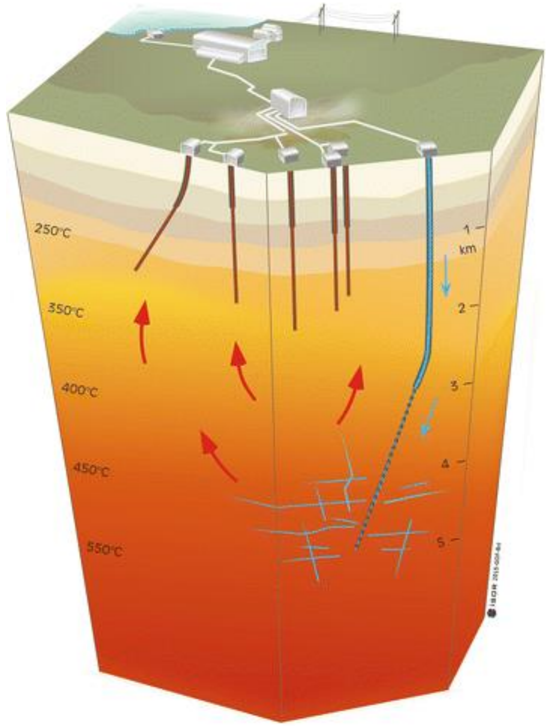
ARPA-E CHANGING WHAT'S POSSIBLE

# The Road to Superhot Geothermal

Robert Mellors,
Program Director
ARPA-E

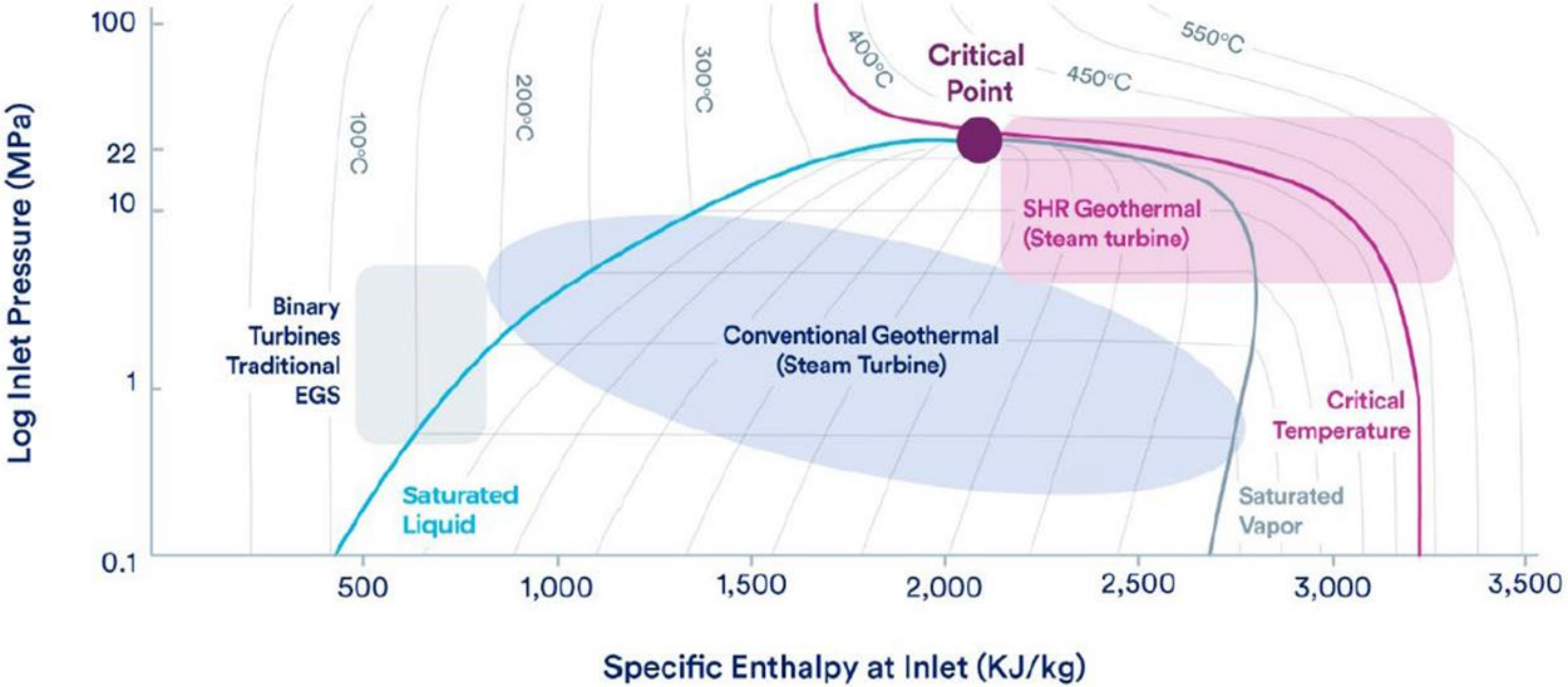
Nov 19, 2024
GEMS Workshop, San Antonio Texas



# Some definitions

Superhot rock – rock above 375° C (Cladouhos and Callahan, 2024) or enthalpy > 3000 KJ/kg (Gunnarson et al., 2024)

Supercritical (water) geothermal system – above critical point.

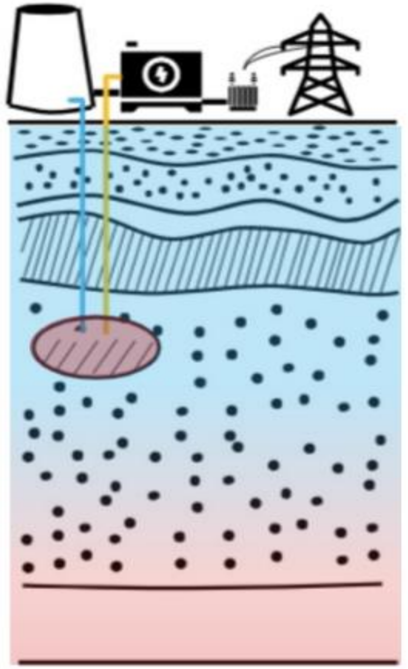



arpa-e CHANGING WHAT'S POSSIBLE

# Types of geothermal heat extraction

## Conventional

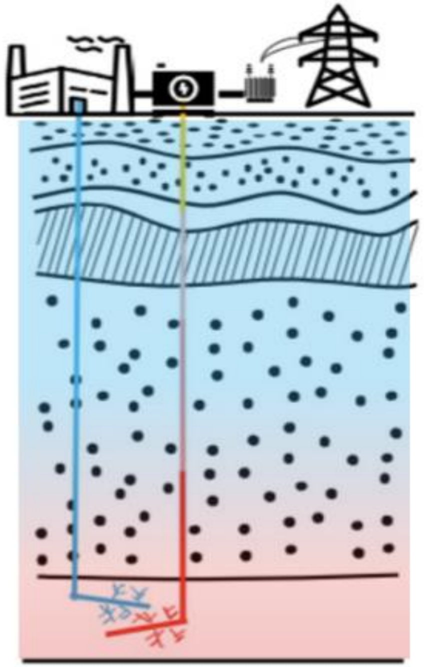
### Hydrothermal



- Fluids circulate openly through naturally occurring fractures
- Limited estimated total resource (~40 GW)
- ~4 GW on the grid today

