The Heat We Can’t Reach… *YET*

Exploring Earth’s Deepest Potential and the Roadblocks to **Superhot Rock Geothermal**

Presented to: GEMS
November 2025

CLEAN AIR TASK FORCE

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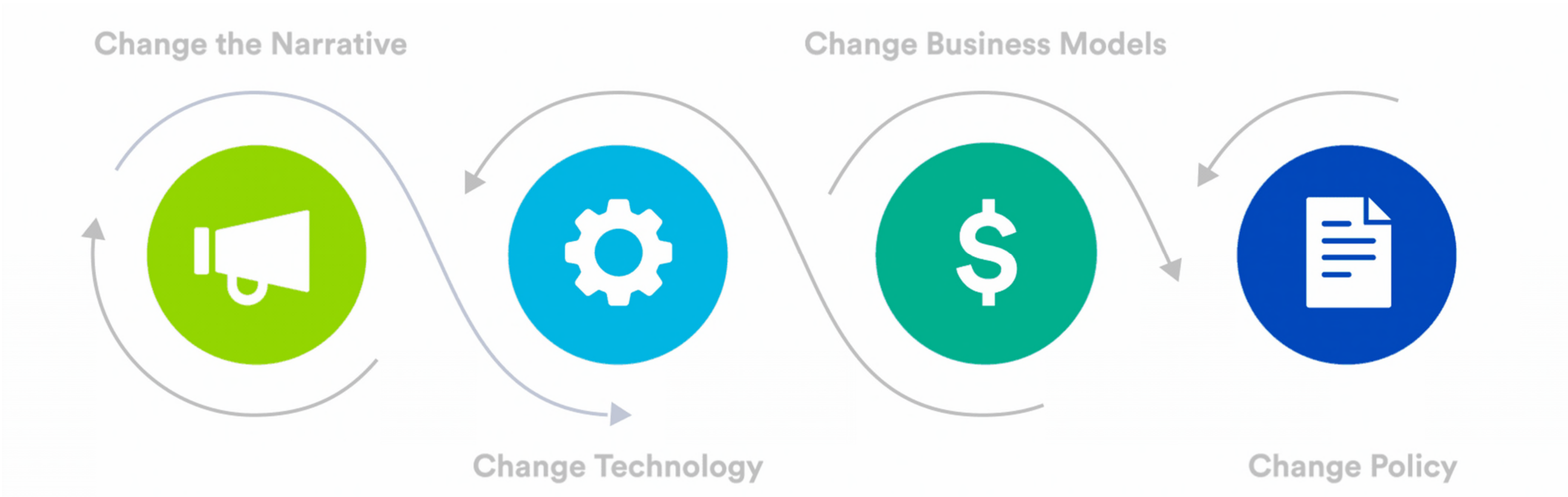
Who is CATF?

Section I(a): Who we are and how we do work

CATF MISSION:

Push the technology and policy changes needed to achieve a zero-emissions, high-energy planet at an affordable cost.

Our approach



Global nonprofit working to safeguard against climate change in a world of rapidly increasing energy demand

We challenge conventional wisdoms and explore every opportunity that offers promise, and we’ve done so for more than 25 years.

Methane Pollution Prevention

Leading the implementation of the Global Methane Pledge, working with countries to develop abatement strategies, working for strong standards in U.S. and EU

Carbon Capture

Leading innovation policy development and implementation in the U.S. and EU, exploring project and market development opportunities in MENA and SSA, though leadership on carbon take back obligations

U.S. Power Plants and Industrial Emissions

Engaged in a range of litigation and rule makings on emission limits for CO2, methane, and criteria pollutants (NOx, Sox, HAPs)

Hydrogen

Focused on the U.S., EU, MENA, SSA, and SE Asia on developing standards and markets for hydrogen and ammonia fuels

Superhot Rock Geothermal

Focused on driving the technology from early development stage through commercial demonstration, as well as addressing needed regulatory and infrastructure issues

Transportation Decarbonization

Focus on both innovation policies and mandates (such as zero-carbon fuel standards) at the U.S. federal level, as well as engagement with international shipping companies and ports to facilitate ammonia bunker fuel adoption

Land Systems

Leading the exploration of the limits of land use in abating global warming, including land availability, limits of biomass use, and complex forest-climate interactions

Advanced Nuclear

Focused on hitting the “re-start” button for nuclear business models and confirming both innovation policy and regulatory strategies appropriately

Fusion

Focused on driving the technology from early development stage through commercial demonstration, as well as addressing needed regulatory and infrastructure issues

Infrastructure Deployment

Developing the tools and strategies, initially in the U.S., that would facilitate the full system decarbonization.

