Advancements in Geothermal Technology: Lessons from Oil & Gas

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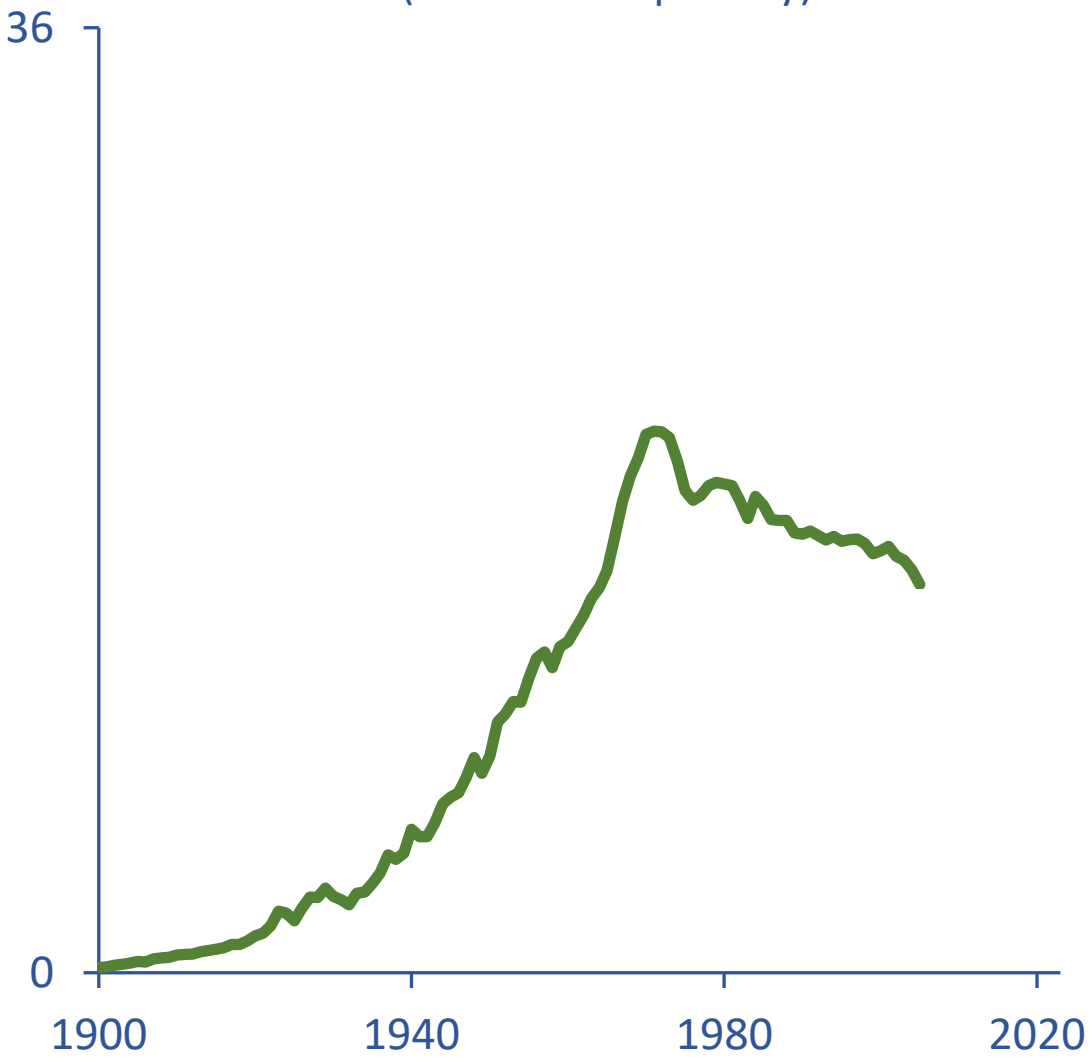
Technology Advancements: Lessons from Oil & Gas

- **Lesson 1:** Crises often spur innovation
- **Lesson 2:** Simple advancements can have a very large impact
- **Lesson 3:** Rapid experimentation is the key to rapid progress

At the turn of the century, America was grappling with an energy supply crisis

U.S. Oil & Gas Production

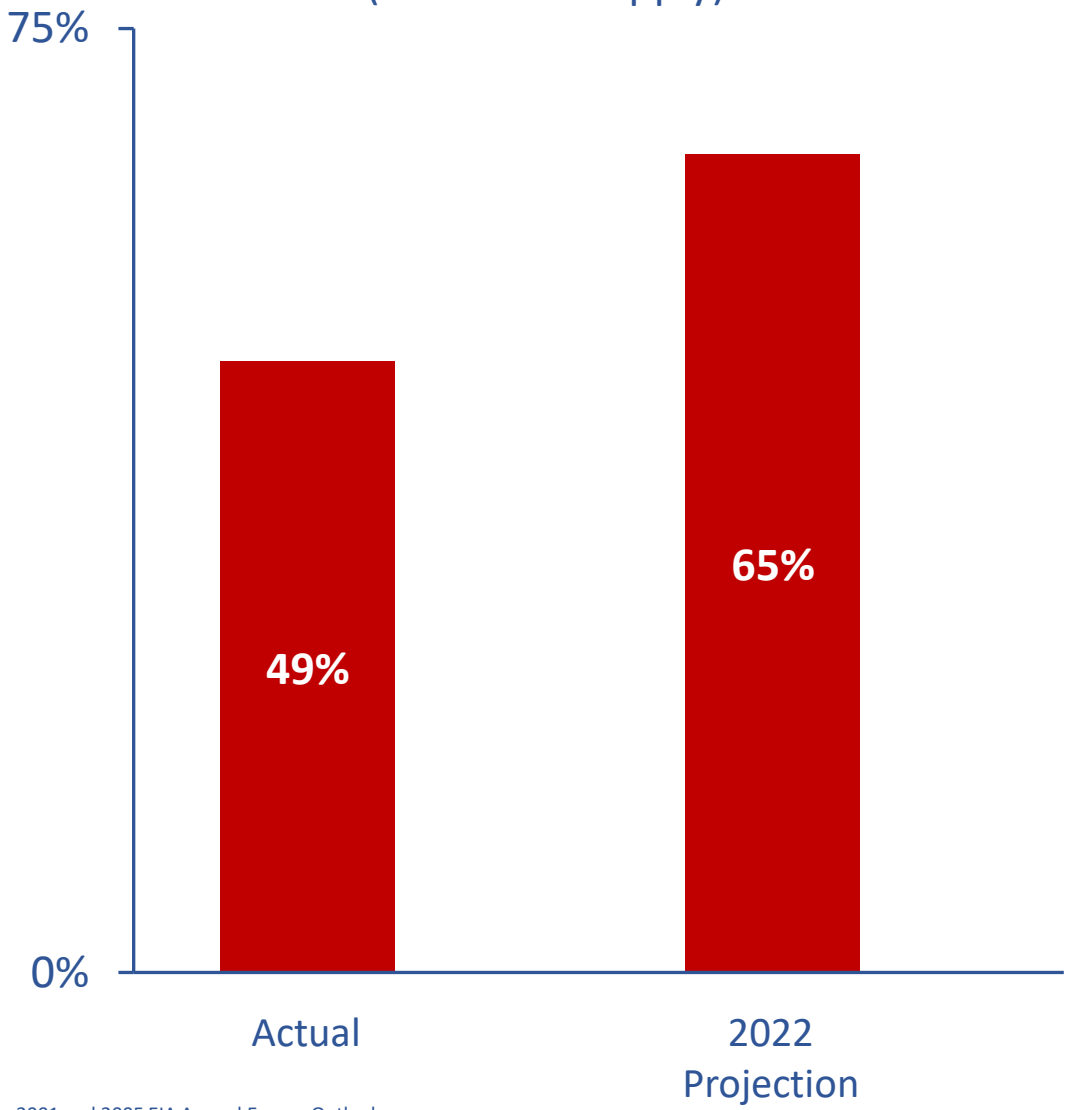
(Million BOE per day)



Source: Post 1965 from World Energy 2024 report; Pre-1965 oil production from EIA; Pre-1965 gas volumes estimated from multiple sources

U.S. Oil & Gas Net Imports

(% of Total Supply)