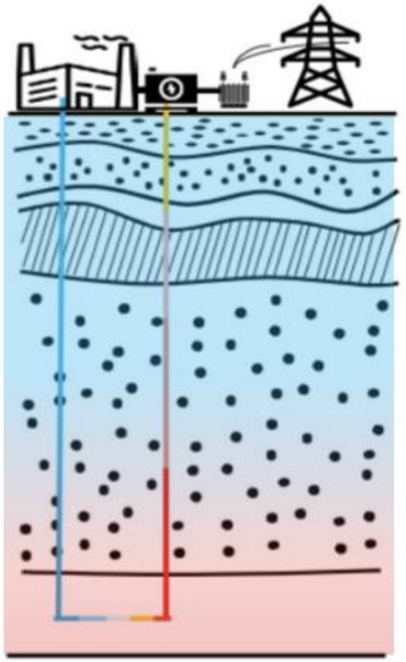
## Next-Generation

### Enhanced Geothermal Systems (EGS)



- Fluids circulate openly within a well pair connected by fractures engineered with hydraulic fracturing & horizontal drilling
- Large estimated total resource (5+ TW all next-generation geothermal)
- Scales through modular deployment of many well pairs

### Closed Loop Geothermal Systems

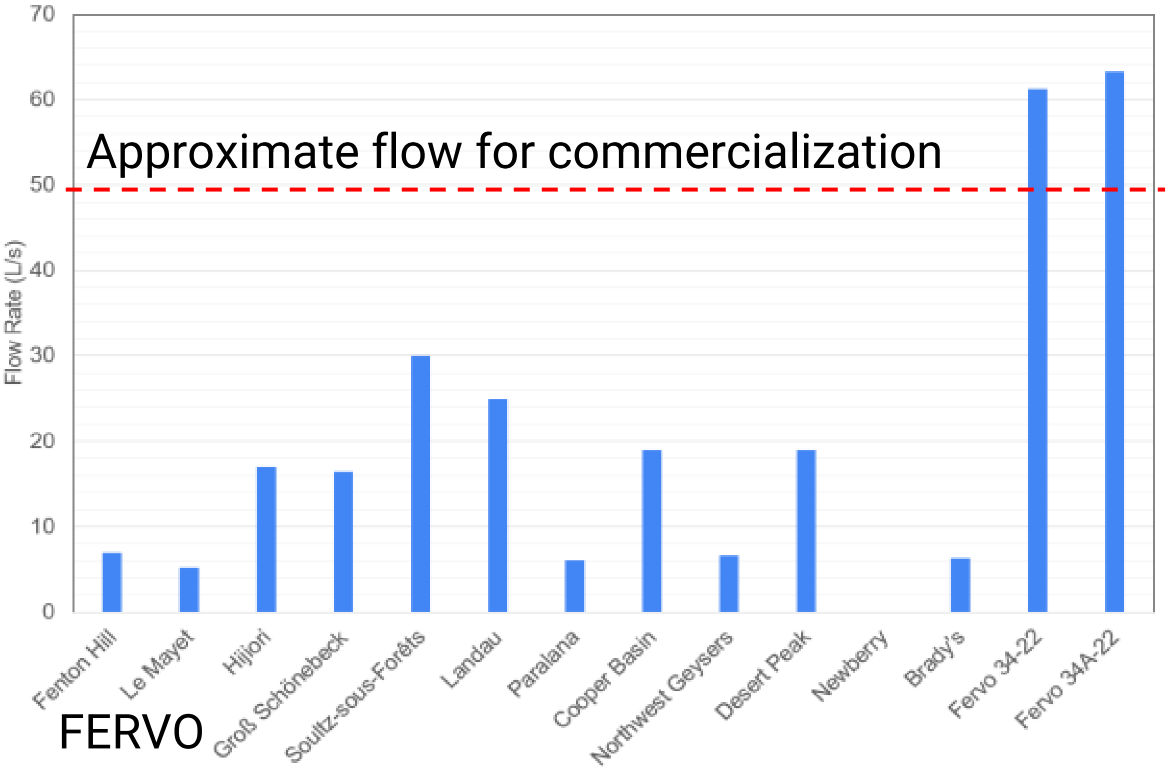


- Fluids circulate through a long series of closed wellbore loops permeating the subsurface
- Large estimated total resource (5+ TW all next-generation geothermal)
- Scales through modular deployment and increasing wellbore lengths