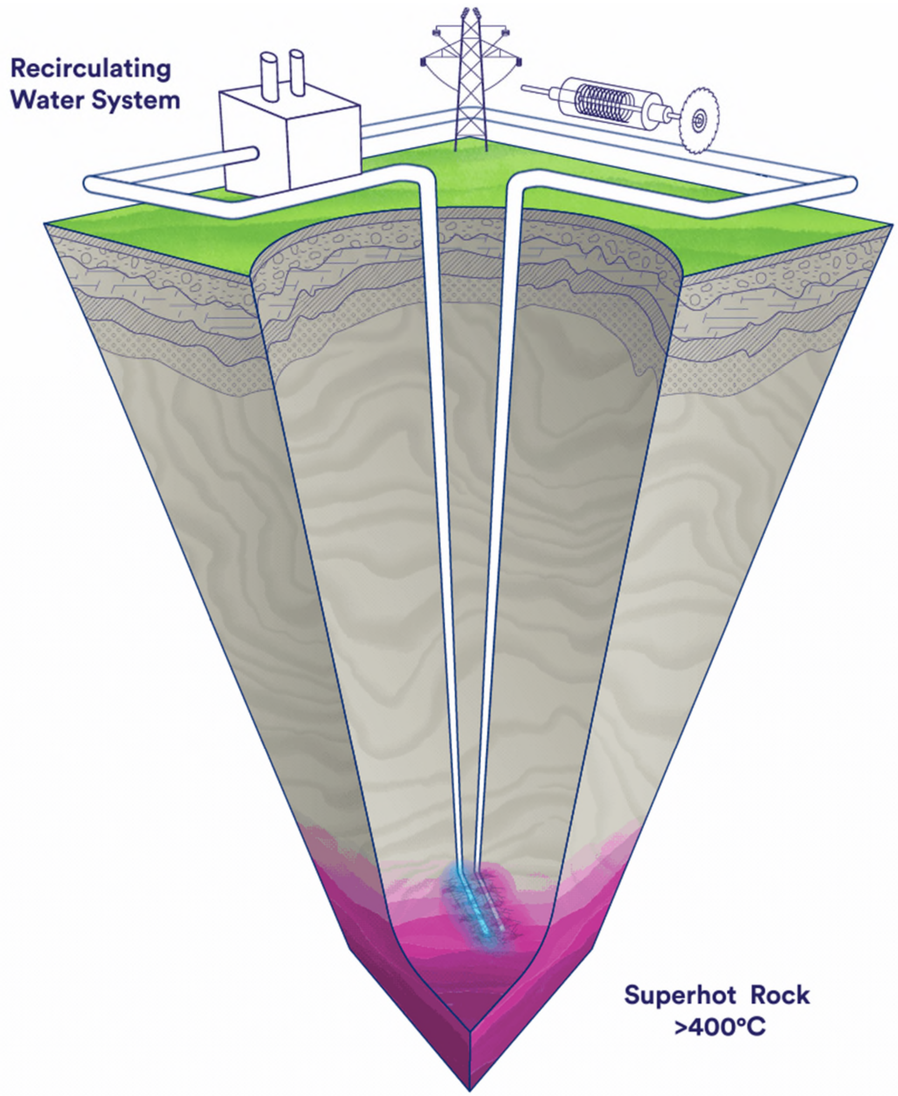
We’re not just environmental advocates

CATF

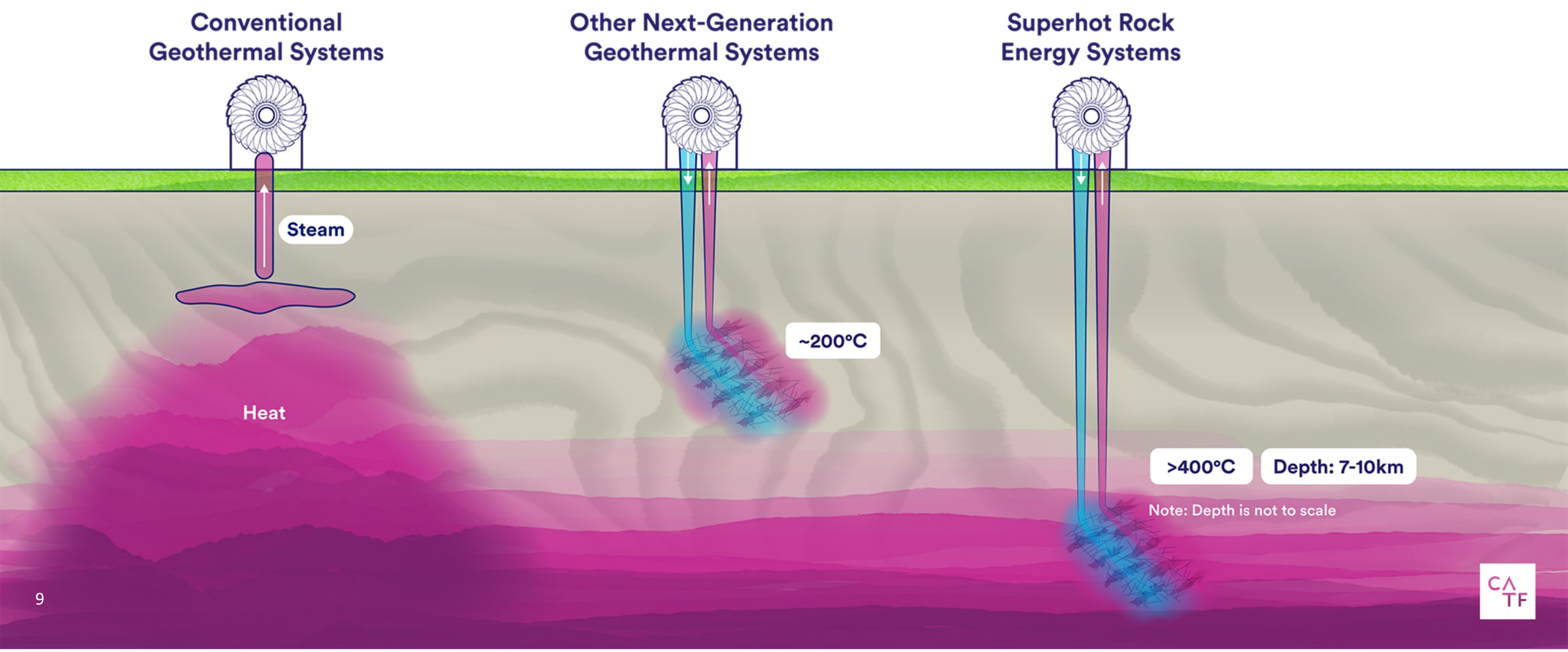
Just **1%** of the world's superhot rock geothermal potential could generate 63 terawatts of clean firm power – **8x more energy than the rest of the world's electricity put together**

Why superhot rock: Speed course on SHR 101

Section I(b): What is SHR and why it has so much potential


Recirculating
Water System
Superhot Rock
>400°C

Building toward superhot



Heat extraction methods

Conventional geothermal systems

- Heat extraction method: Producing power from existing reservoirs of heated water (aka hydrothermal fluid)
- Alternative term: Hydrothermal systems
- Example: Most existing geothermal power plants

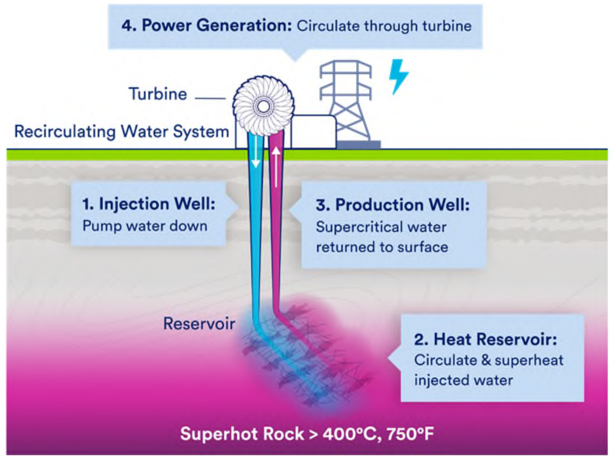
Enhanced (or engineered) geothermal systems (EGS) NEXT GEN

- Heat extraction method: Circulating water through fractures (either existing, created, or enhanced through stimulation) in hot dry rock
- Alternative term: Engineered geothermal systems (EGS)
- Example: Fervo, Utah FORGE, Mazama

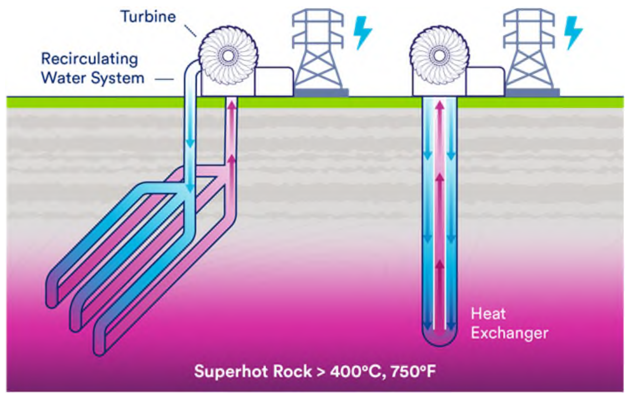
Closed loop geothermal systems (CLGS) NEXT GEN

- Heat extraction method: Heat exchange occurs near wellbore in enclosed and/or fixed radius bore within hot dry rock formtions
- Alternative term: Advanced geothermal systems (AGS)
- Example: Eavor, GreenFire, XGS

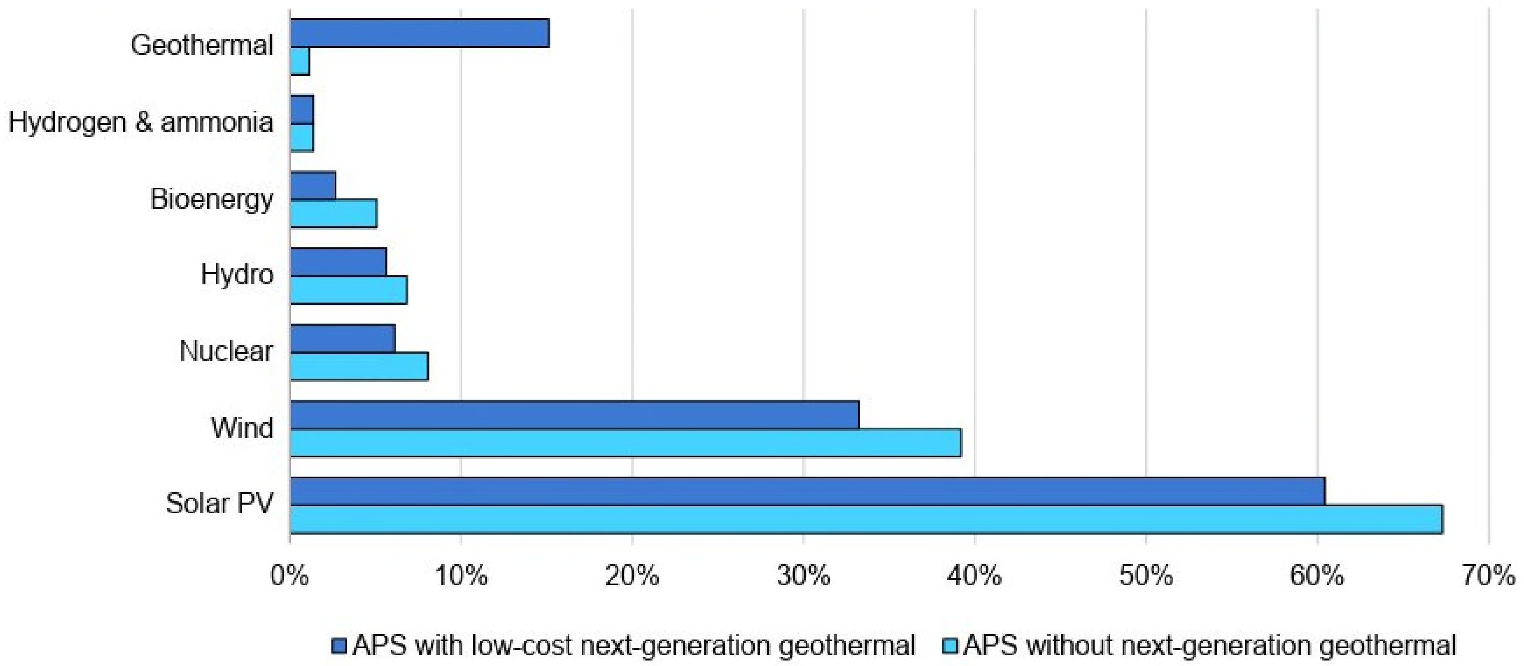
Enhanced Geothermal Systems (EGS)



Closed Loop Geothermal Systems (CLGS)



Explosive market growth predicted



Note: Shares calculated as technology growth divided by increase in total generation, though sum can be over 100% as unabated fossil fuels declines significantly.

Levers to cost reduction: **Dry rock conditions**

"Dry Rock": Drilling wells into dry rock, rather than underground pockets of hot water (as conventional geothermal does)

Mitigates **resource risk** ("dry hole") → Reduces cost of capital

"Resource Risk": The possibility that drilling fails to reach a productive geothermal resource, resulting in an unviable well

Facilitates global deployment → Increases manufacturing capacity → Reduces equipment and well costs through mass production and **standardization**

CATF

Levers to cost reduction: **Ultra high temperatures**

AG1

Enables **higher capacity facilities**

↓

Reduces the cost of the balance-of-plant per MW

Reduces the **number of wells** per MW

↓

Lowers the total cost (and footprint).