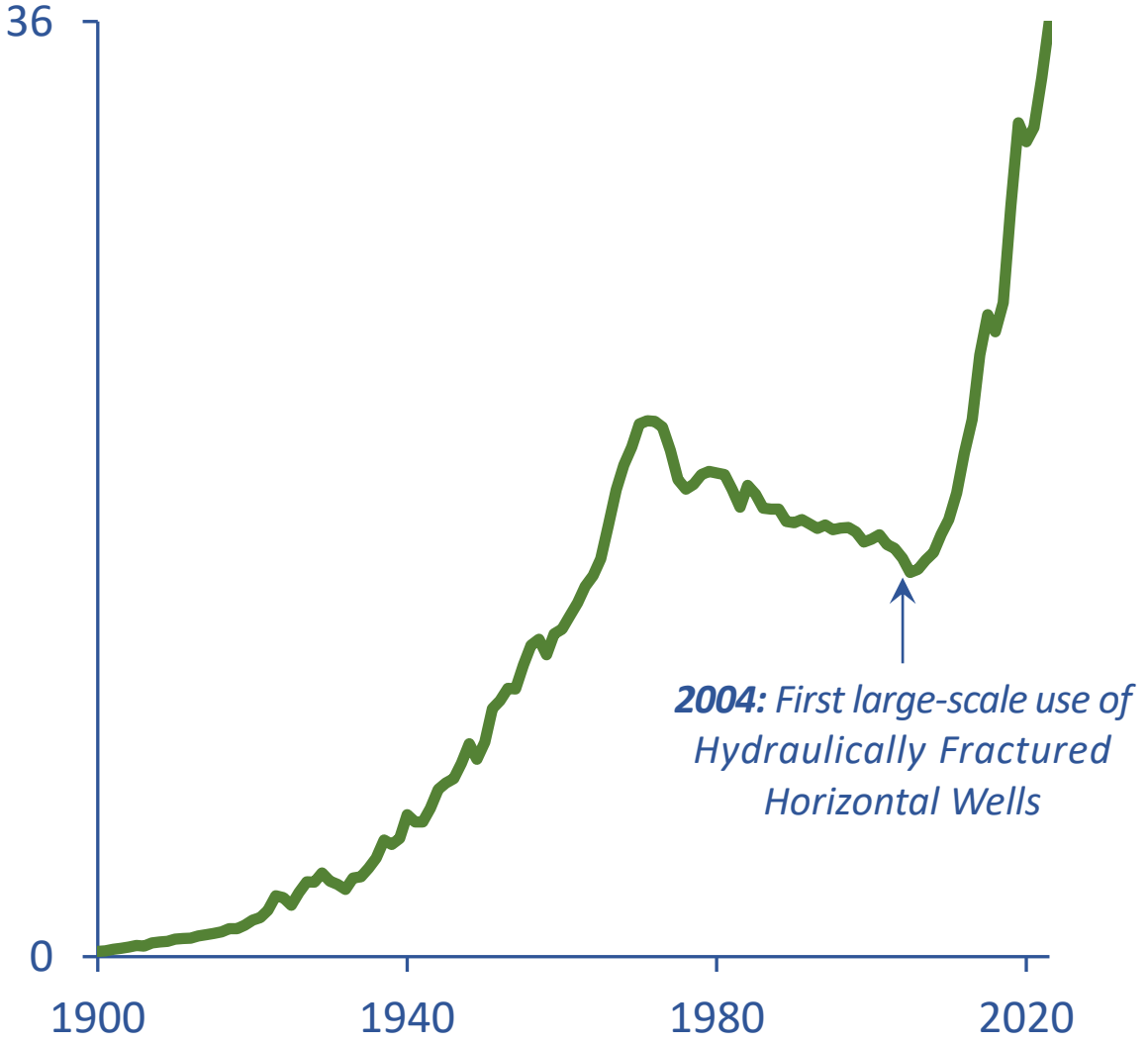


Source: 2001 and 2005 EIA Annual Energy Outlooks

Production from unconventional reservoirs solved the crisis in an unexpected way

U.S. Oil & Gas Production

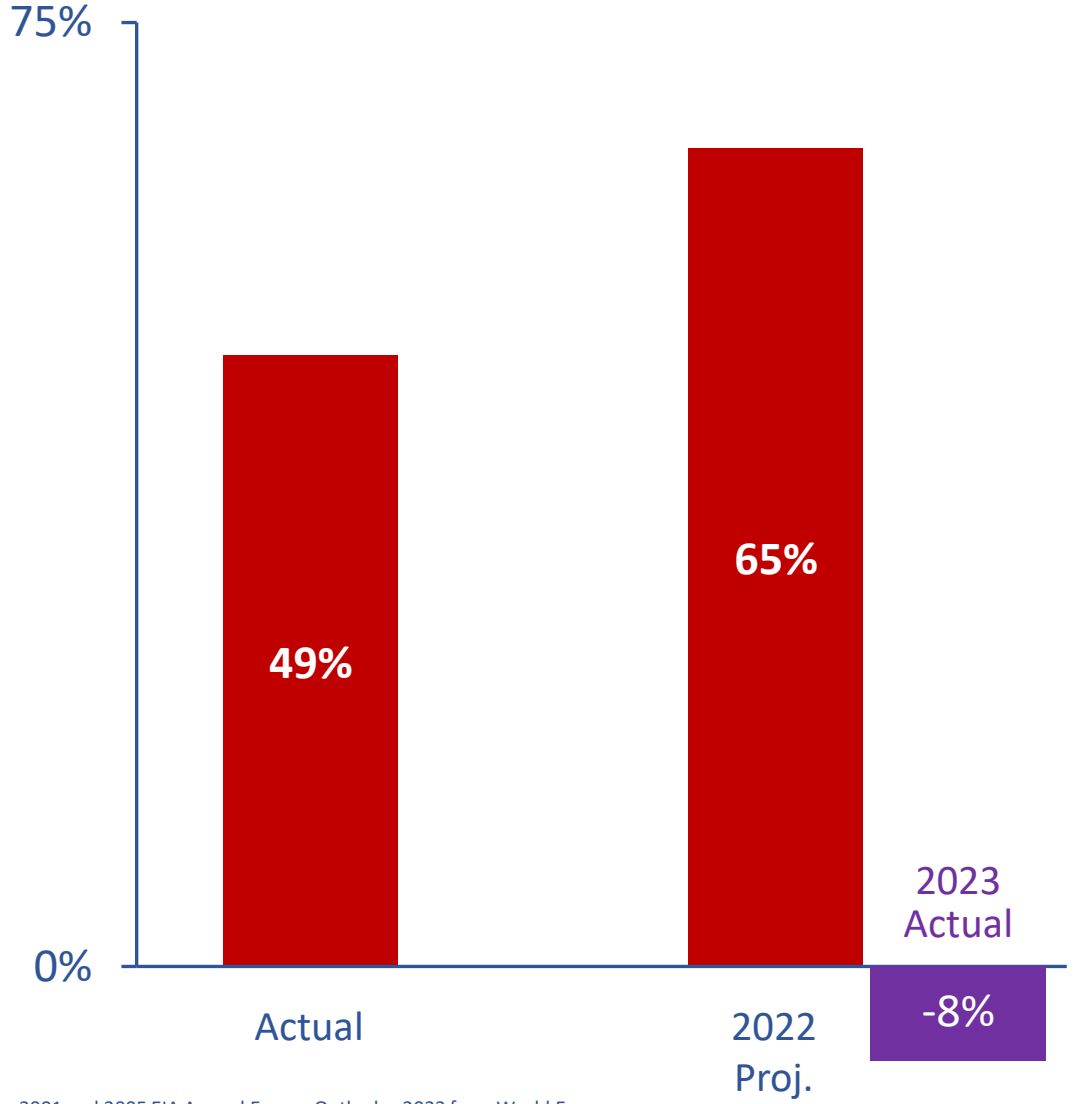
(Million BOE per day)



Source: Post 1965 from World Energy 2024 report; Pre-1965 oil production from EIA; Pre-1965 gas volumes estimated from multiple sources

U.S. Oil & Gas Net Imports

(% of total consumption)