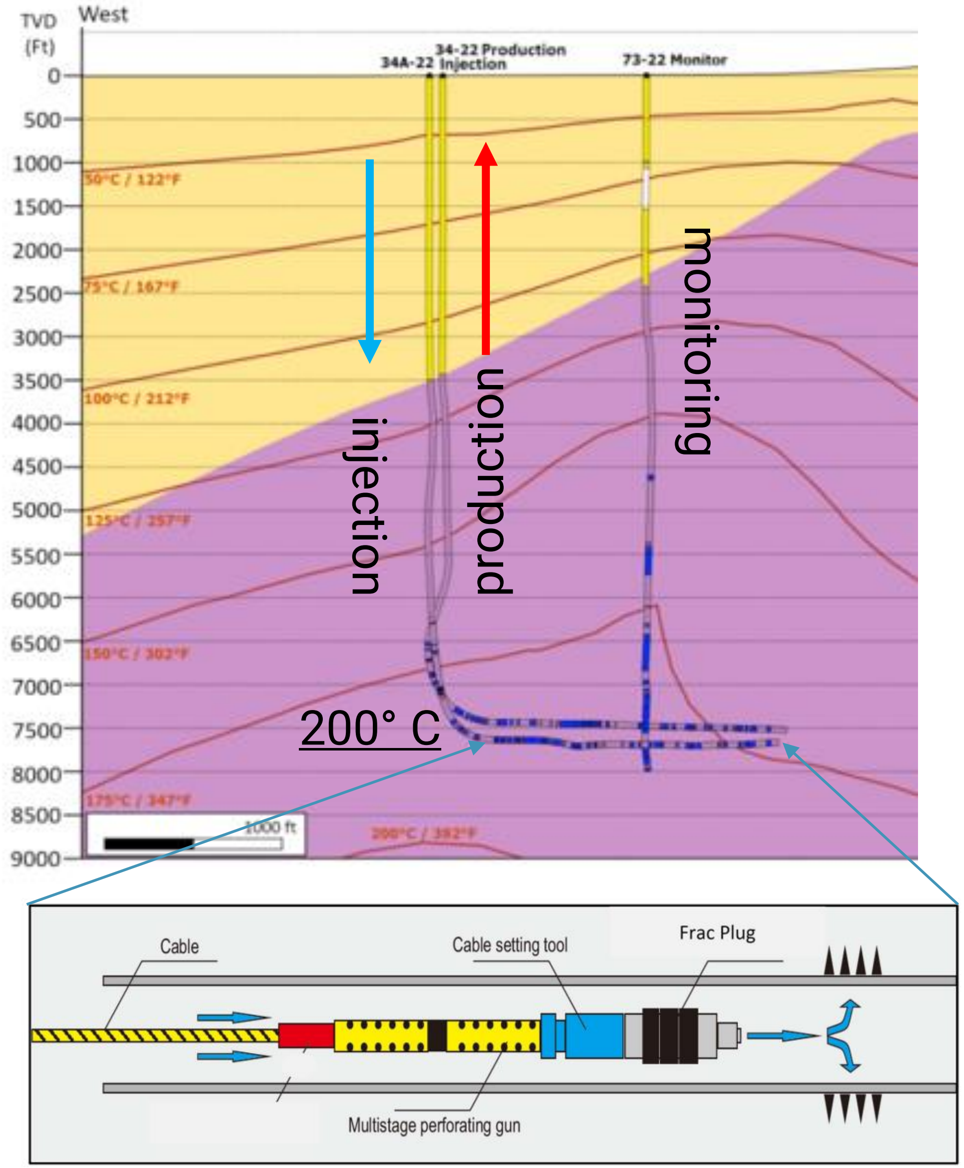
DOE Liftoff report, 2023

# Recent EGS success (not superhot)




FERVO

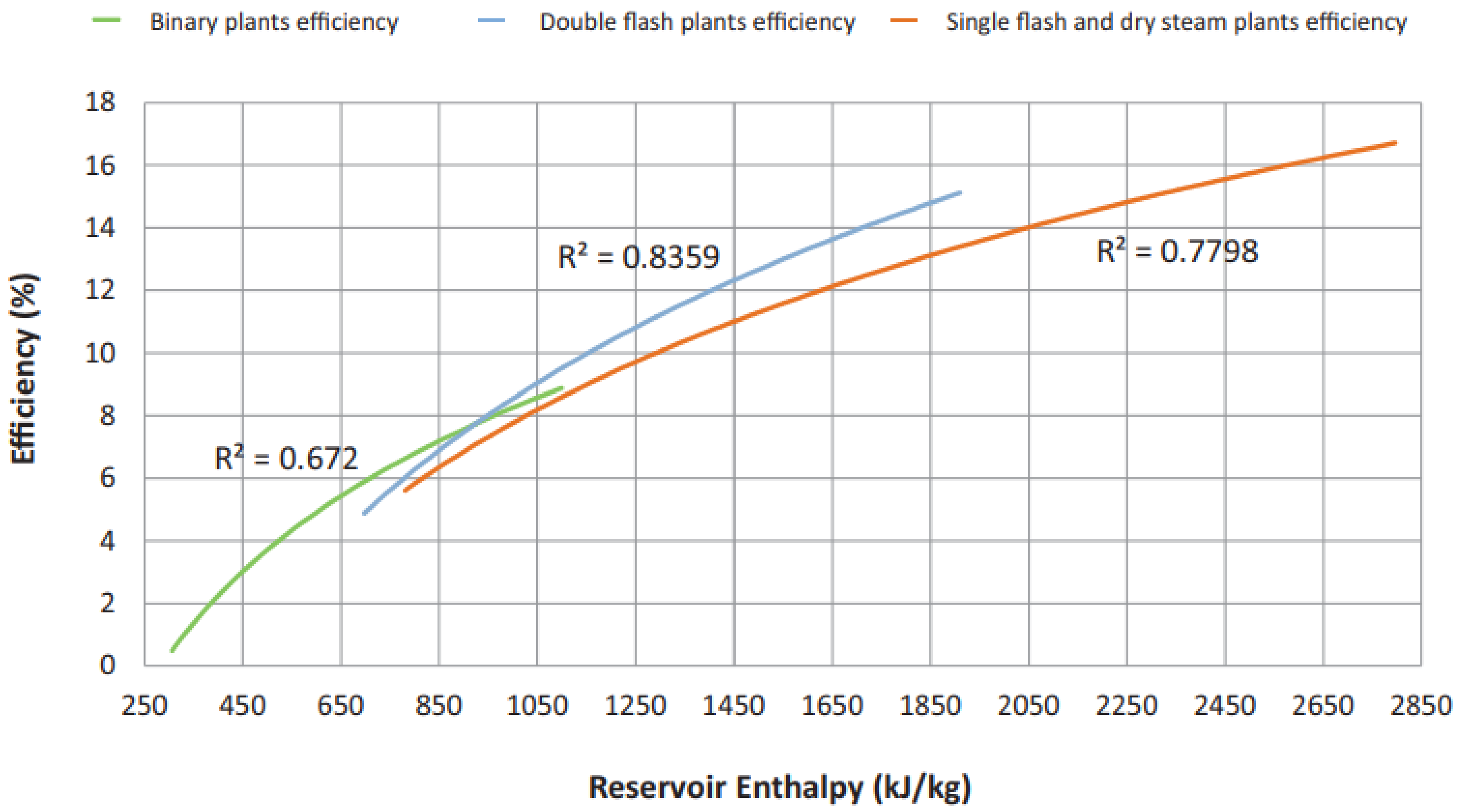
- Adapted state-of-the-art petroleum technology
- First-of-a-kind commercial EGS/storage facility
- 320 MW planned in 2026
- Permitting for 2 GW underway
- Reservoir temperature constrained by equipment limits




CHANGING WHAT'S POSSIBLE

# Why superhot?

- Larger available heat resource for EGS/AGS
- Higher enthalpy per kg of fluid
- Higher thermal to power efficiency (?)
- Lower LCOE (?)




Zarrouk and Moon, 2014

arpa·e CHANGING WHAT'S POSSIBLE

# EGS/AGS heat resource

$$H_{tot} = \int \rho c(T - T_0)\, dV$$

$$H_{recov} = r \int \rho c(T - T_0)\, dV$$

$$E = \eta r \int \rho c(T - T_0)\, dV$$

$$P = \frac{E}{\Delta T}$$

| | |
|---|---|
| $H_{tot}$ | total heat |
| $\rho$ | rock density **2728 kg/m³** |
| $c$ | rock heat capacity **0.77 kJ/kg/K** |
| $T$ | reservoir rock temperature **190° C** |
| $T_0$ | temperature at outlet of turbine **75° C** |
| $dV$ | volume |
| $r$ | thermal recovery from rock **35%** |
| $\eta$ | thermal to electric efficiency **15%** |
| $P$ | average power over lifespan |
| $E$ | total energy |
| $\Delta T$ | lifespan of facility **10 years** |

**Example: FERVO (FOAK, Blue Mountain)**
Volume: (1030 m)(540 m)(240 m) = 0.133 km$^3$
Reservoir temperature: ~190°C
Outlet temperature: 75°C => $\Delta T$ = ~115°C
Thermal recovery: 35% Thermal to electric: 15%
Lifespan: 10 years Power: **~5.1 MW**

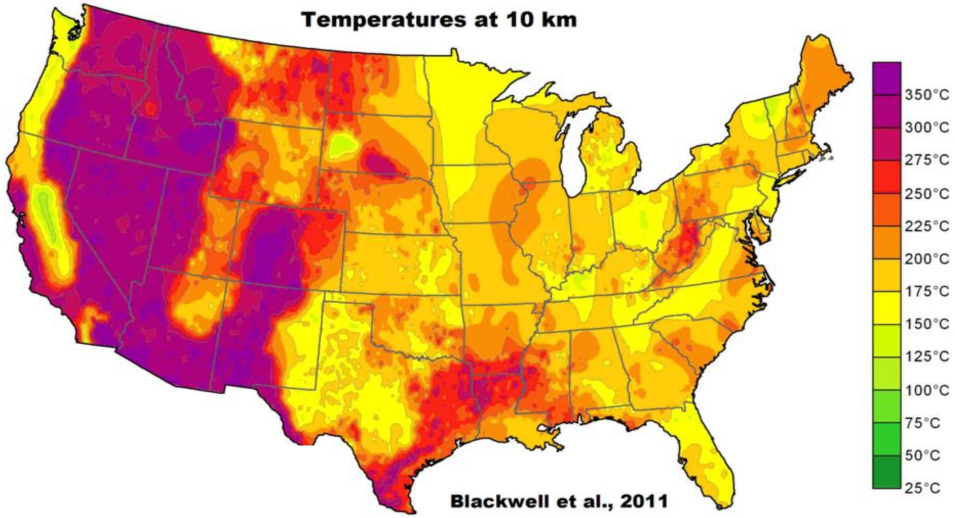
*What if the reservoir was 400° C?*
***ΔT = 325 °C*** ***Power: 14 MW***