Increased turbine **efficiency**

↓

Reduces capital & operational expenses per MW

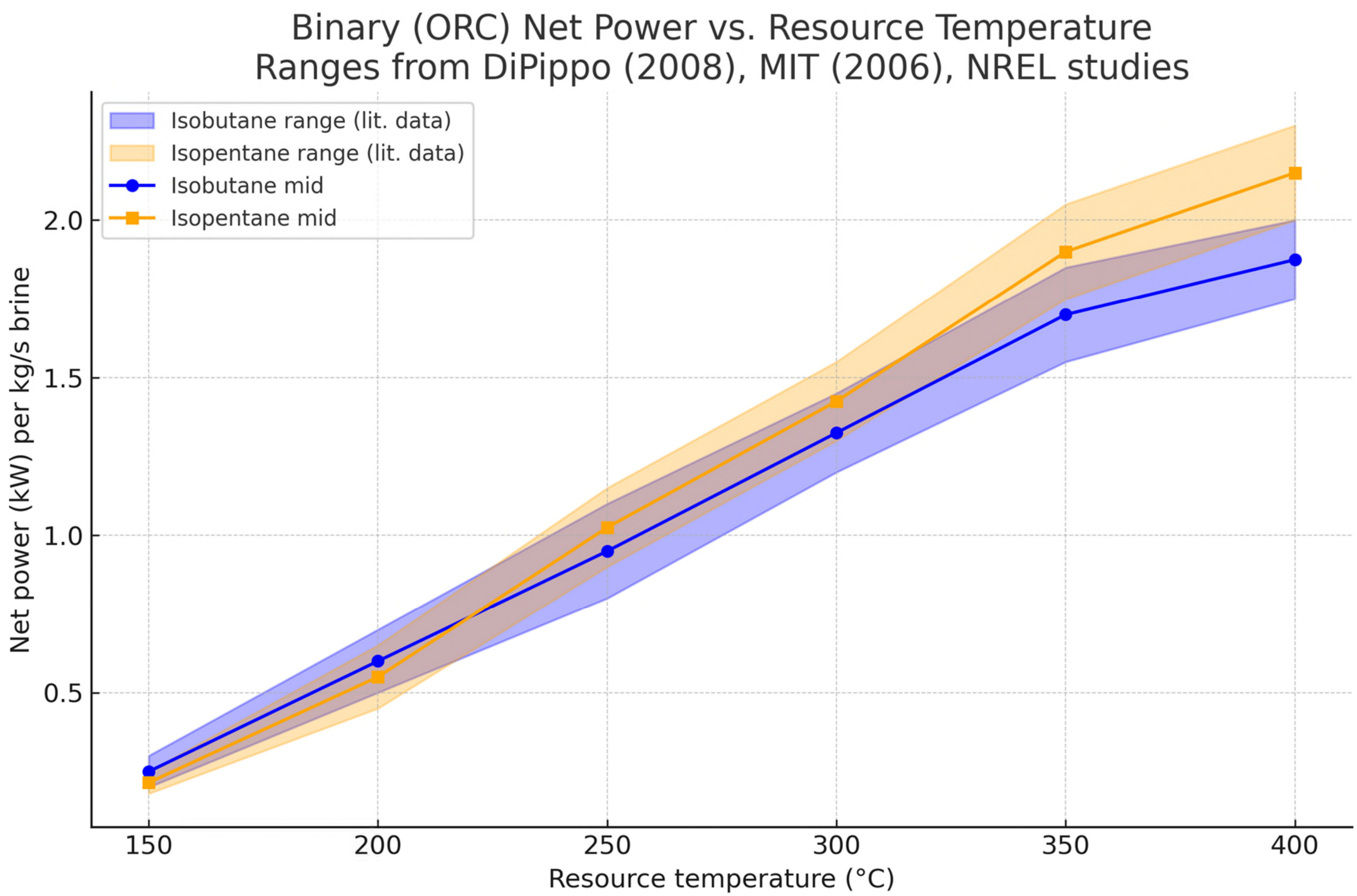
MW = megawatt

Slide 13

AG1 I don't think this slide will be clear to laypeople.
Ann Garth, 2025-03-05T15:47:45.140

TR1 0 [@Kara Hunt] same as slide before…. I am less concerned with the complexity of this slide but perhaps I live in an echo chamber
Terra Rogers, 2025-03-06T20:50:24.682

AG1 1 I changed the title to "ultra high temperatures" instead of "ultra high enthalpy" which I think clarifies it
Ann Garth, 2025-03-06T22:15:11.888

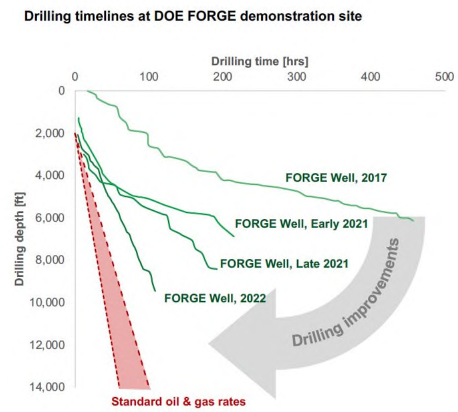


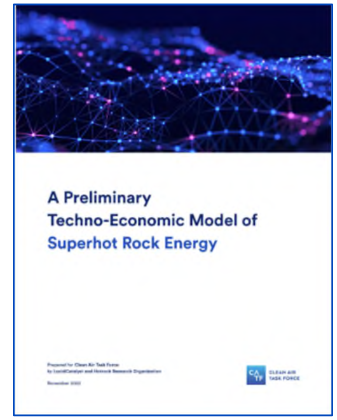
Binary (ORC) Net Power vs. Resource Temperature
Ranges from DiPippo (2008), MIT (2006), NREL studies
Isobutane range (lit. data)
Isopentane range (lit. data)
Isobutane mid
Isopentane mid
Net power (kW) per kg/s brine
0.5
1.0
1.5
2.0
150
200
250
300
350
400
Resource temperature (°C)

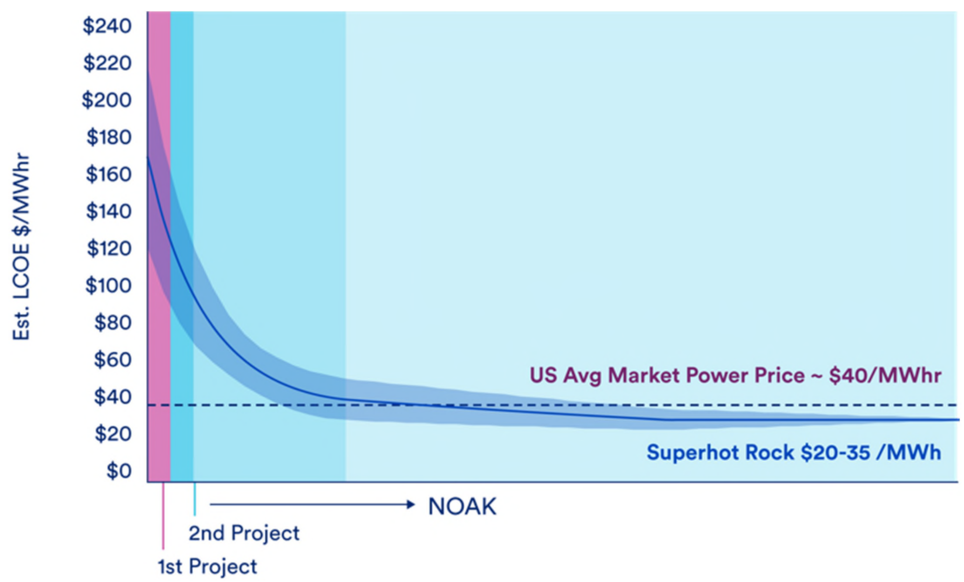
Cost reduction projections

Major CAPEX Reduction Drivers

- Larger facilities = Balance of plant cost reduction
- Higher efficiency thermal conversion
- Reduced financing risk due to standardization of dry rock extraction techniques
- Increase manufacturing and standardization of equipment
- Learning by doing
- Fewer wells
- Cost efficient metallurgy identified through R&D - enabled by larger market