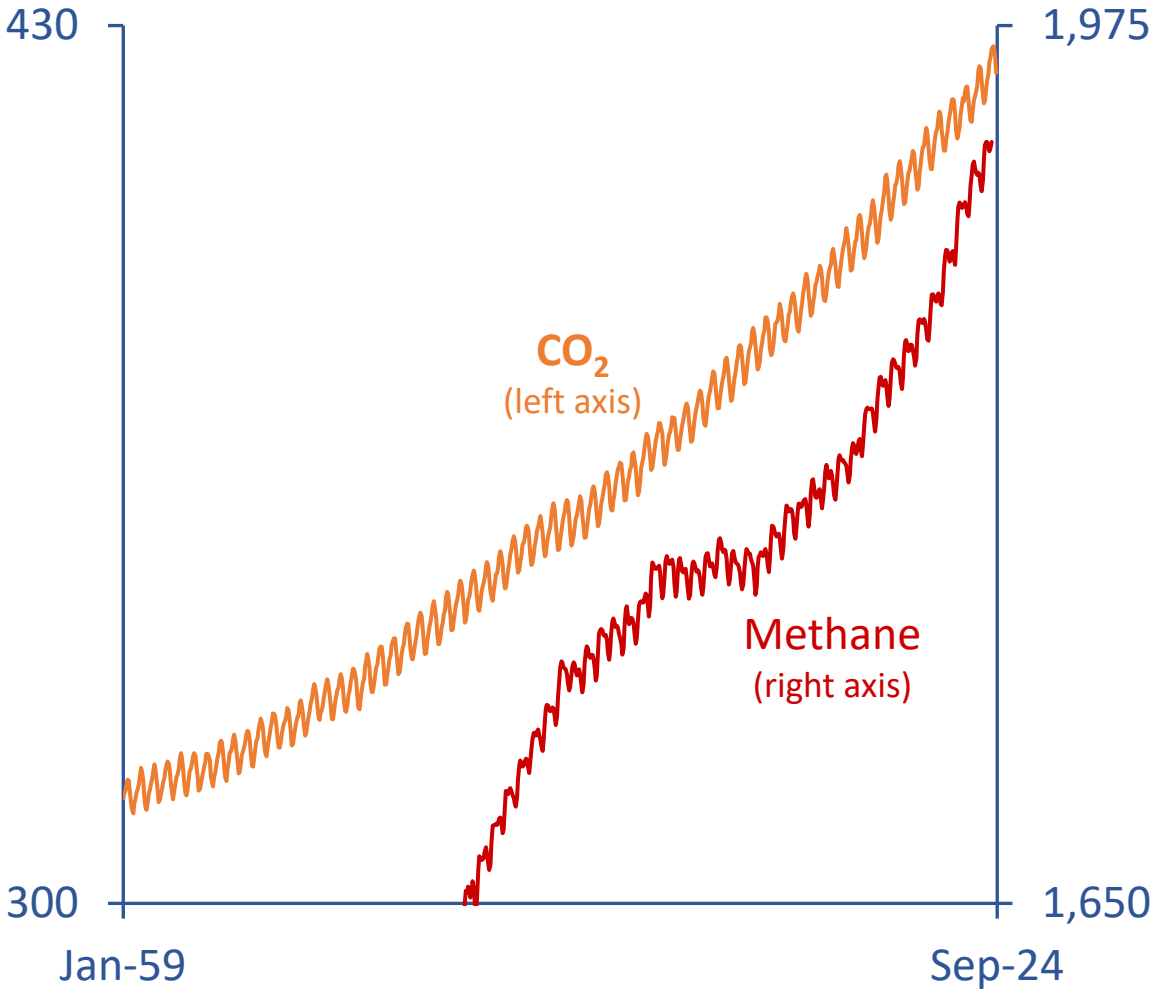


Source: 2001 and 2005 EIA Annual Energy Outlooks; 2023 from World Energy

Today mankind is grappling with a different type of energy crisis

Atmospheric GHG levels are increasing rapidly

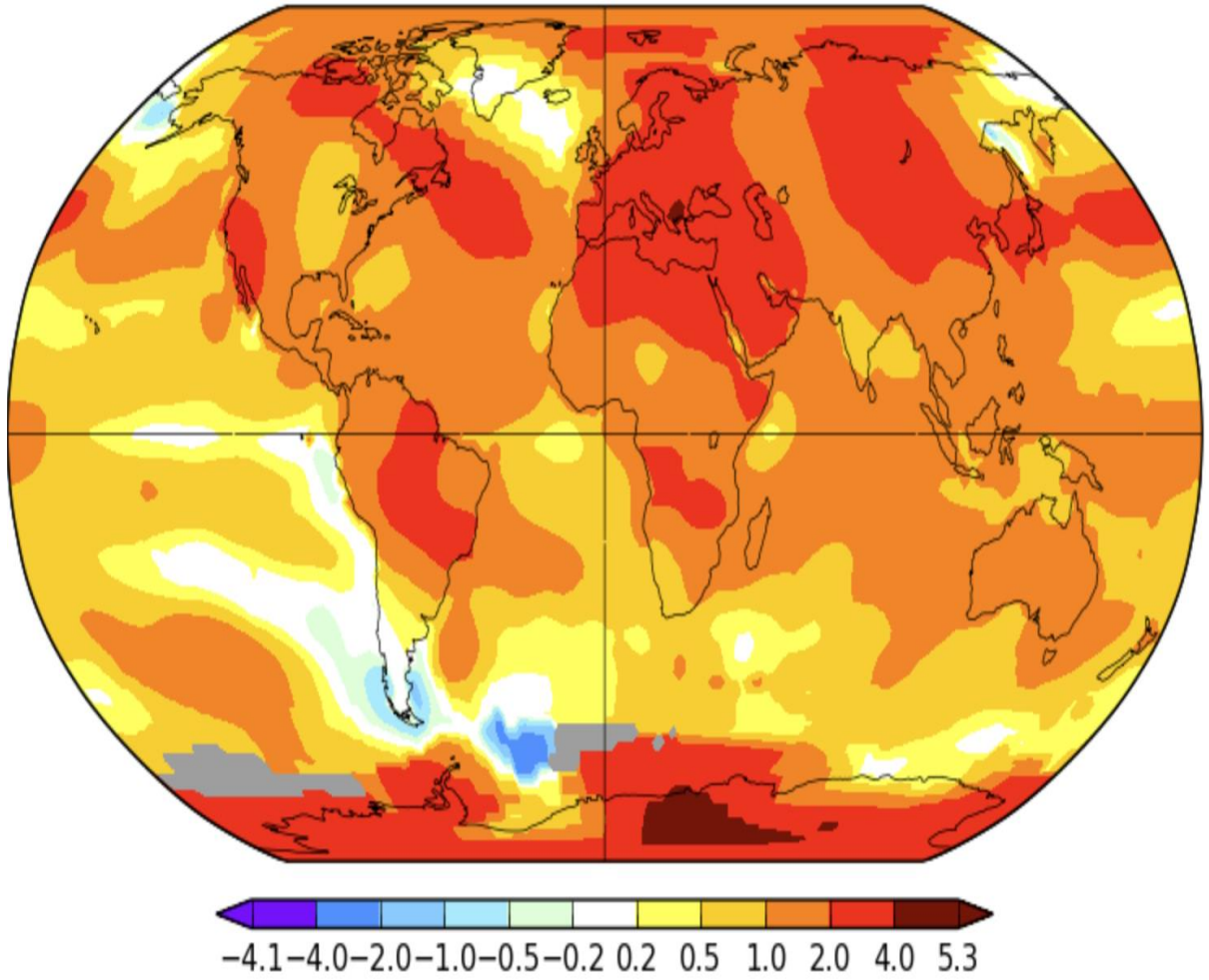
Monthly average atmospheric CO_2 and methane levels
(CO_2 ppm; Methane ppb)



Source: NOAA Global Monitoring Laboratory, Earth System Research website; September 2024

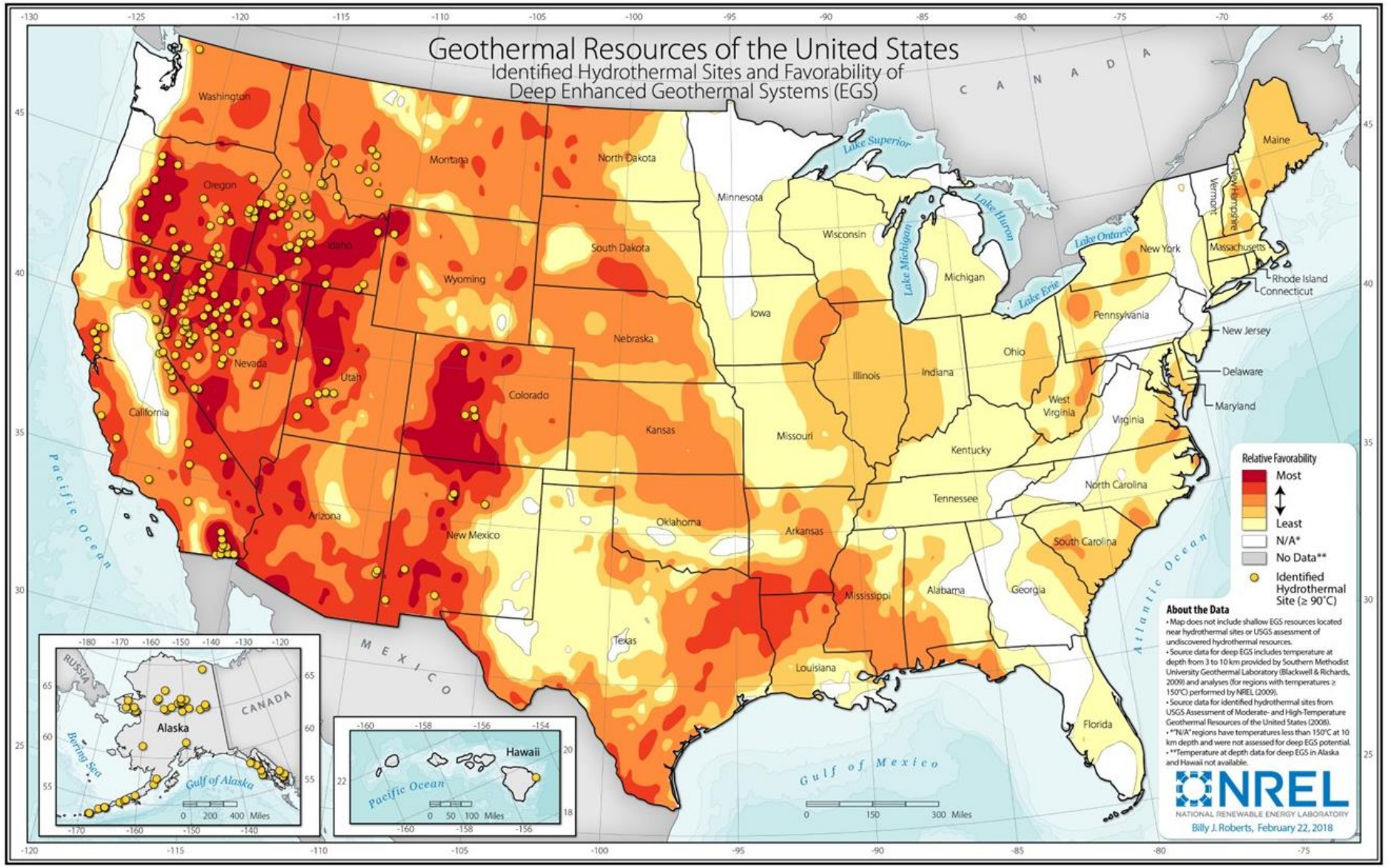
Surface air temperatures are rising

Summer 2024 compared to 1951-1980 summer mean
(Delta degrees Celsius)