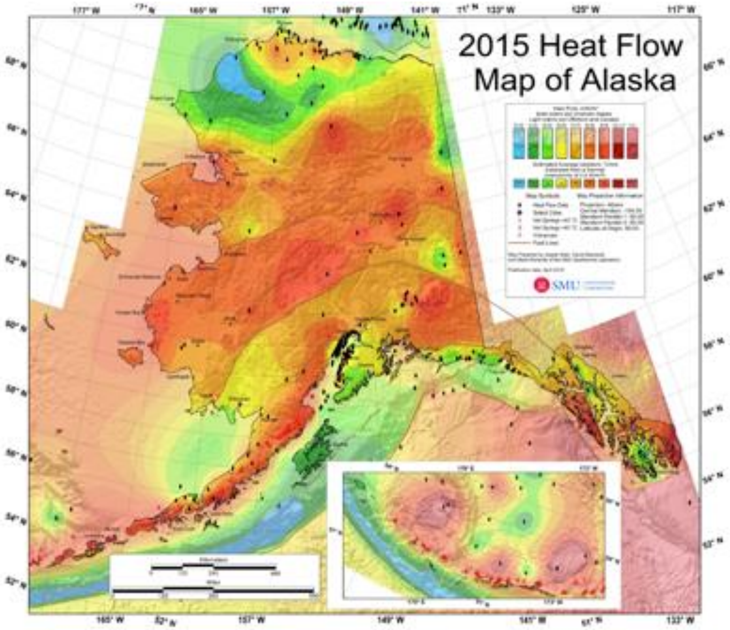
arpa·e CHANGING WHAT'S POSSIBLE

Fercho et al., 2023

# Geologic settings of superhot

- ‘shallow’ magmatic (<6 km)
  - High-temperatures (plus perhaps latent heat of crystallization*)
  - Limited spatial extent/resource in US (dozens? – GW resource)
- ‘deep’ (6 – 12 km)
  - Wide spatial availability (30% of US – TW resource)
  - Higher drilling/completion cost




*4.0 x 105 J kg-1

# Current R&D efforts in superhot and related efforts

- Iceland
- Japan
- New Zealand
- US

US DOE Geothermal Technology office (GTO) Mazama high-temperature field test

- 350 C in 2026
- 400 C in 2027

~ 20 wells drilled into superhot conditions
None have produced power

**Iceland Deep-Drilling Project (IDDP)**

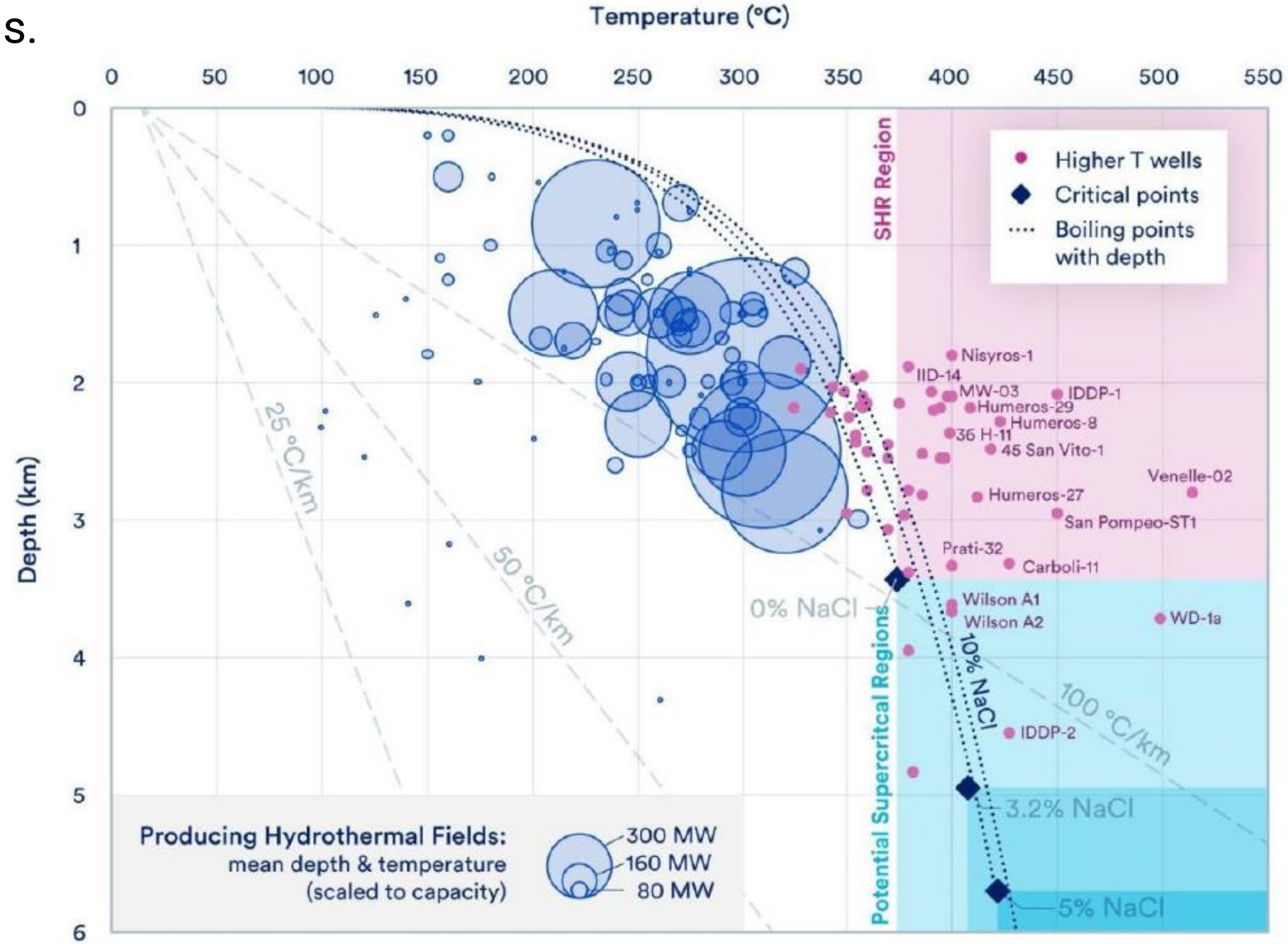
IDDP was launched by a consortium of funders and research institutes, including EU Horizon 2020, Reykjavik Energy, and Statoil. Its primary goal is to drill into super-hot temperatures for geothermal power production. Two wells have been drilled into temperatures >450°C, proving the feasibility of using conventional drilling systems to access superhot temperatures for geothermal energy production (Pearce & Pink, 2024).

**Japan Beyond-Brittle Project (JBBP)**

JBBP is a research project aiming to drill beyond the brittle-ductile transition (where rock changes from brittle to plastic deformation) and conduct well-creation experiments at >300°C. The specific aims are to study rock mechanics in these conditions, improve drilling and downhole monitoring techniques, and to demonstrate the feasibility of EGS reservoir creation in these conditions (Muraoka et al., 2014; Petty, 2020).

# Previous high temperature wells (>350 C)

1. ~20 wells; most failed in hours/days/months.
2. Drilling is possible to high temperatures (depths < 5 km).
3. Many problems with well stability “hostile well conditions”.
4. U.S. wells in Hawaii (Puna) and California (Geysers, Newberry, Salton Sea).