We are learning quickly

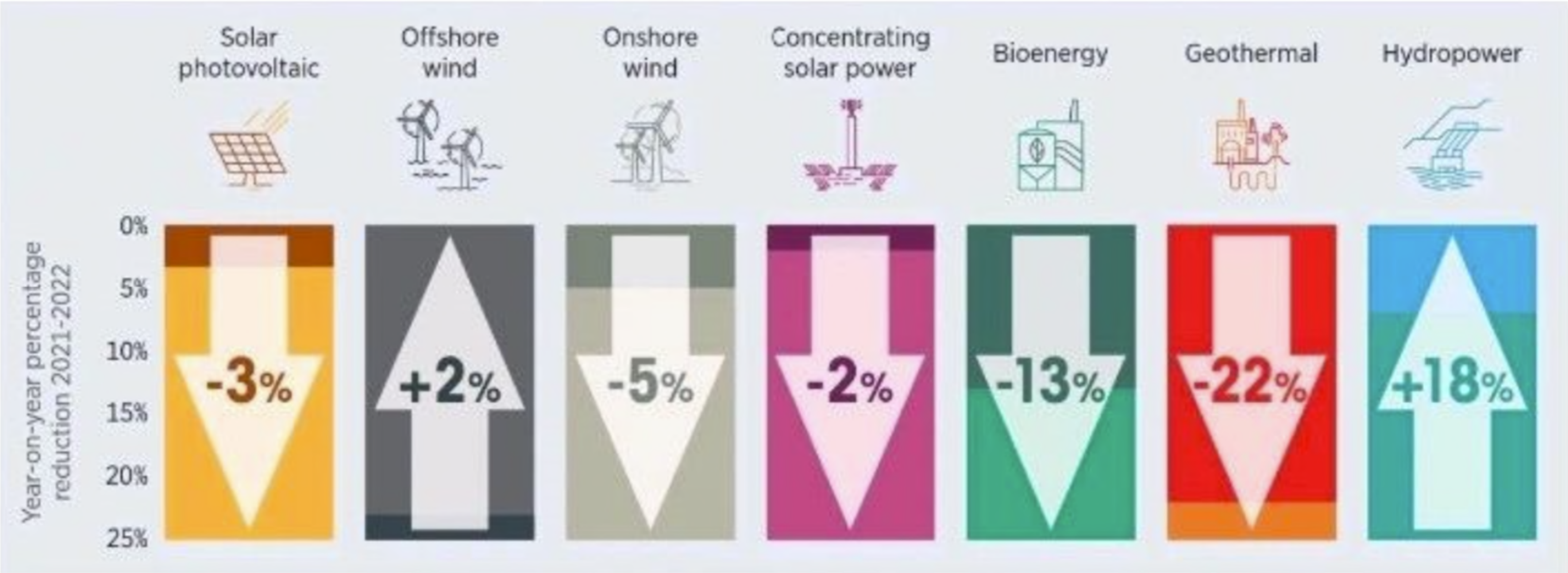
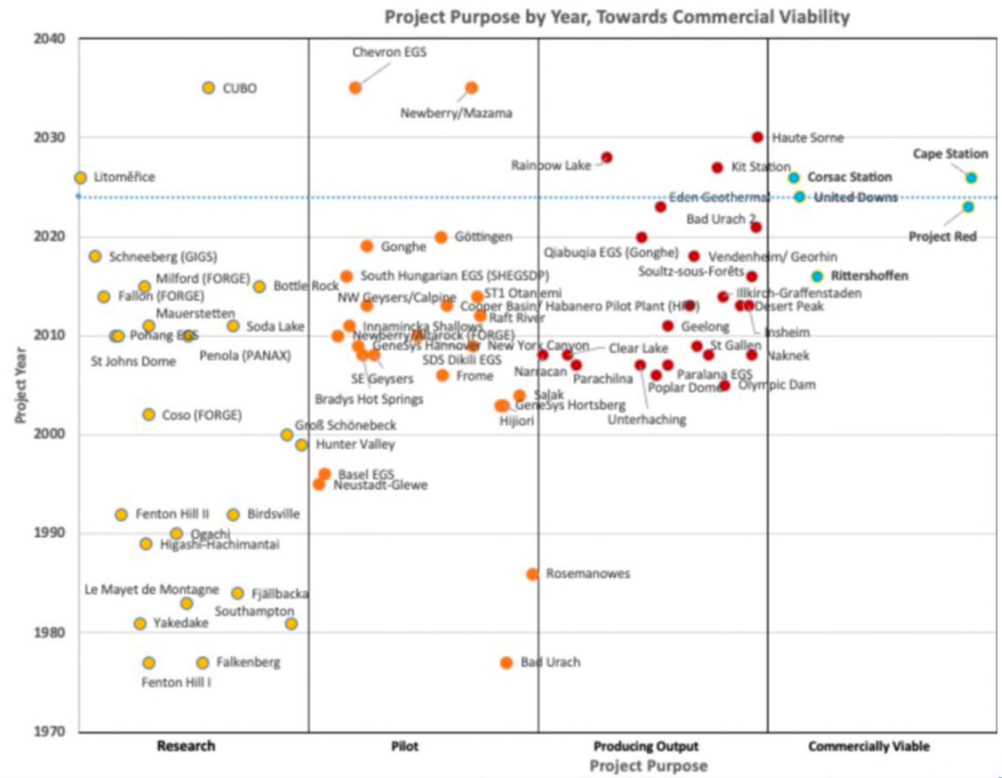


Figure S.3 https://www.irena.org/News/articles/2023/Aug/Infographic-Renewable-Power-Generation-Costs-in-2022

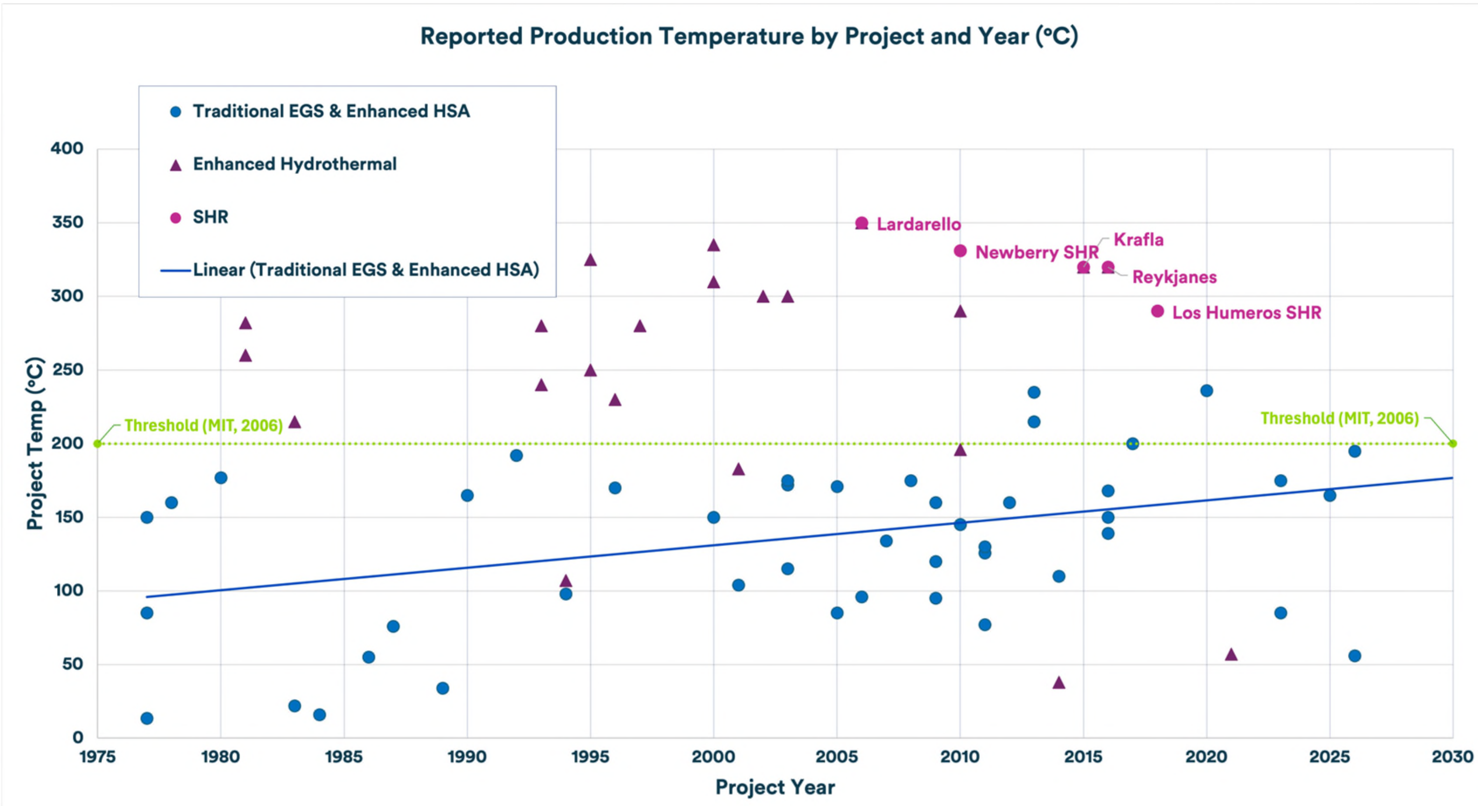
Enhanced Geothermal Systems Report

Key Finding: EGS projects are happening now

- 100+ EGS projects that have happened over the past 50 years.
- The technology is improving.
  - **Temperatures**, on average, for EGS wells, are over 50˚ higher than 20 years ago.
  - Average measured **depth** more than 2x project averages from the 1970s.
  - **Flow rates** are increasing
  - **Costs** are decreasing. From $10-20M/ 4-5km well to $4.6M in 2023.