Source: NASA Goddard Institute for Space Studies; GISS Surface Temperature Analysis (v4); September 2024

Electricity from geothermal holds enormous promise for providing a solution



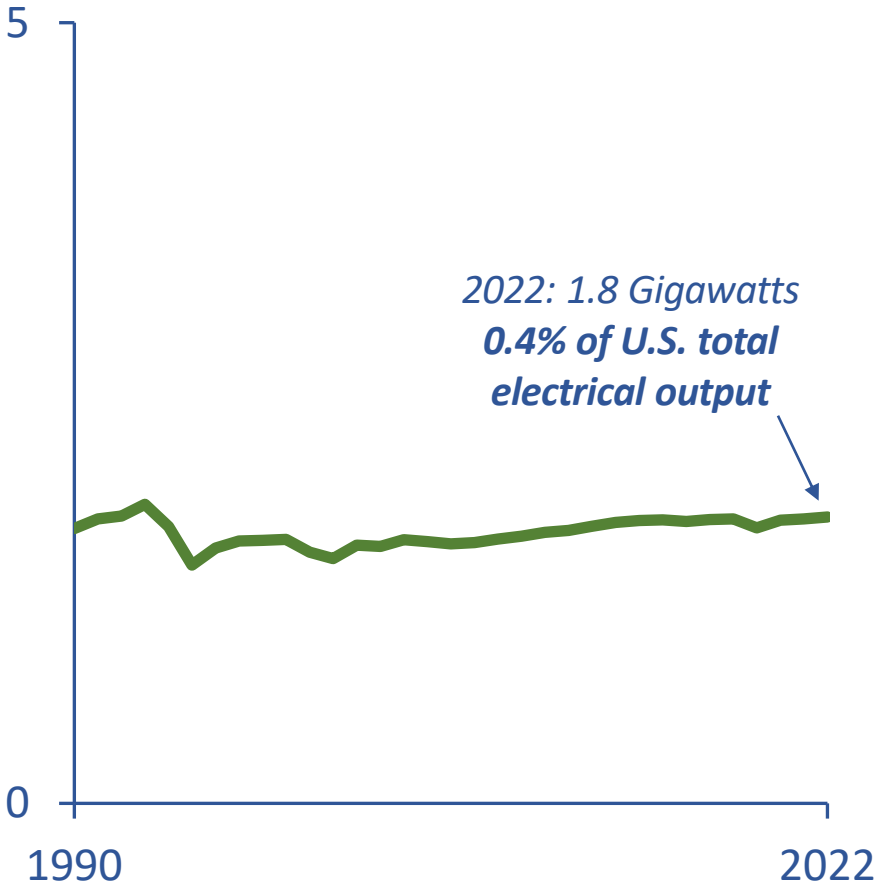
- Near-zero emissions
- Firm, dispatchable, power
- Resources sufficient to deliver 1,000s of years of U.S. primary energy consumption
- U.S. is the world's largest producer of geothermal power

Map taken from U.S. NREL website

However, to date, U.S. geothermal power output has been disappointing

U.S. Geothermal Power Output

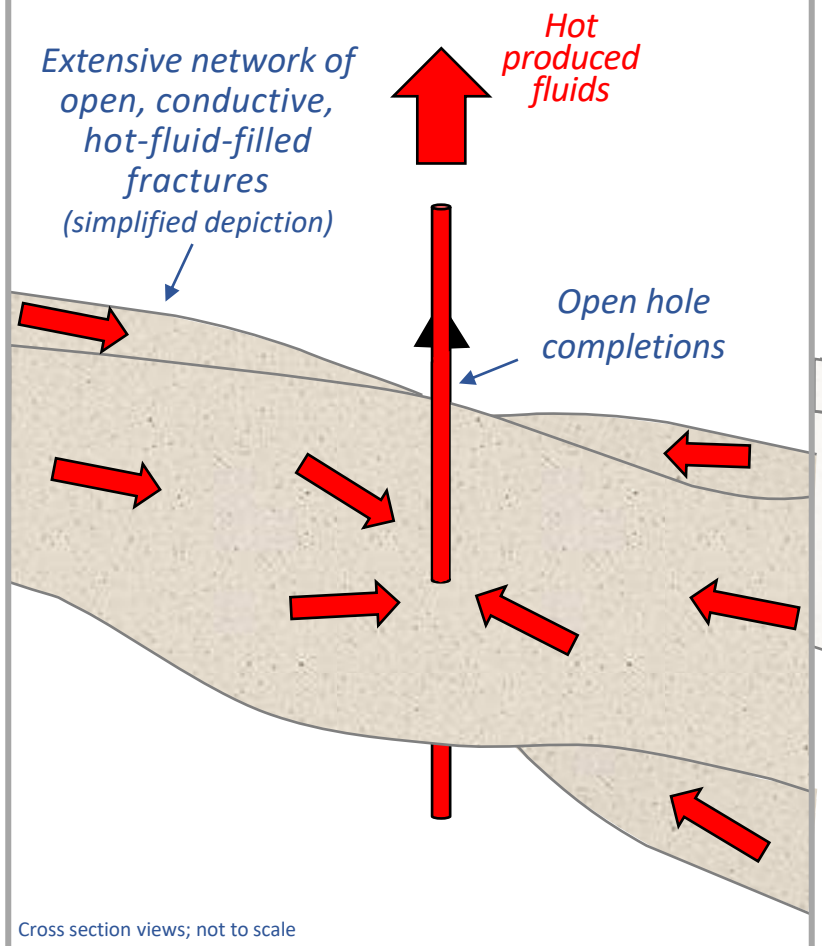
(Average annual GW of instantaneous output)