Black smoke is corrosion (well-head failed, tried to quench with cold water and then the casing collapsed from thermal shock)

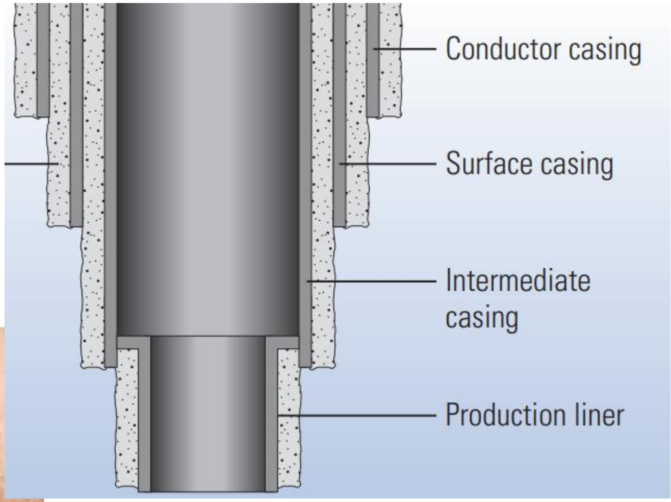
# Technology challenges for superhot

| Area | Current state-of-the-art | Impact on success | Gaps/possible solutions |
|---|---|---|---|
| Exploration and siting | Mature technologies | Low | Geophysical/geological sensing and analysis (AI; quantum sensors). |
| Drilling and borehole operations. | Workable; could be better. Horizontal steering poor. | Moderate to high. | Higher temperature electronics, elastomers. Cooled drilling mud and insulated drill pipe.. |
| Reliable well design and construction. | Low for long-term (> 10 years) | High | Casing, cements under thermal cycling and corrosion [materials]. Lab tests. |
| Heat extraction | Low; may require boreholes for testing. | High | Rock physics at high temperature, pressure (numerical models, lab tests fracturing; closed loop). |
| Power generation | Mature (turbines); other approaches are untested. | Moderate | Innovative solutions (alternate working fluids, thermoelectric). |

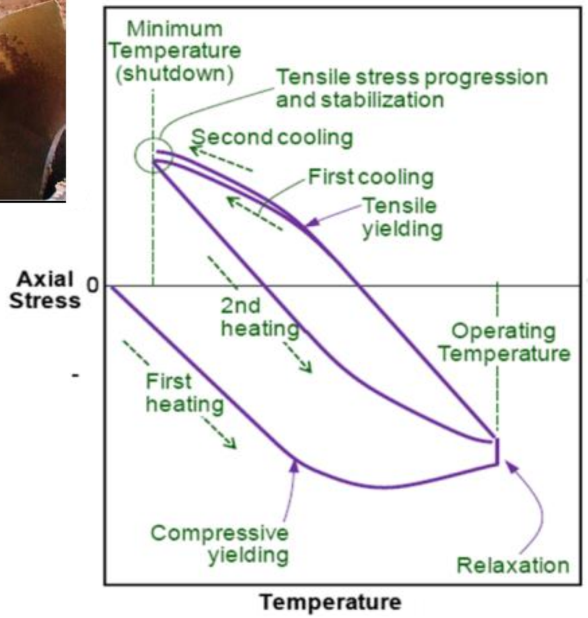
Most existing drilling and borehole tools designed for less than 200° C
Must use chilled mud to accommodate higher temperatures.

# Well design and completion: casing and cement

- Casing
  - Changes in tensile strength (5% at 300° C)
  - Thermal expansion/cycling/shock (~1.8 m/km/150° C)
  - Corrosion (up to 4 mm/year)
  - Connection failure
- Wells need to last 15-20 years
- Correct cement and installation is essential for casing and well integrity.
- Portland cement may fail at about 350° C and subject to corrosion.




Hole, 2008



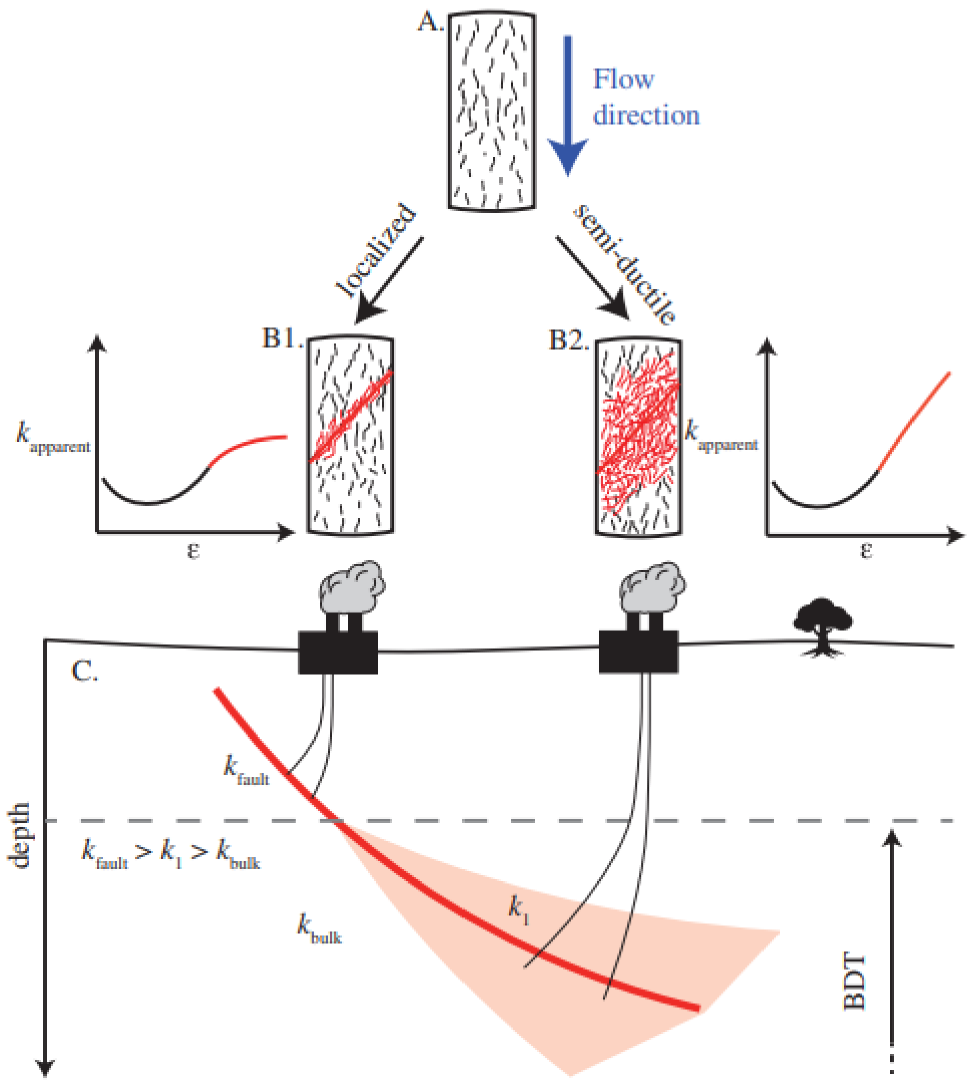

Droesseler et al., 2021

*The casing program is the most crucial feature that influences successful drilling operations and the longevity of the future geothermal fluid production*. Kruszewski and Wittizg, 2018

arpa·e CHANGING WHAT'S POSSIBLE

# Rock physics changes at high temperature

- Ductile (rather than brittle) deformation at higher temperatures.
  - Dependent on rock composition.
  - Fracture geometry and longevity uncertain.
  - Effectiveness of proppants uncertain.
- Effect of supercritical water on rock chemistry poorly understood.
- Risk of induced seismicity uncertain.



# Supercritical power production: what is possible?

- Supercritical (and ultra-supercritical) coal plants demonstrate efficiencies of 44%
- Can supercritical geothermal achieve this?
  - Scenario 1: Supercritical water from reservoir to turbine
    - High pressure and temperature along entire path
    - Geothermal fluids will contain impurities/particles/NCG
  - Scenario 2: supercritical to superheated steam in borehole
    - Direct to turbine?
    - Wash before turbine?
    - Heat exchanger/binary?
  - Scenario 3:
    - Alternate working fluid (sCO2?)
    - Other?