Projects are reaching hotter production temperatures



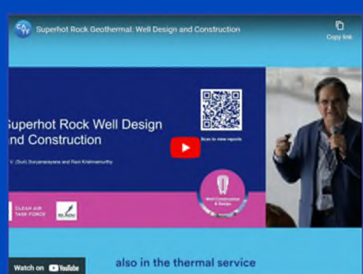
Survey of methods

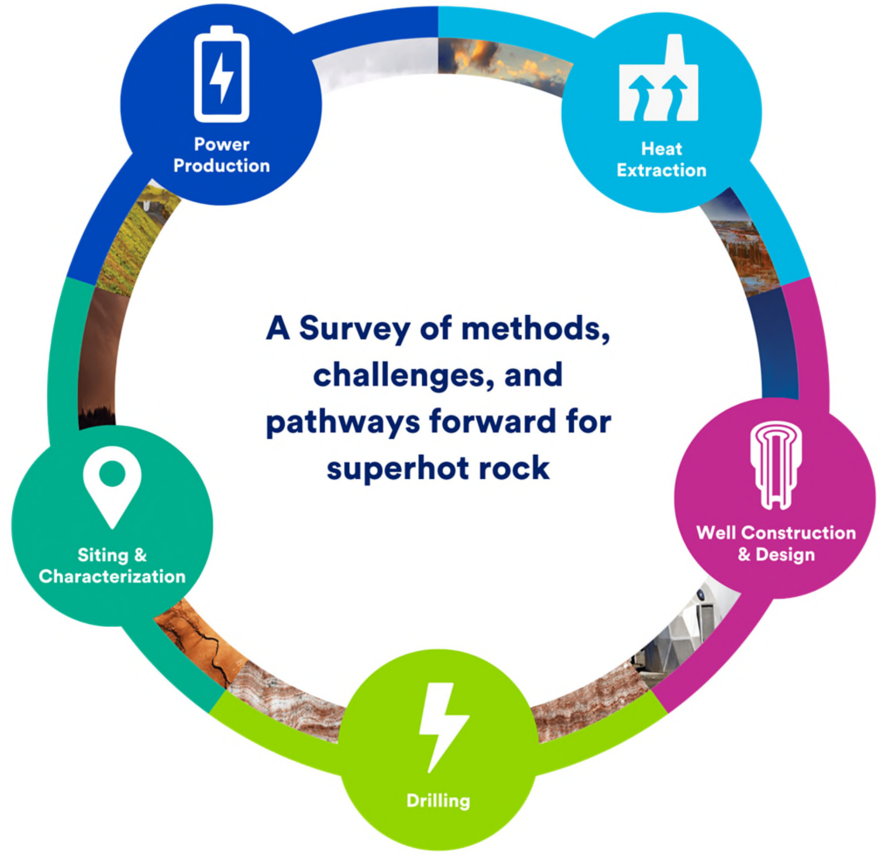
Section III: Challenges and pathways forward to commercialize SHR

Bridging the Gaps

Scan to view:

Full reports (100+ pgs), *Synthesis report (30 pgs)*, At-a-glance (2 pgs), Gap Poster and 5 x 20-min Videos of authors presenting





TRL 2 - 9

Drilling

Tony Pink - Pink Granite Consulting
Rebecca Pearce – Cascade Institute

- Drilling into superhot formations is possible today and continues to occur.
- What is next? Drilling at faster rates, at greater depths, and with lower risk of failure.

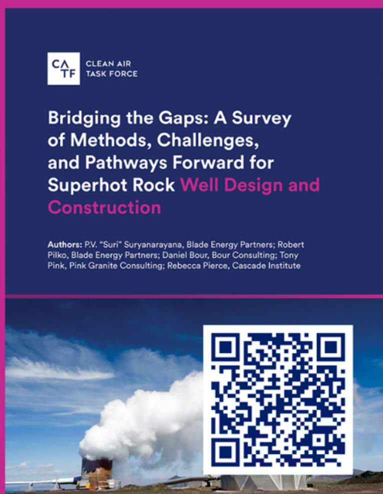
ROPs increasing with every well, driving down costs and improving project economics

Insulated drill pipe combined with drill string optimization can keep tools under 175° C.

If near well bore temps can be lowered as modelled, advanced completions can be run with existing tools.

Casing and cement remain a challenge with increasing interest from labs, academia and industry

Primary Challenge: Lack of end-to-end testing in SHR conditions



TRL 2 - 6

Well Design and Construction

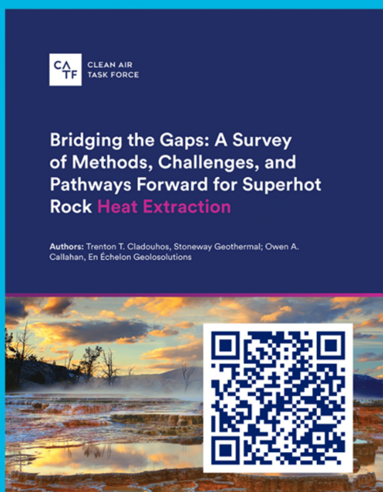
P.V. (Suri) Suryanarayana - Blade Energy

"The most common failure mode for superhot projects is well construction."

- Temperature induced challenges include <u>large cyclic thermal loads</u>, <u>high strain localization at casing connections</u>, and more.
- More field testing is needed for HT<u>HP</u> cement and casing.
- <u>Geochemistry complications</u> in both producers and injectors due to exposure to the formation
- Stimulation load introduces significant cold load with high pressure and <u>axial tension from cooling</u>

Brittle failure at Habanero 3 well, Cooper Basin, AUS

Primary Challenge: laboratory facilities designed for materials testing in SHR conditions



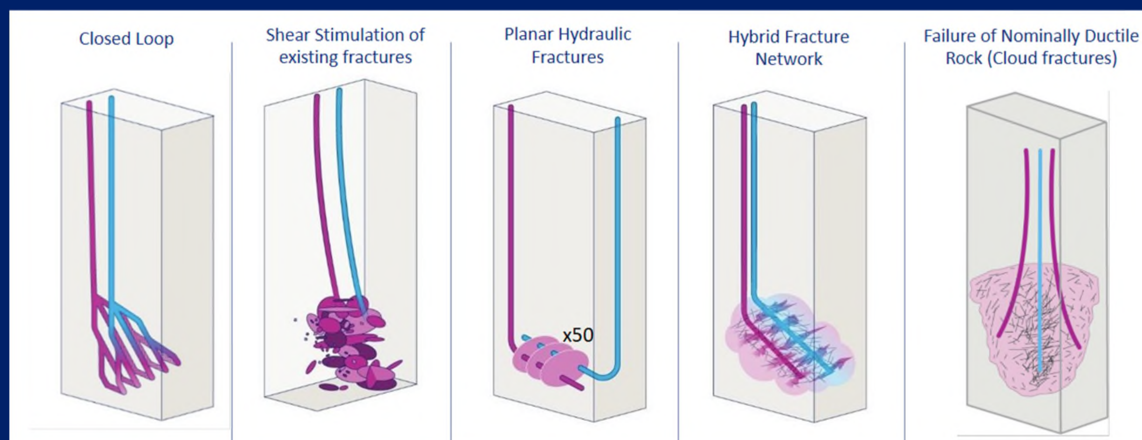
TRL 4 - 8

Heat Extraction (EGS focus – CLGS to come)

Trenton Cladohous - Quaise Energy
Owen Callahan - eeg

Enhanced Geothermal Systems **(EGS) techniques in low-permeability superhot rock have not yet been reported – Activity in the field NOW**.

- **Needed**: Field data and bench scale data to create robust modeling that will more accurately predict fracture propagation and sustained flow.



Primary Challenge: Laboratory development and testing of materials, equipment, and methods for reservoir creation

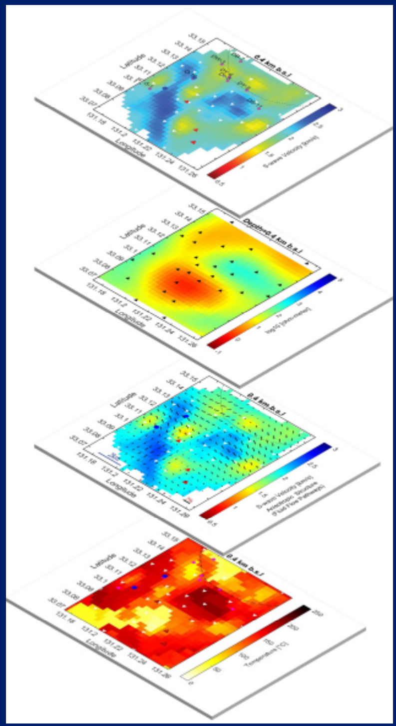
Bridging the Gaps: A Survey of Methods, Challenges, and Pathways Forward for Superhot Rock Siting and Characterization

Authors: Chanmaly Chhun, Kyushu University; Seth Saltiel, Cornell University; Rebecca Pearce, Cascade Institute

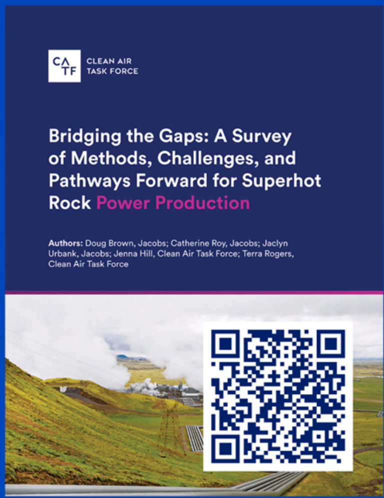
TRL 2 - 9

Siting and Characterization

- Models need to evolve to accurately reflect and predict formation behavior in superhot rock environments, including in the BDT.
- More data is needed from field demonstrations to validate and improve existing subsurface models.
- Lab research is needed to enable downhole sensors to operate in anticipated in SHR environments.
- Study is ongoing. Findings will be relevant throughout the project lifetime, including exploration, siting, development, and life-cycle monitoring phases.