Source: U.S. EIA ; plot shows annual average instantaneous electricity output

NEGLIGABLE GROWTH DESPITE CONSIDERABLE INVESTMENT

Hydrothermal Systems

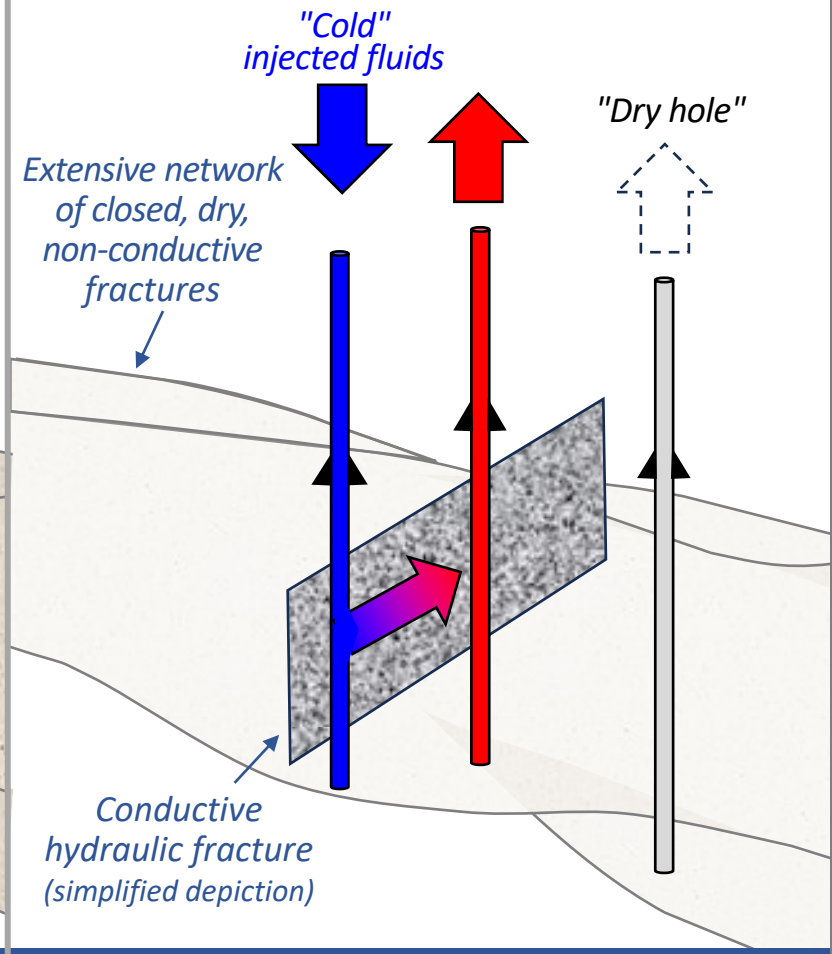


Cross section views; not to scale

EXCEEDINGLY RARE

Example: The Geysers, California

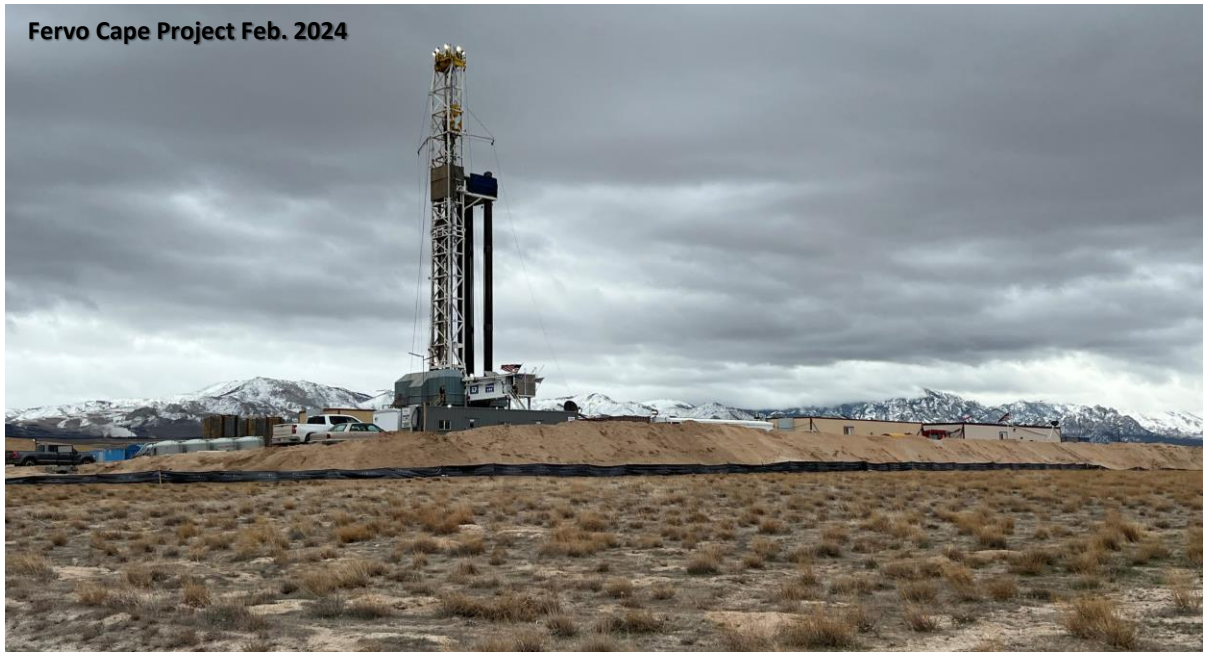
Old Style EGS

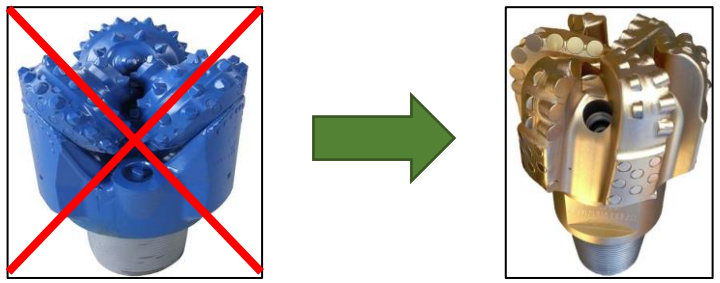


EXCEEDINGLY DISAPPOINTING

Example: Most EGS projects 1970-2023

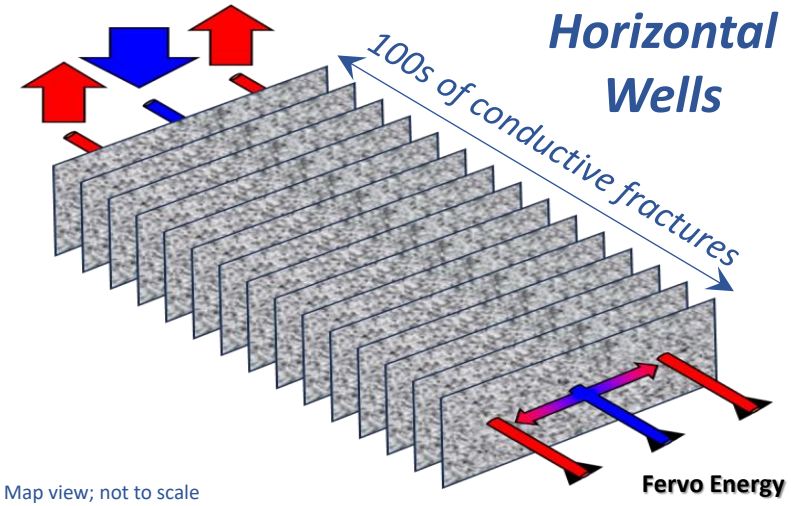
Oil & gas technologies hold the key to improving geothermal power economics





Physics-Based Drilling

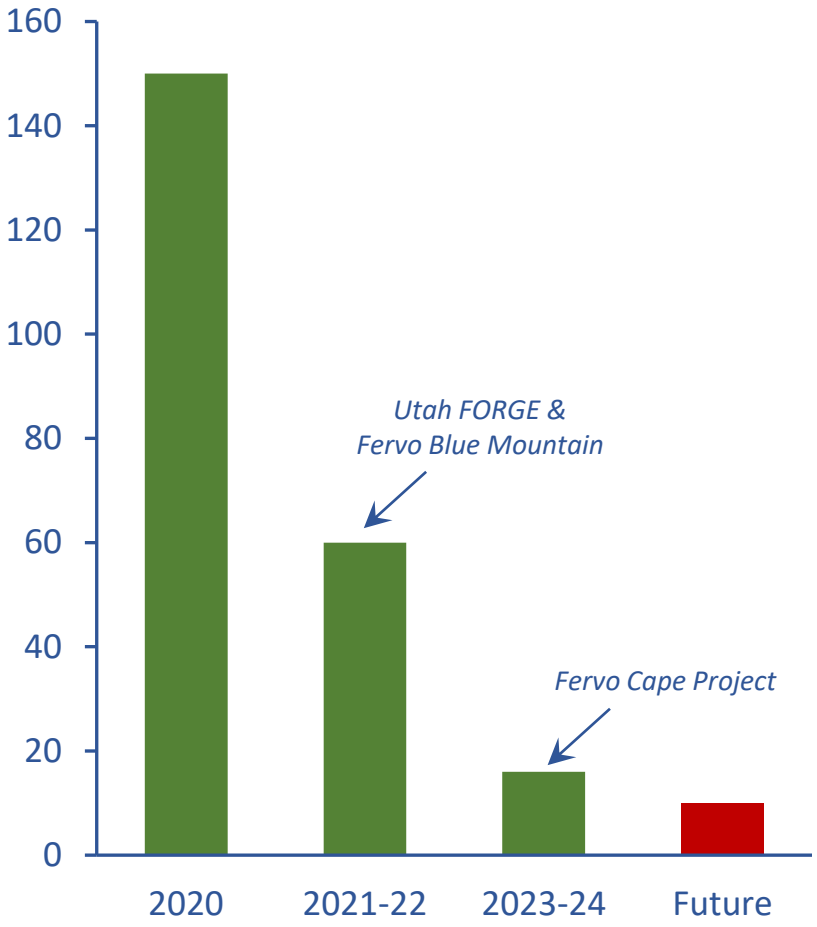
Utah FORGE and Fervo Energy



Improvements achieved to date have been dramatic; Likely more to come!

Spectacular drilling performance improvements

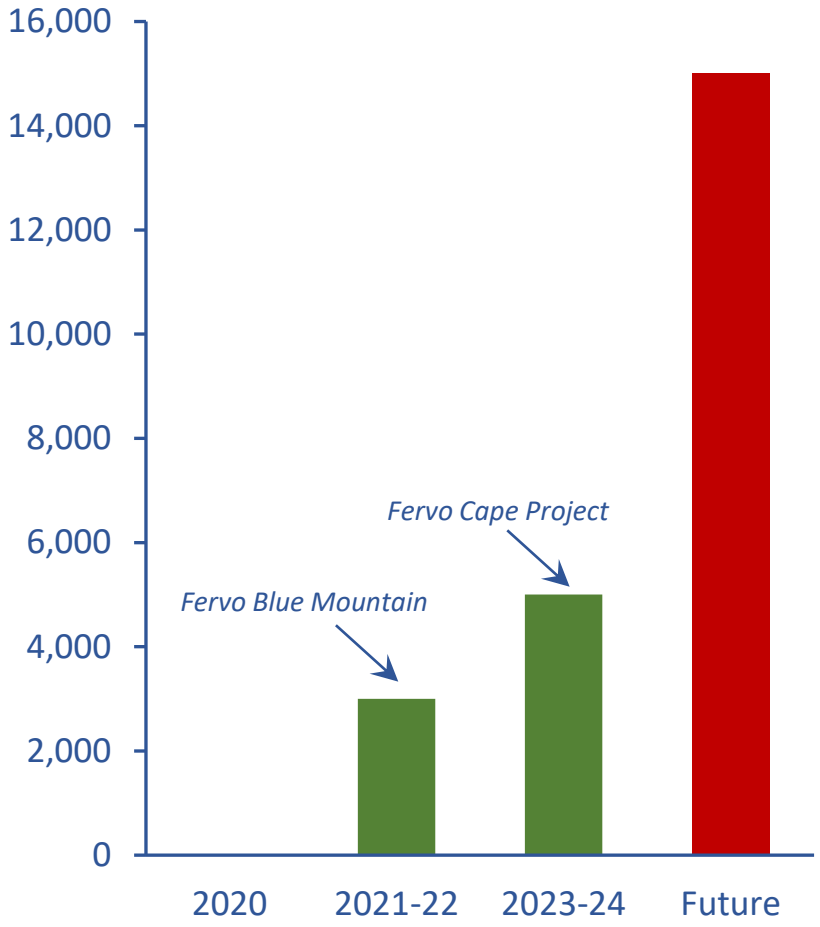
Drilling days to 12,000’ MD



Sources: El-Sadi et al, 2024, Review Of Drilling Performance In A Horizontal EGS Development; Winkler and Swearingen, 2021, Summary of Drilling Activities, Well 16A(78)-32 (Utah FORGE)