**15% < ??? < 44%**

# Geofluids

- Hydrothermal geothermal fluids vary in composition.
  - Will cause corrosion and scaling
  - Some hydrothermal fields (e.g, Salton Sea, Iceland IDDP) have extremely hostile fluids.
  - Contain NCG as well as particulates and dissolved solids, all of which will impact the performance of a turbine.
  - Higher temperatures amplify these problems.
- EGS fluids may be less damaging.
- AGS fluids should be very clean.

**TABLE 1. SIMULATED GEOTHERMAL BRINE COMPOSITION**

| Temperature | Phase | Component | Amount | Duration |
|---|---|---|---|---|
| 304 °C | Gas | $CO_2$ | 205 $psi_a$ | 30 days |
| | | $H_2S$ | 16.6 $psi_a$ | |
| | | $N_2$ | 15.9 $psi_a$ | |
| | | Water vapor | 776.4 $psi_a$ | |
| | Liquid | NaCl | 4 molar (233.8 g/L) | |
| | | KCl | 0.45 molar (33.5 g/L) | |
| | | $CaCl_2 \cdot 4H_2O$ | 20,000 ppm $Ca^{2+}$ (73.4 g/L) | |
| | | $MnCl_2 \cdot 4H_2O$ | 2,000 ppm $Mn^{2+}$ (7.2 g/L) | |
| | | $FeCl_2 \cdot 4H_2O$ | 2,000 ppm $Fe^{2+}$ (7.1 g/L) | |
| | | $NaHCO_3$ | 3.01 g/L | |
| | | Total $Cl^-$ | 198,270 ppm $Cl^-$ | |
| | | pH | 5.51 @ RT 4.41 at 580 °F predicted | |

- Scenario 1 Fenton Hill: 1718 ppm TDS, 0.05% NCG
- Scenario 2 “Fresh” water: 500 ppm TDS, 0.003% NCG
- Scenario 3 IDDP-1 Krafla: 70 ppm TDS, 0.08% NCG



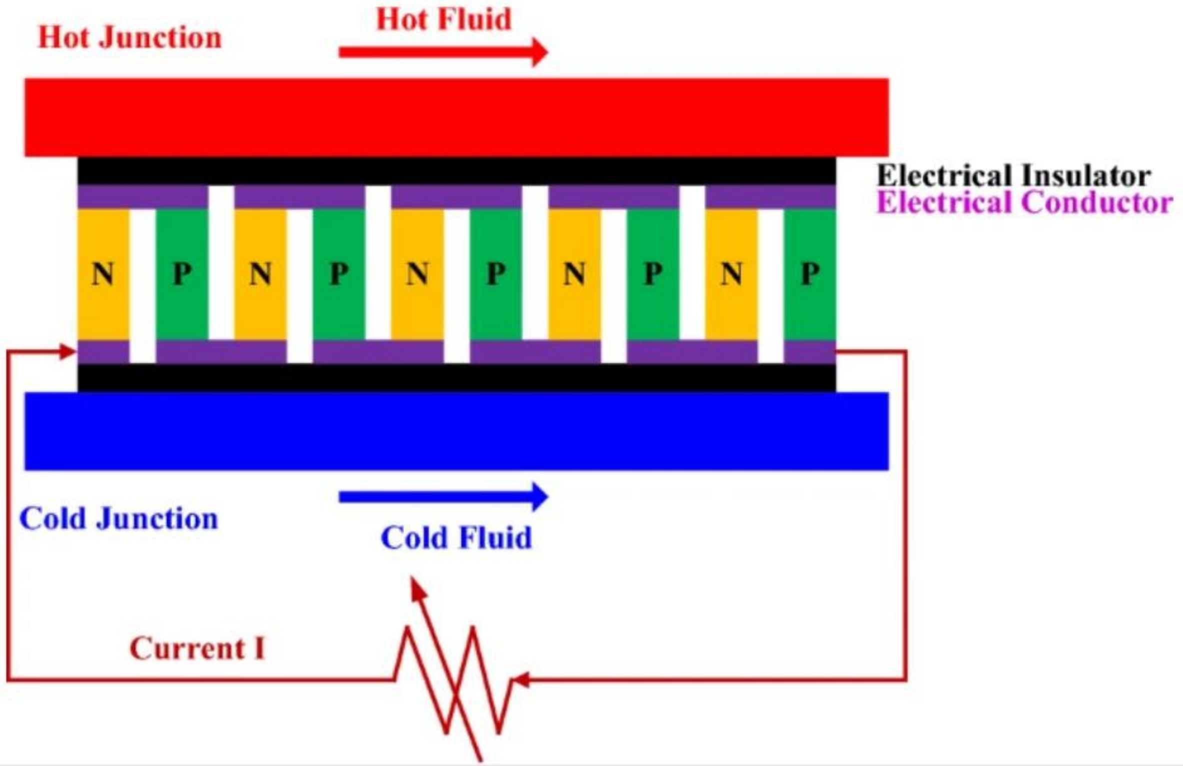
https://www.materialsperformance.com/articles/material-selection-design/2019/02/testing-corrosion-resistant-alloys-for-use-in-geothermal-power-plants

