoir** (LINK)
- Gonzalez et al., 2026, **Twinned at 300°C+: High-Performance Geothermal Drilling — Newberry Case Study** (LINK)
- Chandrasekhar and Suryanarayana, 2026, **Thermal Decline and Management in Energy Generation from Fractures in Super Hot Rock Formations** (LINK)
- Dichter et al., 2026, **Concept of a High-Temperature EGS Plant in Central Oregon** (LINK)

Other key geothermal power production papers and publications

- NOAA Global Monitoring Laboratory, 2026, ***Trends in CO2 and CH4*** (LINK)
- CATF, 2022, ***Superhot Rock Energy - A Vision for Firm, Global Zero-Carbon Energy*** (LINK)
- CATF, 2024, ***Gaps, Challenges, and Pathways Forward for Superhot Rock Energy Summary Report*** (LINK; LINK; LINK)
- United States Department of Energy, 2024, ***Pathways to Commercial Liftoff: Next-Generation Geothermal Power*** (LINK)
- Lazard, 2024, ***Levelized Cost of Energy Comparison*** (LINK)
- McClure, M., 2021, ***Why Deep Closed-Loop Geothermal Is Guaranteed To Fail*** (LINK)
- Mark McClure, 2023, ***Thermoelastic fracturing and buoyancy-driven convection – Surprising sources of longevity for EGS circulation*** (LINK)
- Mark McClure, 2023, ***Technical barriers for deep closed-loop geothermal*** (LINK)
- United States Energy Information Administration, 2025, ***Crude Reserves and Production*** (LINK) ***& Natural Gas Gross Withdrawals and Production*** (LINK) ***& Electricity Net Generation by Energy Source*** (LINK)

Key electricity demand and O&G fracture stimulation papers and publications

Demand for Clean Firm Electricity and High-Tech Companies' Net Zero Goals

- Scientific American, 2023, ***The AI Boom Could Use a Shocking Amount of Electricity*** (LINK)
- Sam Altman, 2024, ***Age of AI will require an 'energy breakthrough'*** (LINK)
- Microsoft, 2020, ***Microsoft will be carbon negative by 2030*** (LINK)
- Google, 2024, ***Google Commitment to net-zero carbon*** (LINK)
- Google, 2024, ***A new initiative with Microsoft and Nucor to accelerate advanced clean electricity technologies*** (LINK)
- Meta, 2024, ***Climate: We commit to reaching net zero emissions across our value chain in 2030*** (LINK)
- Amazon, 2024, ***Amazon's Climate Pledge – Net zero by 2040*** (LINK)
- Nvidia, 2024, ***NVIDIA Corporate Responsibility Report - Fiscal Year 2023*** (LINK)

Insights from Oil & Gas Horizontal Well Hydraulic Fracturing Characterization Projects

- Kevin T. Raterman et al., 2017, ***Sampling a Stimulated Rock Volume: An Eagle Ford Example***, URTeC paper 2670034 (LINK)
- Kevin T. Raterman, Yongshe Liu, and Logan Warren, 2019, ***Analysis of a Drained Rock Volume: An Eagle Ford Example***, URTeC paper 2019-263-MS, (LINK)
- Caner Karacaer et al., 2021, ***Multi-well Modeling in the Eagle Ford: An Investigation of Redevelopment, Infill and Refrac Opportunities***, URTeC paper 2021-5066-MS (LINK)
- Jordan Ciezobka and Debotyam Maity, 2023, **HFTS-1 Final Report** (LINK)
- Jordan Ciezobka and Debotyam Maity, 2022, **HFTS-2 Final Report** (LINK)

Example of technology integration capabilities that exist within oil & gas operators

Upstream: industry-leading, advantaged portfolio

Capital-efficient, high-return business with demonstrated execution excellence and advantaged, high-value oil and gas production

Upstream: *Strengthening energy security by expanding low-cost-of-supply oil and gas operations; ExxonMobil is creating long-term value by leveraging our unique competitive advantages*

Unconventional	Deepwater	LNG	Conventional	Heavy Oil
A unique resource where hydrocarbons are trapped in very tight rock and don't flow naturally; this requires non-traditional methods, such as horizontal drilling and hydraulic fracturing (fracking), to produce	*Deepwater resources are located at significant water depths offshore and are very complex; they require advanced subsea technologies and are typically produced and stored via Floating Production Storage and Offloading (FPSO) vessels before being shipped to market*	*Liquefied Natural Gas (LNG) business processes and cools natural gas to a liquid state for ease of storage and transportation to consumers across the world*	*Conventional resources are extracted using traditional drilling methods whereby natural pressure within the reservoir brings the oil and gas to the surface, and secondary recovery methods like water or gas injection can be used to maintain production*	*Heavy oil is denser than conventional crude oil; it can be extracted via mining process or with a technology that uses steam to heat the oil so it can flow*
ExxonMobil has applied its unmatched technical capabilities and experience to become the largest Unconventional producer in the U.S., with main assets in the Permian basin (Texas and New Mexico)	ExxonMobil has harnessed its global experience, deep knowledge base, and differentiated technology to build a deepwater presence in Guyana, Angola, Nigeria, and Brazil	ExxonMobil has more than 40 years of LNG experience supplying the global market, with interest in LNG facilities in Qatar, Papua New Guinea, Australia, Mozambique, and the U.S.	ExxonMobil has conventional operations in onshore and shallow water fields in Malaysia, Indonesia, Kazakhstan, Germany, Australia, and United Arab Emirates (UAE)	ExxonMobil has both oil mining and in-situ operations in Canada, including the Kearl heavy oil development, extracting value by deploying cutting-edge technology at scale

ExxonMobil

Slide from ExxonMobil's February 2026 investor presentation