Ability to D&C horizontal laterals in basement rocks

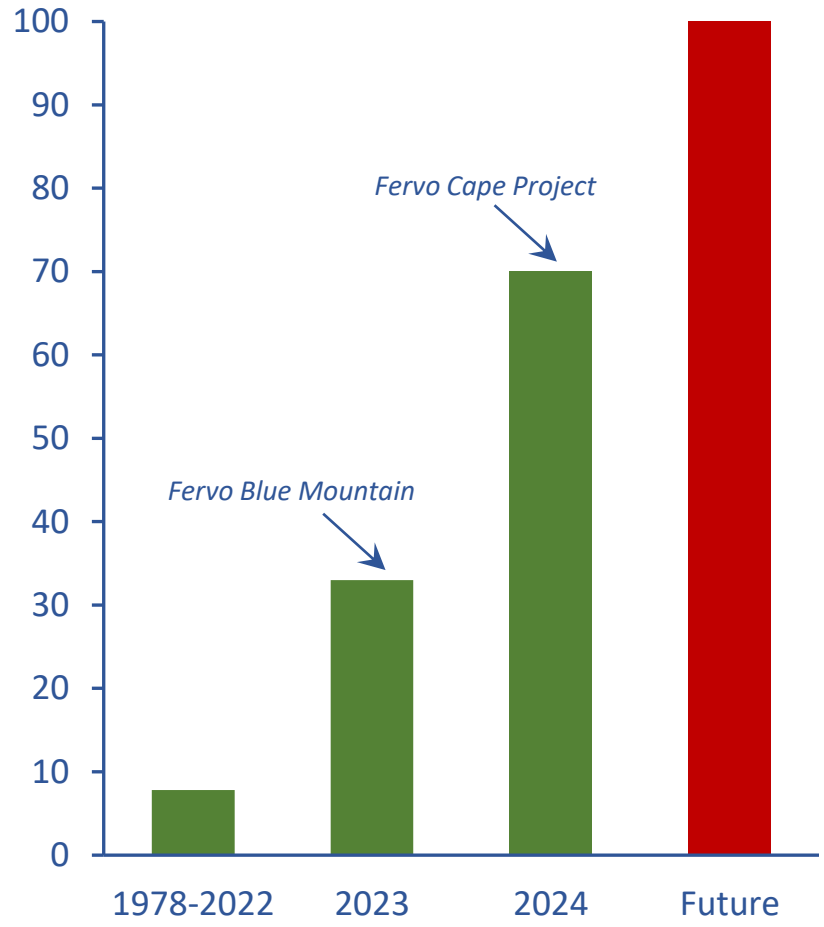
Lateral length (feet)



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

Ability to achieve high flow rates and good conformance

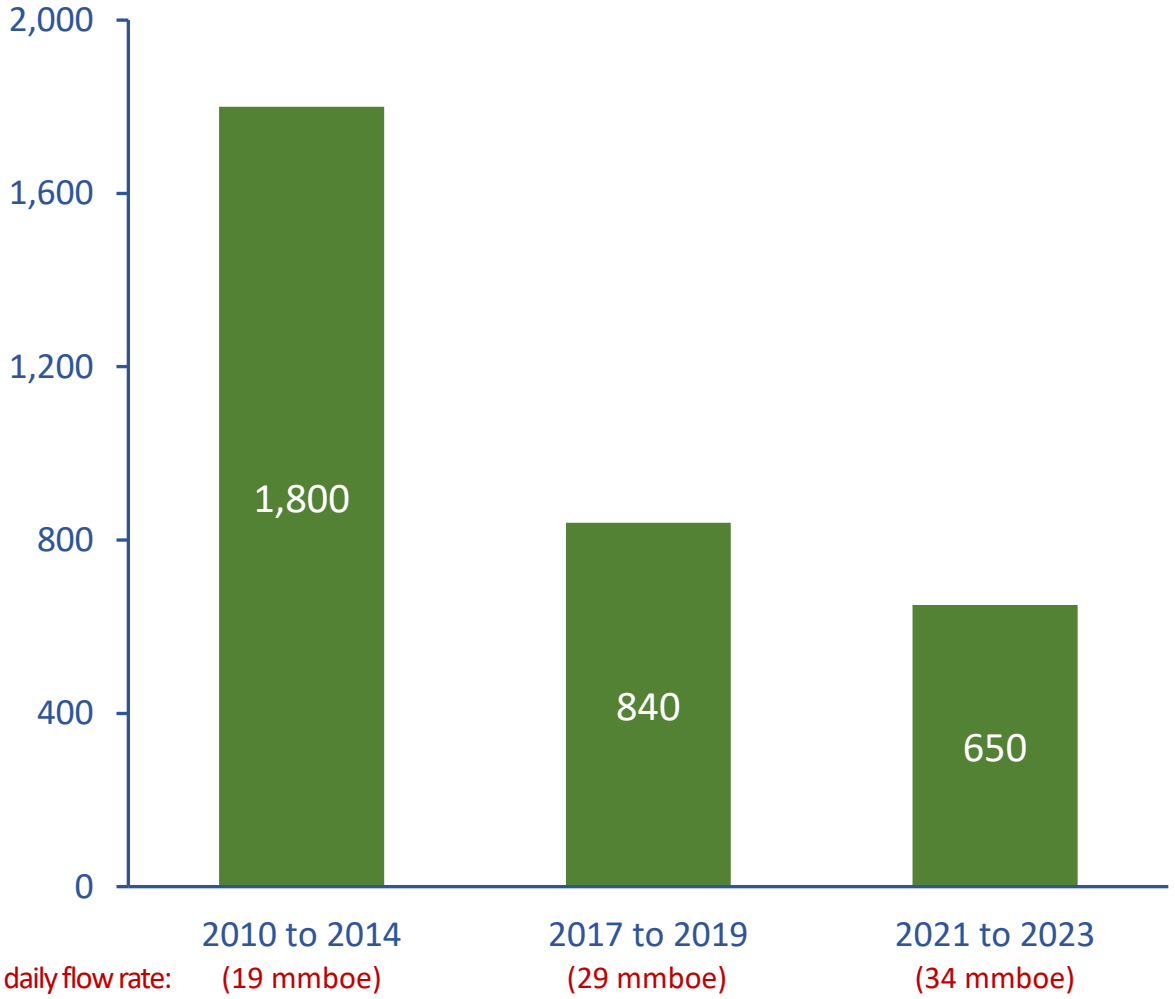
Peak production flow rate (MBFPD)



Note: 1978 – 2020 data from 11 projects; average peak flow rate shown (7,800 bfpd); range was from 2,700 to 16,300

Going forward, EGS could replicate unconventional reservoirs' learning curve

U.S rig count needed to grow annual production by > 1,000,000 BOE per day



Sources: U.S. production = U.S. EIA, Energy Insights, and BP websites; Rig count = Baker Hughes; BOE = Barrels of oil equivalent; natural gas converted at 6 mcf per barrel of oil. mmboe = million barrels of oil equivalent