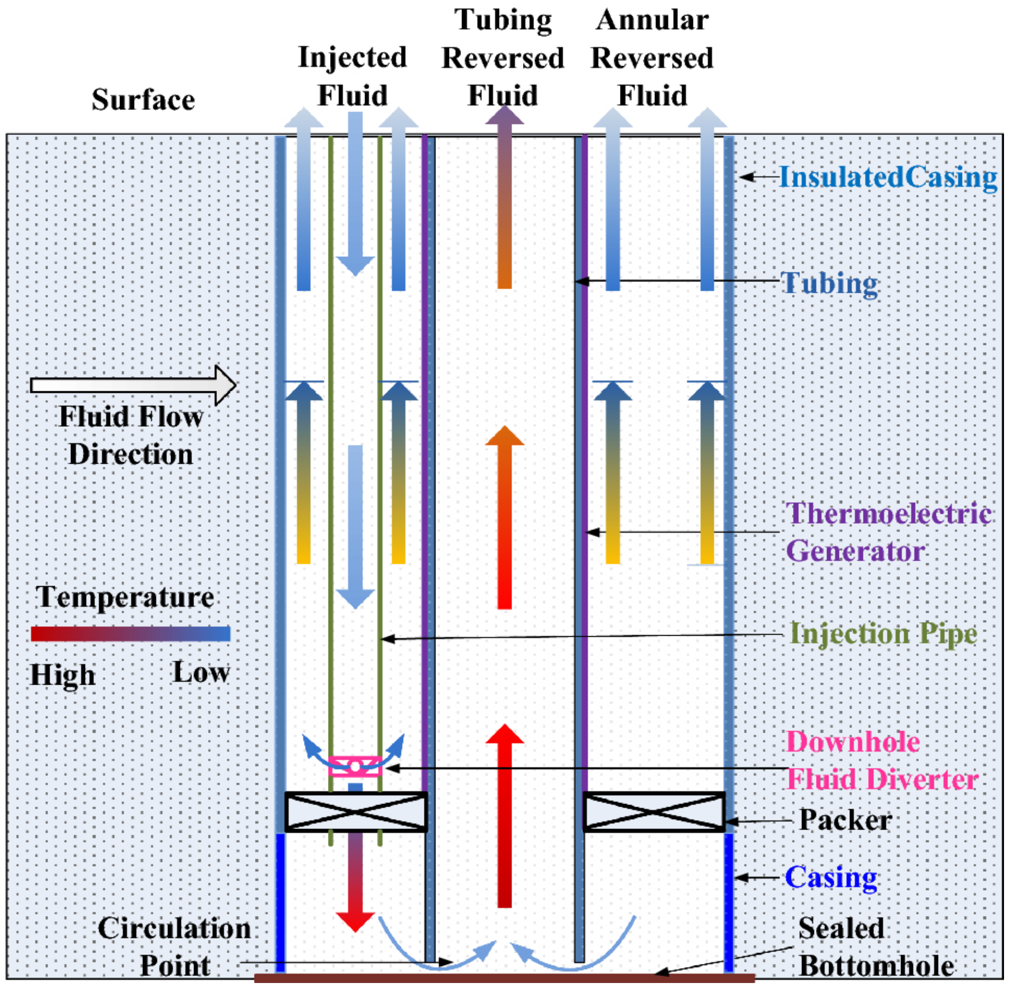
# Examples

- *“Acidic gases can become entrained in steam in hydrothermal/magmatic settings. For example, the Iceland Deep Drilling Project (IDDP) I well at Krafla experienced casing failure as a result of hydrochloric acid entrained in the production steam. When vapor condensed, extremely acidic water droplets corroded the steel casing” (Brown et al, 2024)*

Kruszewski and Wittig, 2018

# Non-turbine solutions solutions: thermoelectric coaxial borehole



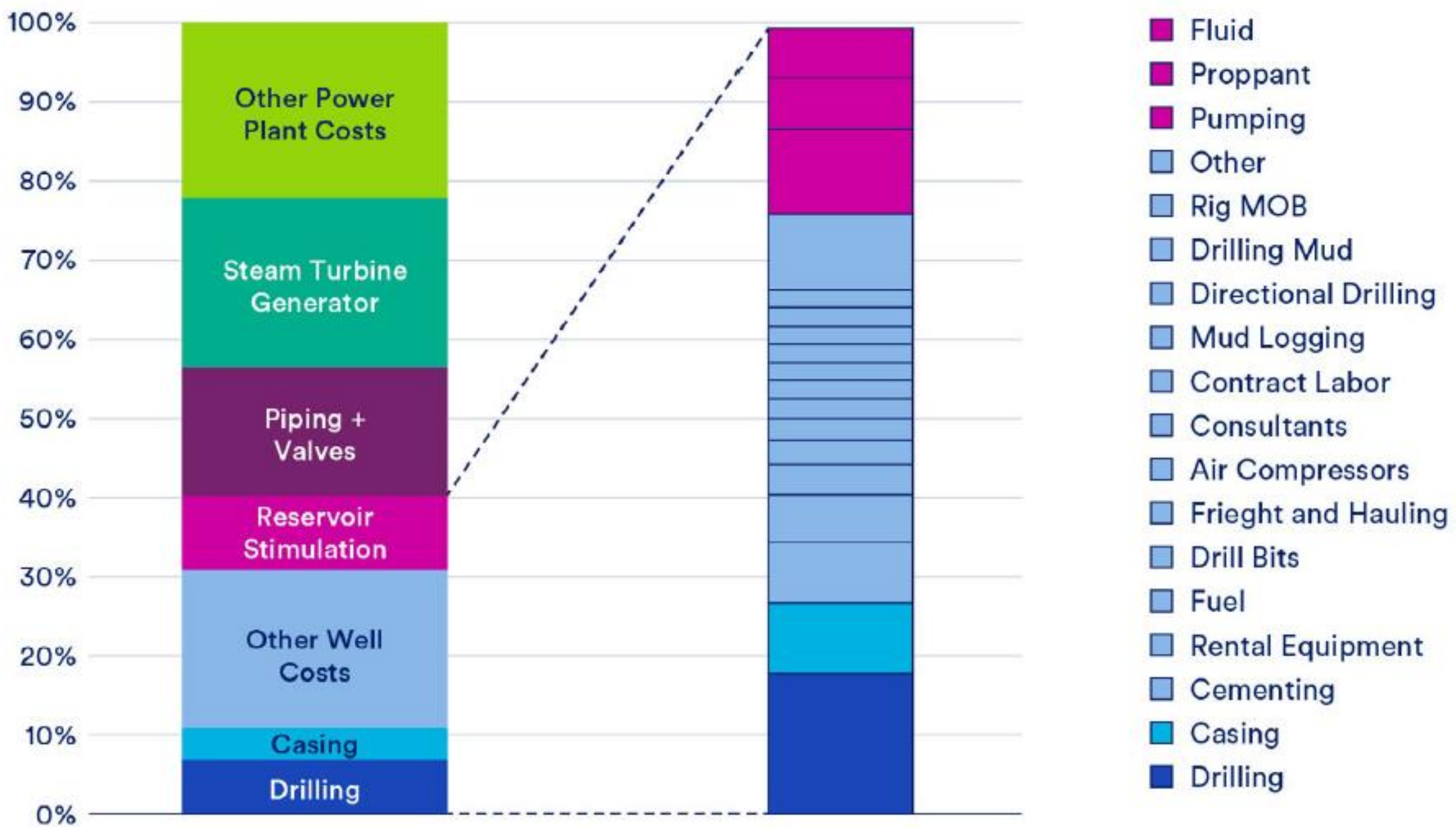

Qiao, Y., Shi, K. & Liu, J. Analytical study of integrating downhole thermoelectric power generation with a coaxial borehole heat exchanger in geothermal wells. *Sci Rep* **14**, 505 (2024). https://doi.org/10.1038/s41598-024-51226-0

arpa·e CHANGING WHAT'S POSSIBLE

# Some superhot power production possibilities

- Machinery
  - Binary - heat exchanger, mitigate turbine damage
  - Dry steam - efficient, but challenging for turbines
  - Supercritical steam - most efficient, but challenging for pipes and turbines
  - Cooling - air or water
- Innovative
  - Supercritical $CO_2$
  - Thermoelectric
- Storage and grid
  - Storage provides ancillary revenue stream
  - Grid connections may take time

# Techno-economics: Capex estimate for superhot



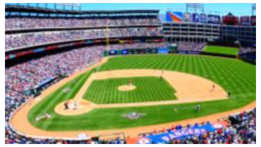

A Preliminary Techno-Economic Model of Superhot Rock Energy, 2024, CATF

# Conclusions and questions

- Superhot geothermal is possible but with some challenges
- State-of-the-art power facilities may be able to handle superhot/supercritical.
  - Scrubbing and fluid handling
  - Designs for power conversion and cooling
  - **Need solid estimates of possible efficiencies**
  - **Need constraints on fluid composition and chemistry**
- Surface facilities represent a significant portion of the capex (and opex)
- Path forward
  - Address issues, increase efficiency
  - Decrease costs (modular solutions, technical advances)
  - Alternate solutions

What efficiency might be possible with a superhot geothermal plant?
What are the challenges? (design, materials, cooling)
What are the costs?
What needs to be done?
What other industries can we leverage? (nuclear?)