Primary Challenge: Field-validated datasets and laboratory experiments



TRL 5 - 9

Power Production

Doug Brown, P.E. - Jacobs
Jaclyn Urbank, P.E. – Jacobs

"All pieces needed for a superhot rock plant **already exist**, and manufacturers can do it if asked. Development of all the necessary components has already occurred, **but the full power plant system has not been constructed**."

"Future R&D for superhot rock power production should be **focused on achieving cost reductions** and moving from the use of specialized equipment to **off-the-shelf materials**"

Primary Challenge: Develop lower-cost alternatives to materials necessary for optimal power plant design and comparative modeling across design options

SHR power production challenges

Production Pathways and Electricity Demand

- Review the production pathways that can generate 500 MW

Review Cooling System Analysis

- Evaluate the water requirements of the various cooling technologies

Component Specifications and Technology Gap Analysis

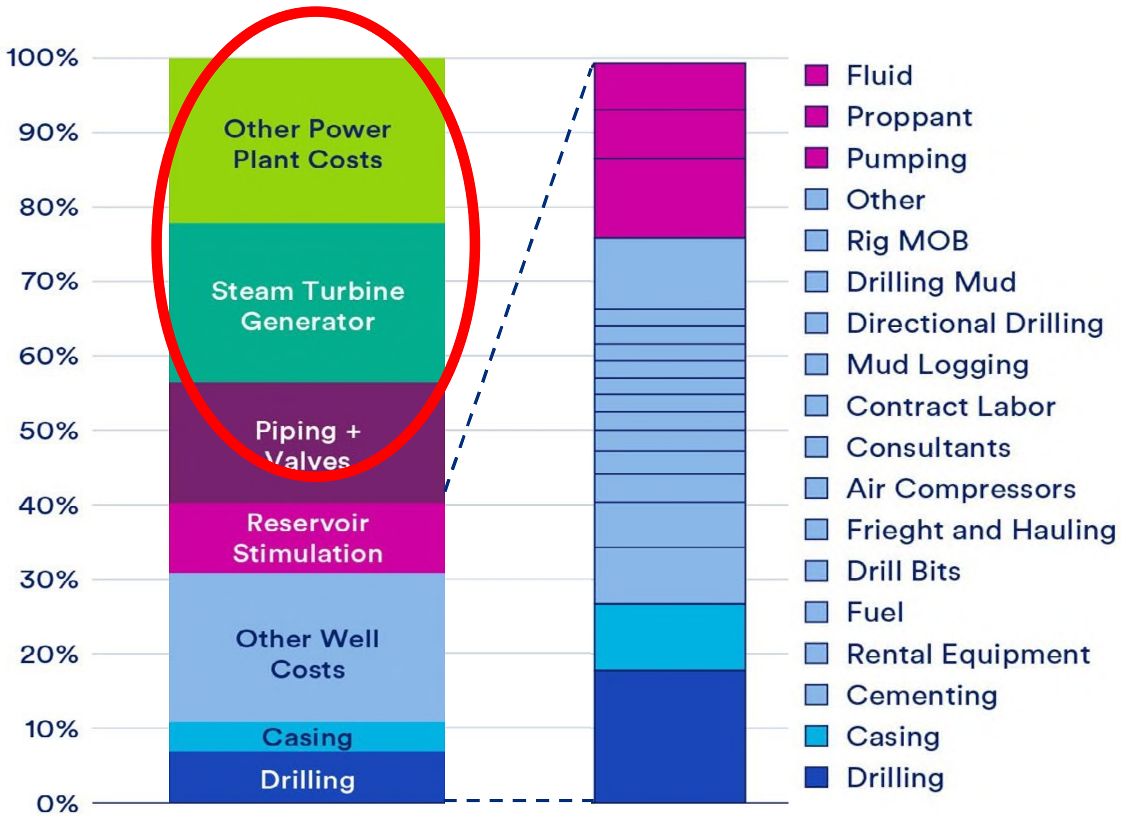
- Develop an equipment list and assess TRL

Cost Estimate

- FOAK Cost estimate for the construction and operation of a Superhot rock (SHR) geothermal power plant

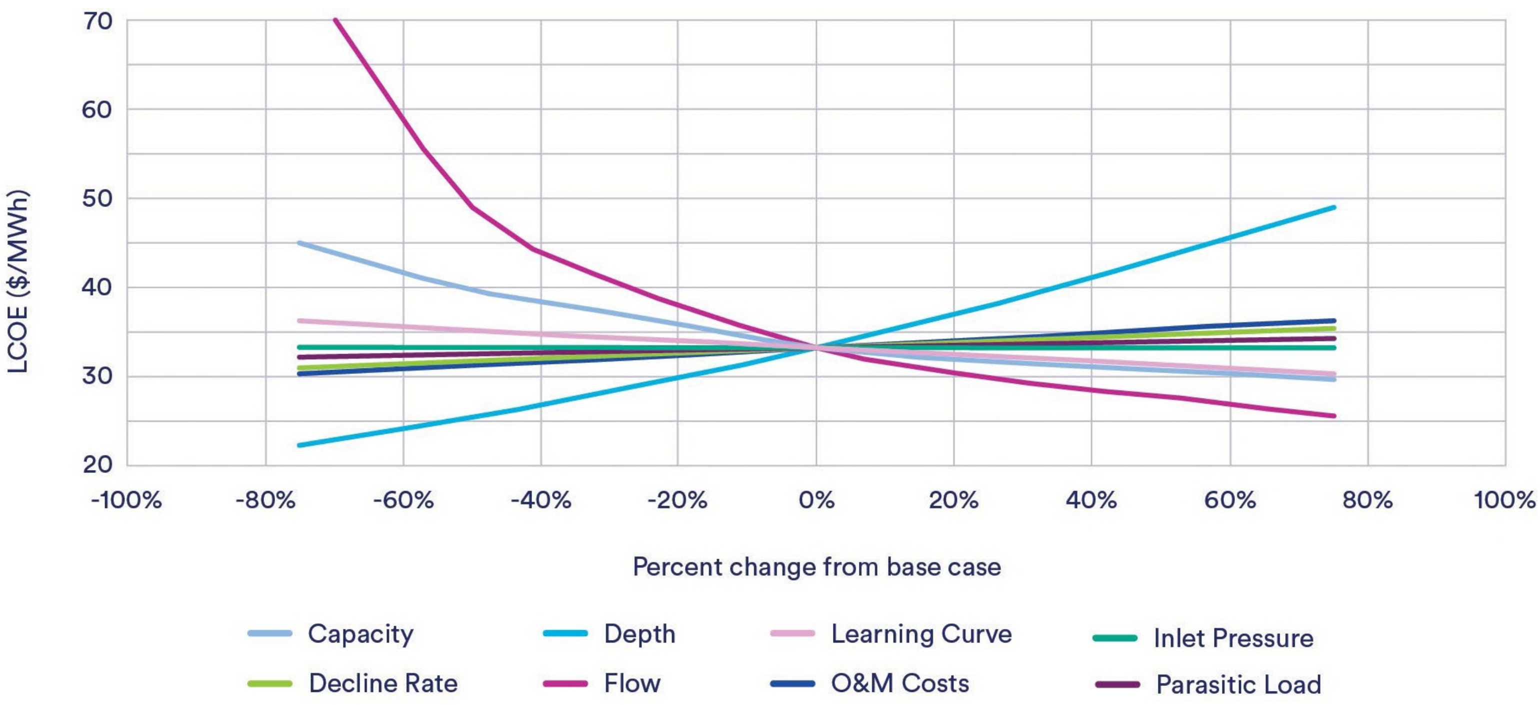
- **Overall system TRL is 5.** All the **equipment** required for surface engineering have a **TRL between 7-9**
- **Steam turbine** for the environments considered to have a **TRL of 5-6**
  - Turbine design requires adaptations to design to handle superheated steam with impurities
- R&D Opportunity: replace high-cost materials used in the design, such as duplex stainless steels or Inconel with **next-generation materials or coatings.**
  - The geothermal environment presents significant challenges for material, so any new materials should undergo **extensive in situ testing.**
  - Develop off-the-shelf materials that both **modularize and standardize** to reduce cost.