Eagle Ford unconventional learning curve

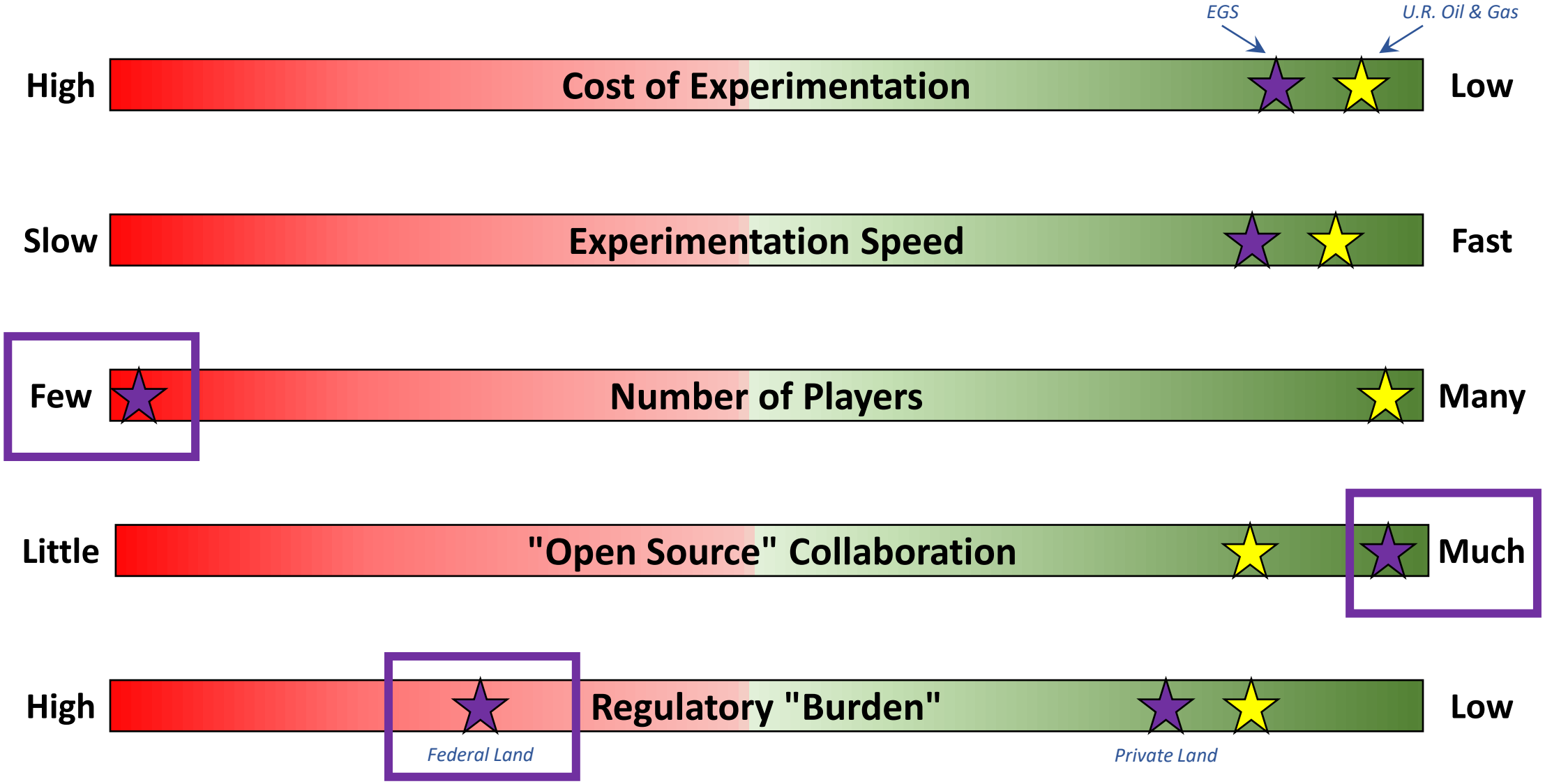
	Vintage 1 2010-14	Vintage 2 2014-16	Vintage 3 2017-20	Vintage 4 2021-24
Lateral Length	3,000' to 5,000'	5,000' to 7,5000'	7,500' to 10,000'	10,000' to 15,000'
Perf Cluster Spacing	50' to 70'	25' to 50'	15' to 25'	15' to 25'
Proppant (lbs./foot)	750	1,500	2,100	2,100

EGS historical and future learning curve

	Vintage 1 2023	Vintage 2 2024	Vintage 3 2025-28	Vintage 4 2028-30
Temp. F	350	400	>425	>450
Lat. Length	3,000'	5,000'	7,500'	≥10,000'
Inj.-Prod. Spacing	300'	500 - 600'	600 - 700'	≥ 700'
Production Rate (BPD)[1]	25,000	70,000	100,000	≥100,000

Data sources: Unconventional numbers based on ConocoPhillips Eagle Ford actuals; EGS numbers based on Fervo Blue Mountain (V1) and Cape (V2) Projects. Numbers shown in blue are projections that are yet to be achieved. [1] Blue Mtn. 5" casing; Cape 7" casing; Vintage 3+ 8 5/8"

Innovation macro-scale factors that enabled rapid O&G production growth



Open Source = degree to which information about results of new technologies and approaches rapidly become available to a large portion of the players pursuing an opportunity.
Regulatory Burden = degree to which regulation slows down the pace of exploration and development, adds cost, or makes it difficult for a player to protect their advantage.

Experimentation focus areas that could further improve EGS economics

Potentially Significant "Upsides"

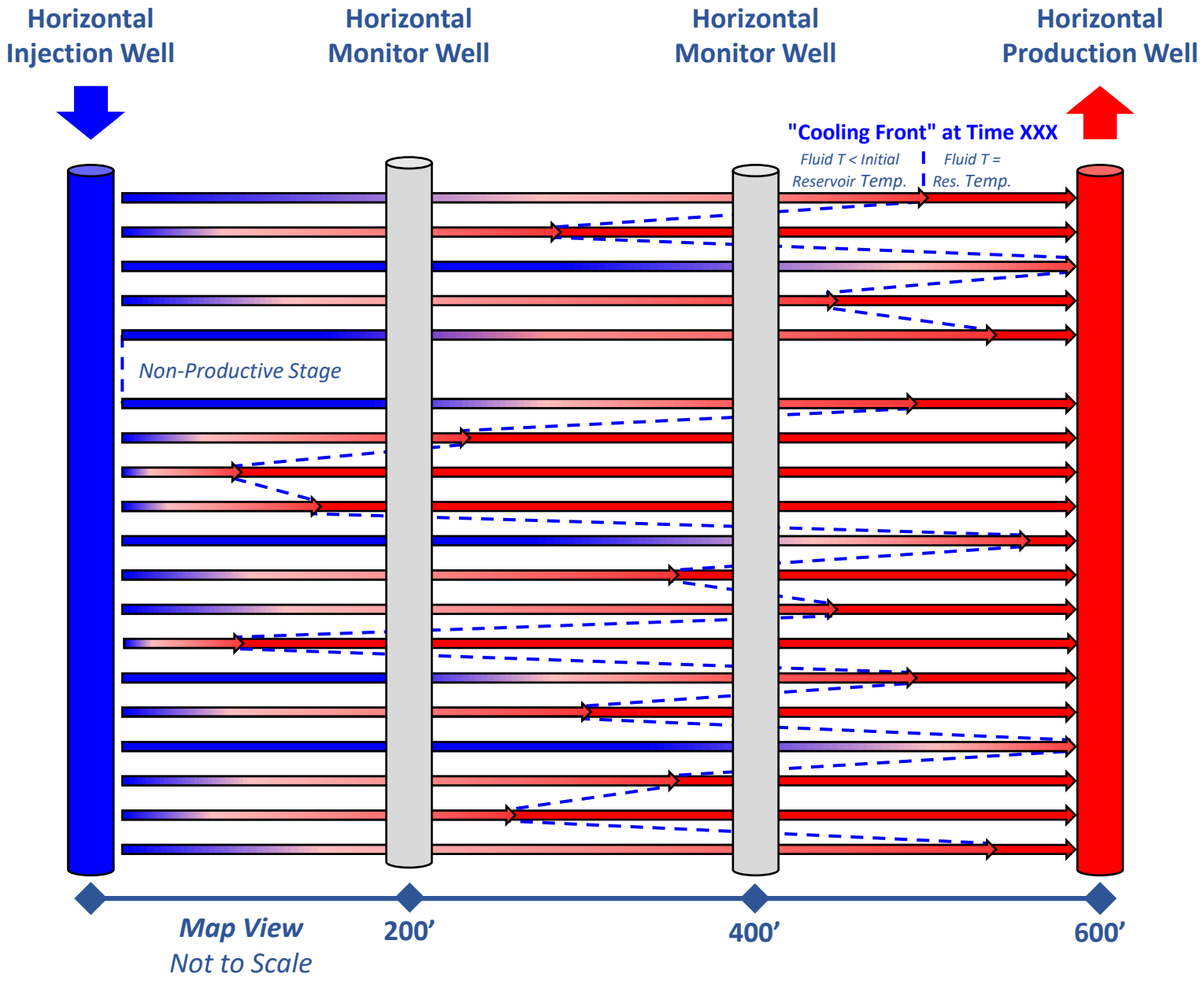
Improved Conformance	*Greater Surface Area*	*Super Hot Rocks*	*Higher Flow Rates*	*"Open Hole" Producers*[3]	*One Plant / Deeper Layers*
• Well placement • Completion design • Operating practices • Remediation options	• Longer laterals • Wider well spacing • LL: 3M → 5M → 15M ft. • WS: 300' → 600' → __	• Blue Mtn. ≈ 375° F • Cape 400° to 435° F • SHR target 705° F[1] • ≈ 1 MW per 25° F[2]	• Larger casing = >rate • > Fracture conductivity • Blue Mtn. 25M bfpd • Cape design 70M bfpd	• $5 MM or more per well cost reduction • Uncertain flow rate impact, but could yield higher rates	• Synergy with Super Hot Rocks progress • Reuse as much of plant as possible after initial wells die
>Thermal Longevity	***>Thermal Longevity***	***> Thermal Output***	***> Thermal Output***	***Less D&C Cost***	***Less Plant Cost***

Potentially Significant "Downsides"[4]

Thermal Breakthrough	*Fluid Leakoff*	*Induced Seismicity*	*Loss of Fracture Conductivity*	*Scaling*	*Corrosion*
• Well length, spacing & stacking, flow rates • Completion design • Operating practices • Remediation options	• Avoiding tectonically stressed localities • Completion design • Operating practices • Remediation options	• Avoiding tectonically stressed localities • Completion design • Operating practices • Remediation options	• Proppant placement best practices • Proppant and frac fluid selection • Operating practices	• Robust scaling characterization and treating programs	• Robust corrosion characterization and treating programs • Materials selection
Thermal Longevity	***Plant & OPEX Cost***	***License to Operate***	***Thermal Longevity***	***Plant & OPEX Cost***	***Plant & OPEX Cost***