# Total resource is huge; what might be possible?

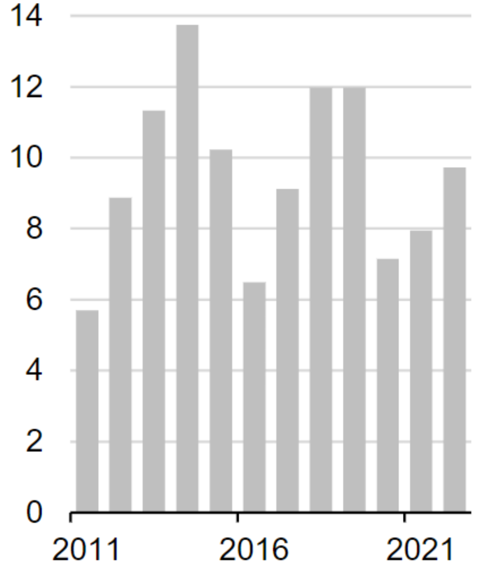


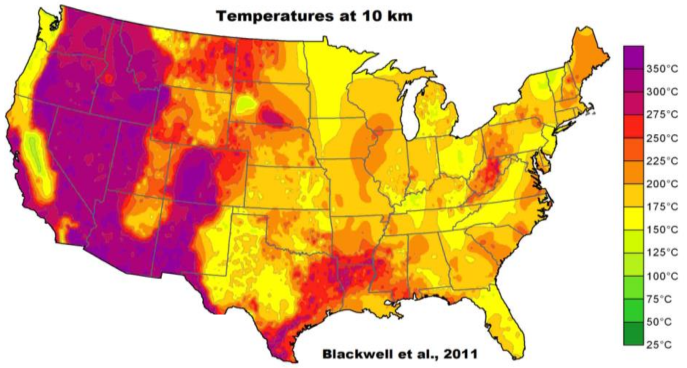
Using current oil and gas drilling as an example:

- ~10,000 wells per year currently drilled
- Average length: 2 km
- Assume:
  - All wells are drilled for geothermal instead
  - ~5,000 well pairs
  - Current EGS technology:
    10 MW/well pair – adds 50 GW/year
  - Superhot (assuming 2-3X):
    adds 100-150 GW/year

  [drilling costs will be higher].

**Annual number of new crude oil wells in oil bearing basins (2011–2022)**
thousands of wells




arpa·e
CHANGING WHAT'S POSSIBLE

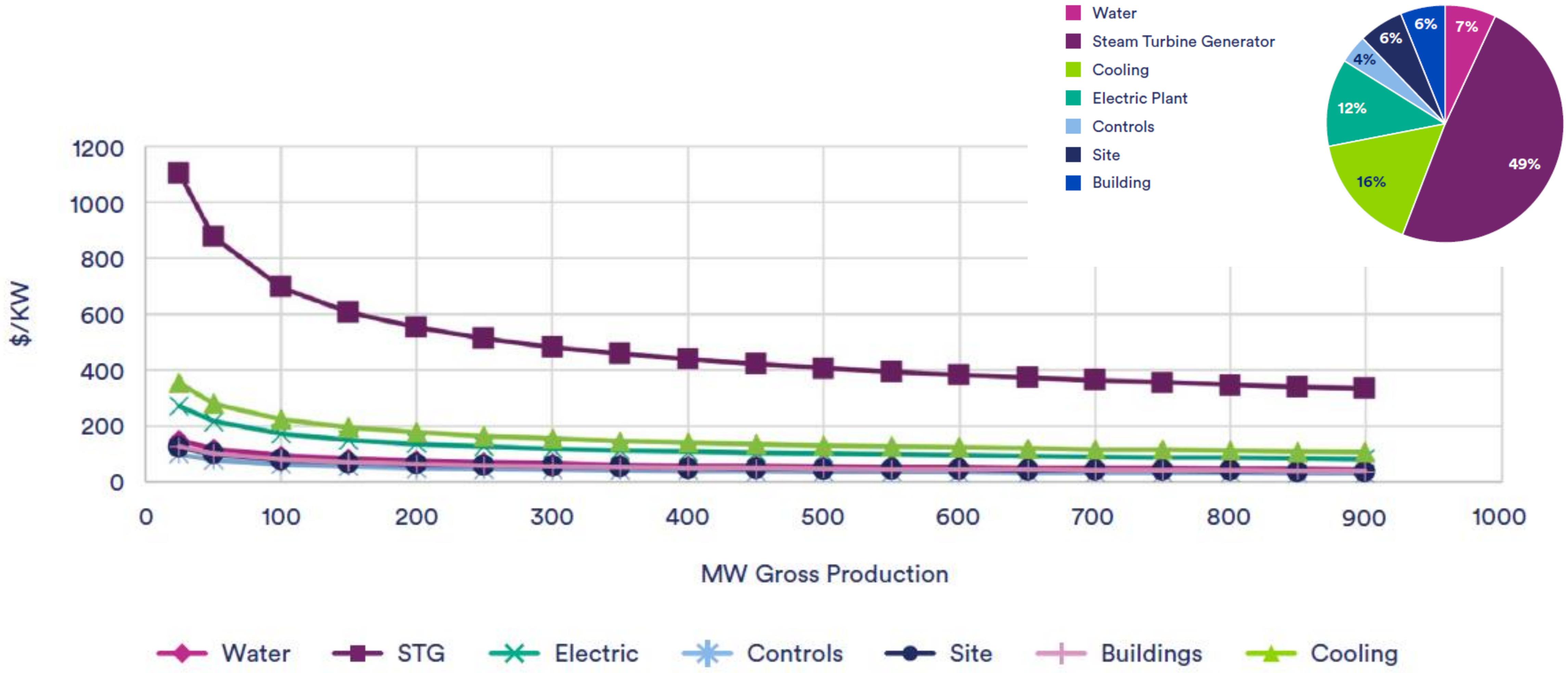
https://www.eia.gov/todayinenergy/detail.php?id=61523

# References


- Brown, D., C. Jacobs, J. J, Urbank, J. Hill, Clean and T. Rogers, Clean Air Task Force Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Power Production https://cdn.catf.us/wp-content/uploads/2024/05/20144617/shr-bridging-gaps-power-production.pdf.
- Cladouhos, T. T., and O. A. Callahan, 2024, Heat Extraction from SuperHot Rock - Technology Development, PROCEEDINGS, 49 th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, 2024 SGP-TR-227.
- Droessler, M., G. Tao , K. Hamilton, B. Skelton, and M. Yoshikawa, 2020, Casing Connection Evaluation for High-temperature Geothermal Applications – A Case Study, Proceedings World Geothermal Congress 2020+1 Reykjavik, Iceland, April - October 2021
- Fercho , S., G. Matson, E. Mcconville, G. Rhodes, R. Jordan, J. Norbeck, Geology, Temperature, Geophysics, Stress Orientations, and Natural Fracturing in the Milford Valley, UT Informed by the Drilling Results of the First Horizontal Wells at the Cape Modern Geothermal Project, PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, 2024 SGP-TR-227.
- Gunnarsson, G., A. Pálsdóttir, K. R. Ragnarsdóttir, B Friðriksson, 2024, Towards Utilization of Superhot Geothermal Resources – the IDDP Project and Beyond, PROCEEDINGS, 49 th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, 2024 SGP-TR-227
- Hole, H., 2008, Geothermal well design: Casing and wellhead, Petroleum Engineering Summer School, Dubrovnik, Croatia. Workshop #26 June 9 – 13, 08
- Qiao, Y., Shi, K. & Liu, J. Analytical study of integrating downhole thermoelectric power generation with a coaxial borehole heat exchanger in geothermal wells. *Sci Rep* **14**, 505 (2024). https://doi.org/10.1038/s41598-024-51226-0
- Reinsch, T., Dobson, P., Asanuma, H. *et al*. Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities. *Geotherm Energy* **5**, 16 (2017). https://doi.org/10.1186/s40517-017-0075-y
- Kruszewski, M. and V. Wittig, 2018, Review of failure modes in supercritical geothermal drilling projects, Geotherm Energy (2018) 6:28 https://doi.org/10.1186/s40517-018-0113-4


arpa·e
CHANGING WHAT'S POSSIBLE

# Techno-economics: Relative costs




A Preliminary Techno-Economic Model of Superhot Rock Energy, 2024, CATF

arpa·e CHANGING WHAT'S POSSIBLE