Cost Breakdown of a SHR facility

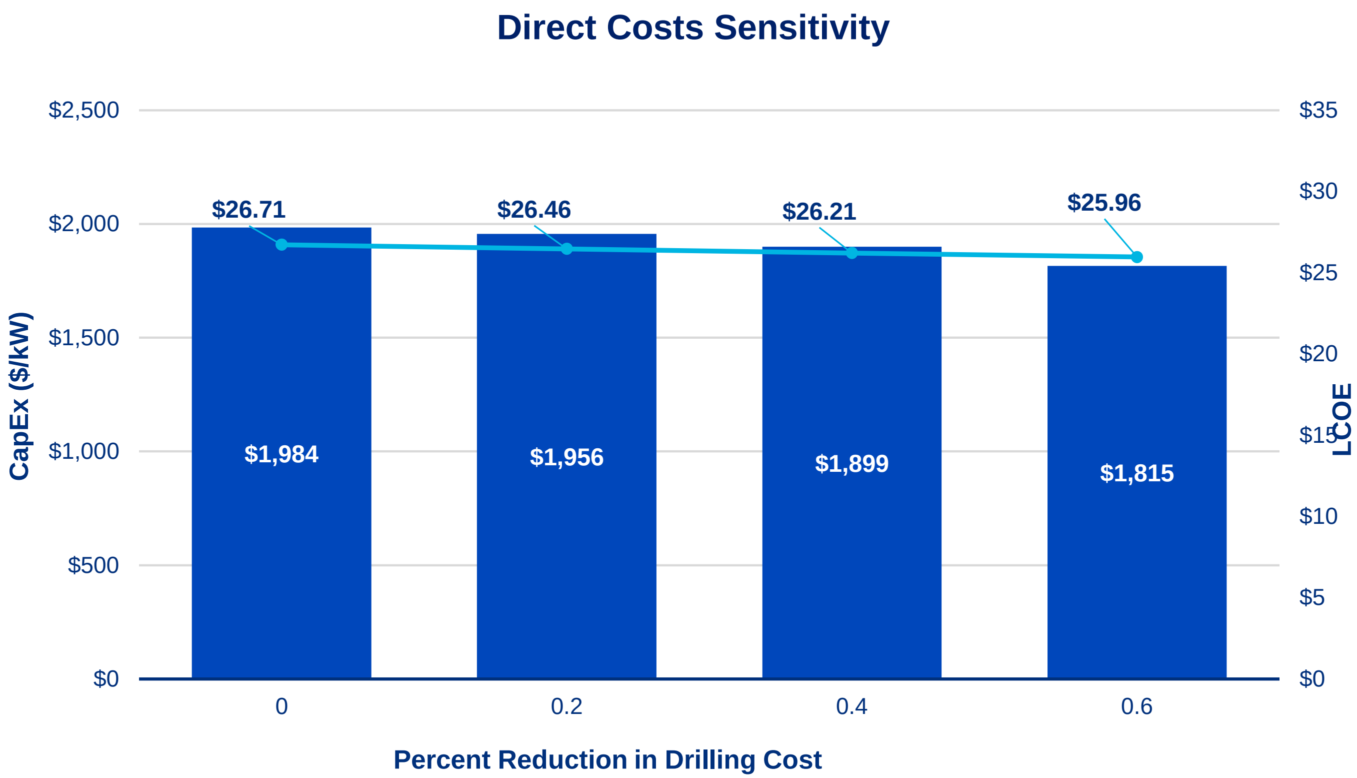


- Cost of first well. The model includes a logarithmic cost reduction curve such that the 10th well is 75% the cost of the first well.
- This cost reduction is applied to all wells beyond the 10th well; however, the incremental cost reduction between each subsequent well is minimal.

Sensitivity Analysis: What variables are most impactful to unlocking competitive costs for Superhot Rock Energy



LCOE Sensitivity to Drilling Costs



Aligning stakeholders and building coalitions

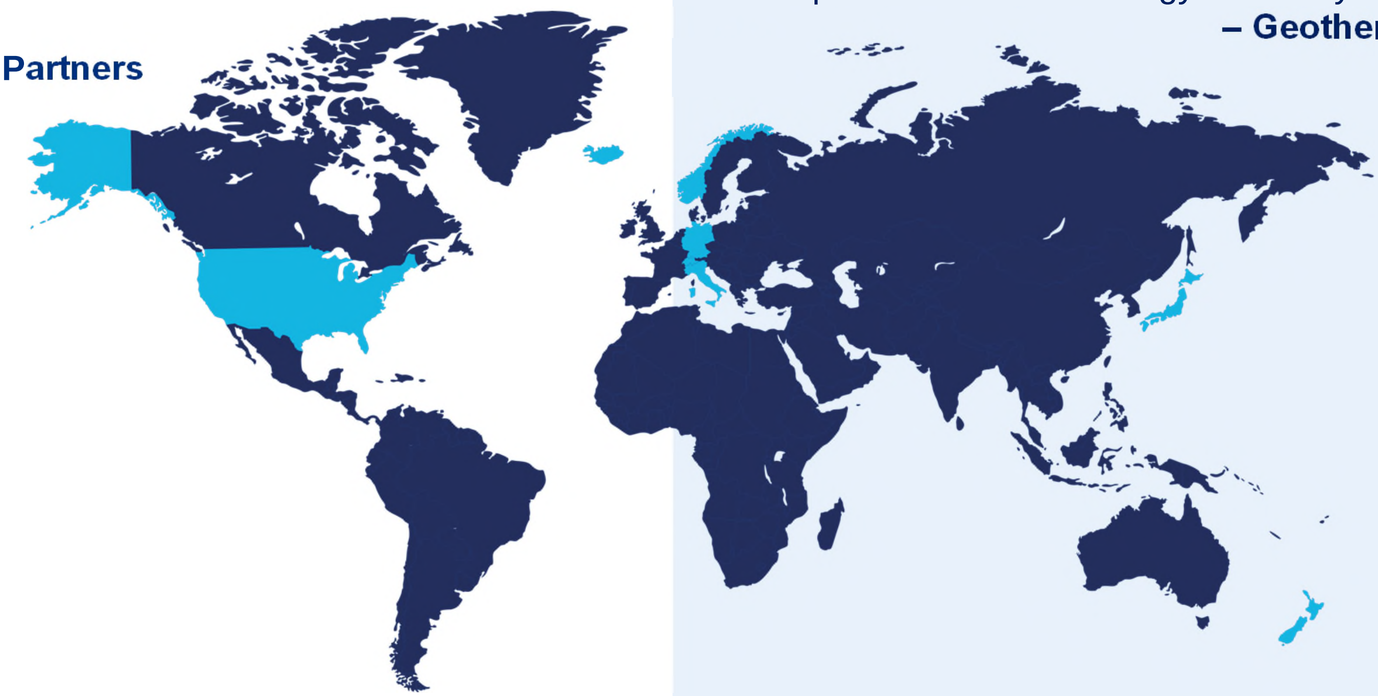
Problem statement: First of a Kind SHR testbeds and **pilots are being designed TODAY** and they need a “place” to share and learn from each other.

What I would give to know what worked (and what didn’t) at other projects **so that we don’t make the same mistakes** and can use our project to push the *real* technology boundary.