[1] 374° C; [2] at 50,000 bfpd flow rate; [3] Wells could be completed open hole or with a slotted liner; [4] Downsides that could be mitigated

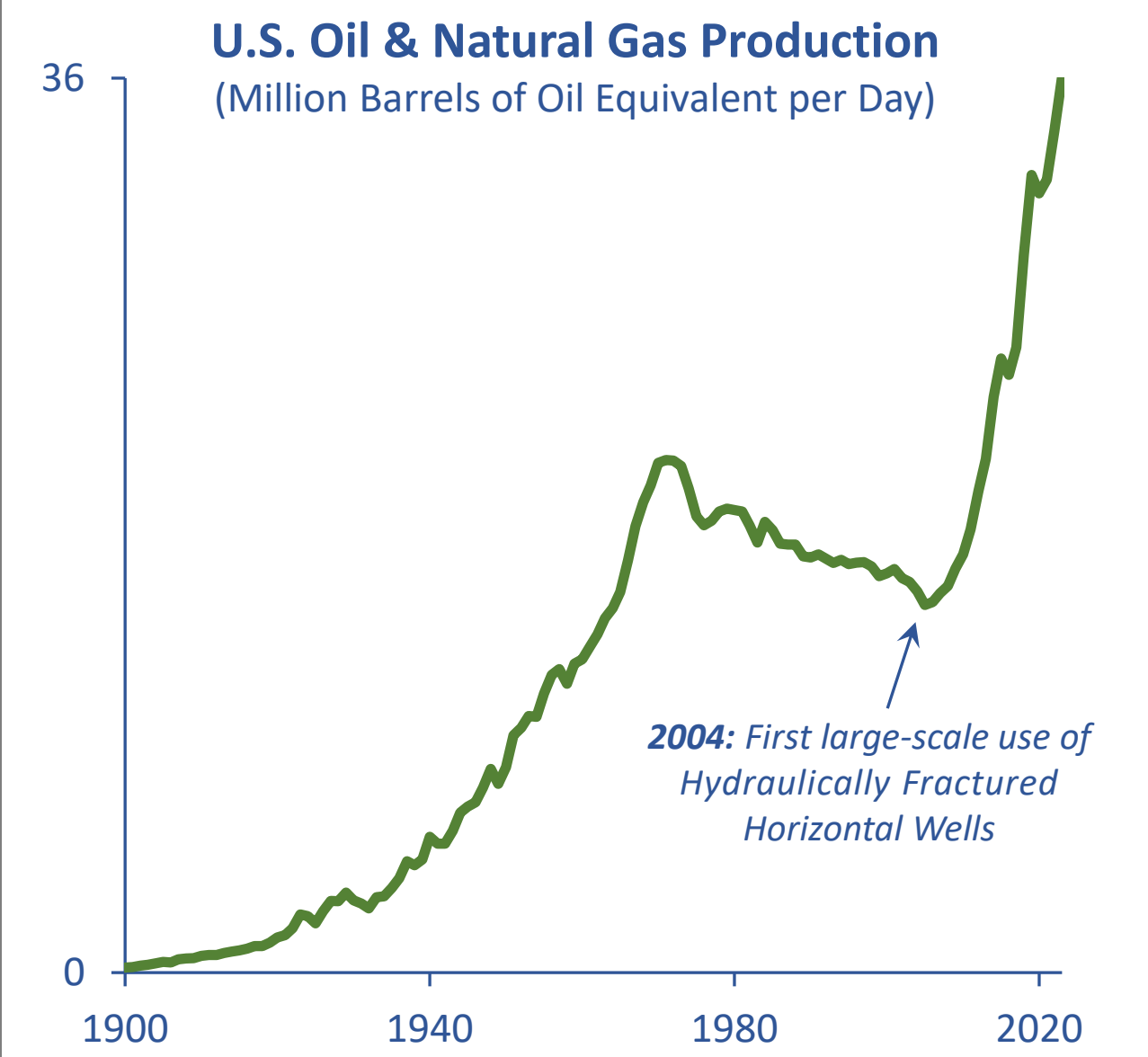
Conformance Experiment: Multiple Monitor Wells between Injector & Producer



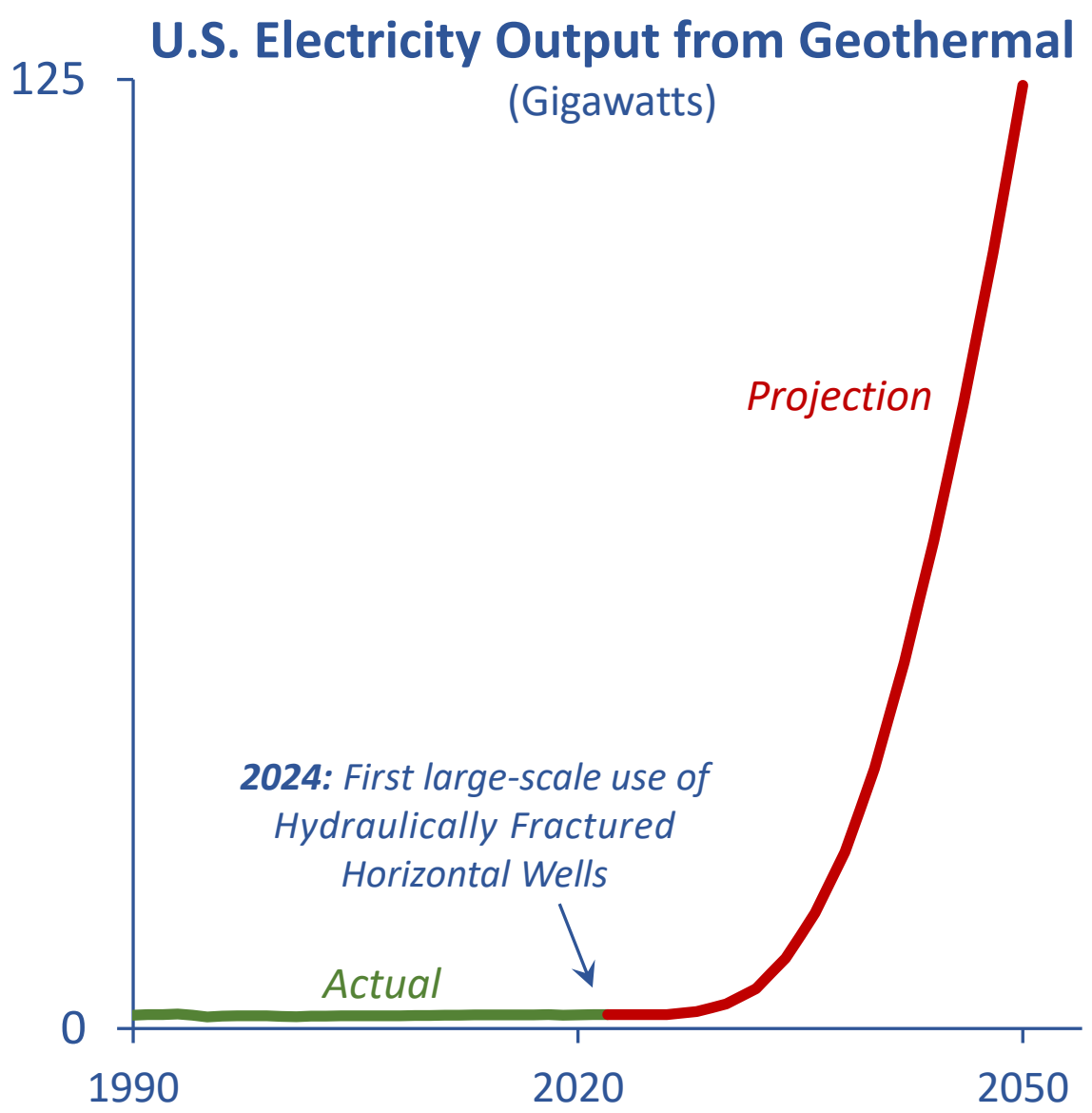
- **Concept:** Place multiple monitor wells between injector and producer to learn how "cooling front" migrates over time
- **Execution:** Drill and fracture stimulate injector and producer; assess data indicating location of fractures; place monitor wells at optimal locations
- **Benefits:** Learning how front moves through fracture system in 3D space will help with optimizing placement of future wells; learning from a project like this will be far more effective from a value optimization perspective than learning from trying different placements of producers relative to injectors; likely to also help with completion designs (e.g., stage & perf cluster spacing)
- **Approximate Cost:** $15 to $30 MM depending on the number of monitor wells deployed (2 to 4 wells)
- **Requirements:** Must be done in producing field

Simplified depiction of a complex physical phenomenon; Depiction of cooling characteristics are for demonstration purposes only; they are not based on actual data

Could oilfield technologies enable a geothermal power breakthrough like that achieved in unconventional O&G reservoirs?



Sources: U.S. EIA, Energy Insights, and BP 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

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