– Geothermal Operator

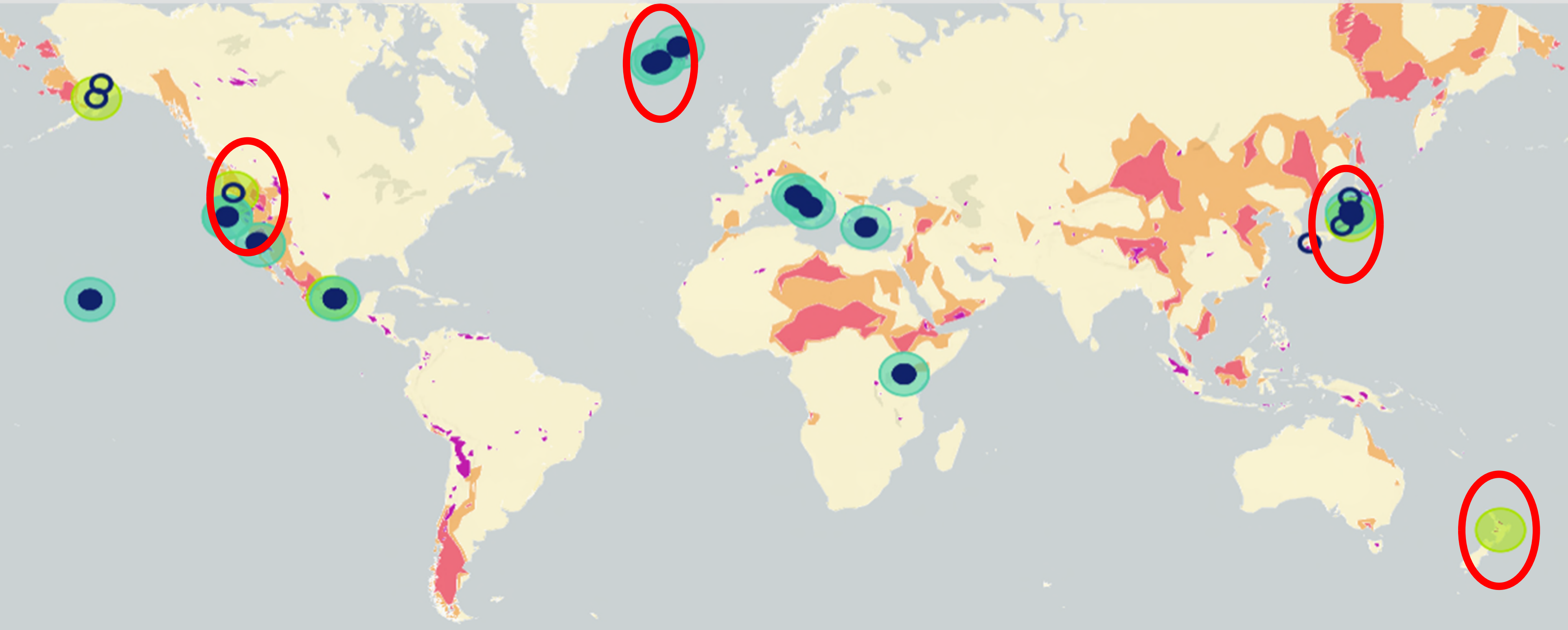
Key International Partners

Iceland
Italy
Japan
New Zealand
Norway
Netherlands
U.S.*



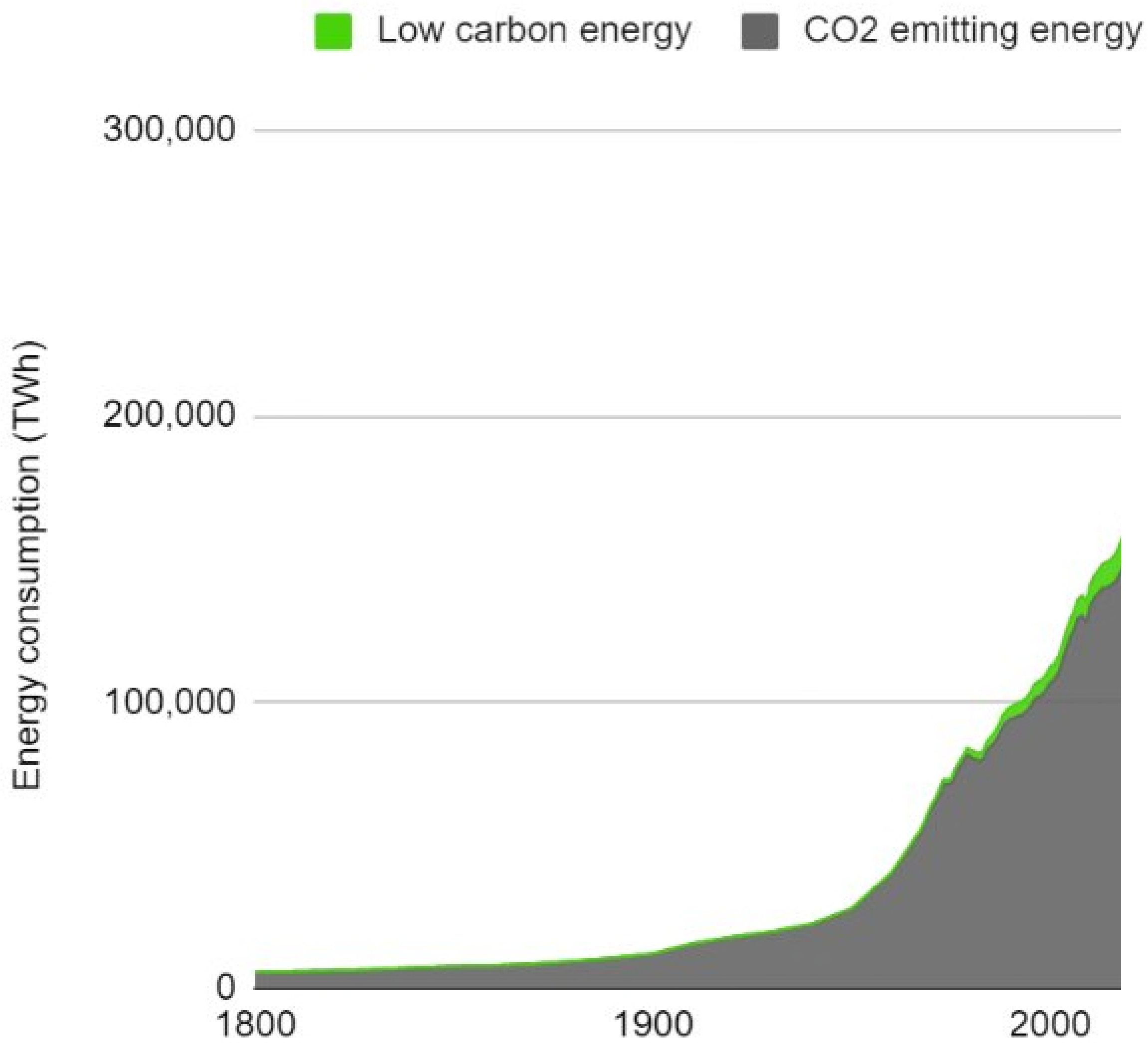
SHR geothermal is happening NOW…

Mazama Energy – In the field in Oregon as we speak
GNS Science – Awarded NZ $60M
Reykjavik Energy – In planning stages of 3 Phase approach
JOGMEC – 4 each 100MW Supercritical projects

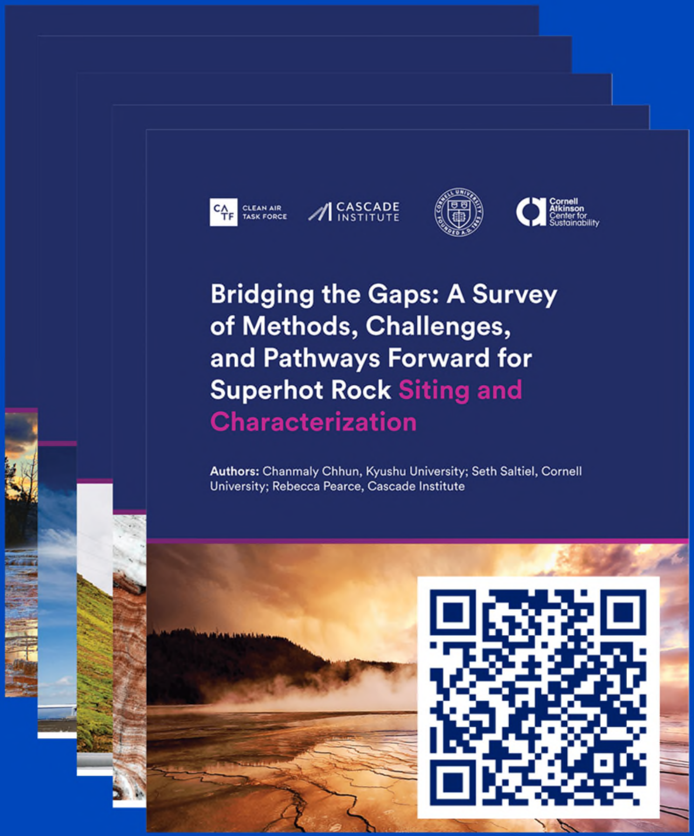


Summary

- **The disruptive potential of SHR is unparalleled** in both its impact on climate as well as the global energy market.
- SHR resources are capable of significant energy market disruption (**Anywhere, Cost Competitive, Renewable**).
- Nth of a Kind SHR facilities are projected to be **cost competitive with fossils in unsubsidized markets.**
- Innovation in electricity production technologies are anticipated to be influential in our effort to **drive down cost and increase penetration.**


Low carbon energy
CO2 emitting energy
300,000
200,000
100,000
0
Energy consumption (TWh)
1800
1900
2000

Thank you



Scan to view reports

What we are facing in practice:

- Demand growth outside of OECD → increased oil and gas consumption
- Focus on affordability
- Energy security and autarky (cuts both ways)
- Inflation and tariff barriers cost of all new build
- End of cheap money that helped fuel the renewables boom
- Fiscal exhaustion
- Ideological opposition to climate goals and green energy

Geothermal energy’s benefits to the grid

Figure 2. **Reliability services provided by clean firm power and other energy technologies**

	Voltage control	Frequency control					Other	
	Voltage control	Inertial response	Primary frequency response	Regulation	Load following	Spinning reserve	Black start capability	On-site fuel inventory
Next-generation geothermal	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	**N/A**
Natural gas CT	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Does not exhibit attribute
Natural gas w/ CCS	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Does not exhibit attribute
Coal w/ CCS	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Partially exhibits attribute	● Exhibits attribute	● Exhibits attribute
Hydropower	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Partially exhibits attribute
Nuclear	● Exhibits attribute	● Exhibits attribute	● Does not exhibit attribute	● Does not exhibit attribute	● Does not exhibit attribute	● Does not exhibit attribute	● Does not exhibit attribute	● Exhibits attribute
Solar	● Exhibits attribute	● Partially exhibits attribute	● Exhibits attribute	● Partially exhibits attribute	● Partially exhibits attribute	● Partially exhibits attribute	● Does not exhibit attribute	**N/A**
Solar + battery	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Partially exhibits attribute	**N/A**
Wind	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Partially exhibits attribute	● Partially exhibits attribute	● Partially exhibits attribute	● Partially exhibits attribute	**N/A**
Wind + battery	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Exhibits attribute	● Partially exhibits attribute	**N/A**

● Exhibits attribute ● Partially exhibits attribute ● Does not exhibit attribute

Notes: CCS = carbon capture and storage; CT = combustion turbine; N/A = not applicable. This is not an exhaustive list of such services.

Sources: WRI authors, adapted from NERC (2023) and EPRI (2015) and supplemented with personal communications with industry experts.

Source: https://www.wri.org/research/next-generation-geothermal-considerations-and-opportunities-responsible-development