Super Hot EGS

Reducing the Cost of Geothermal Through Technology Breakthrough

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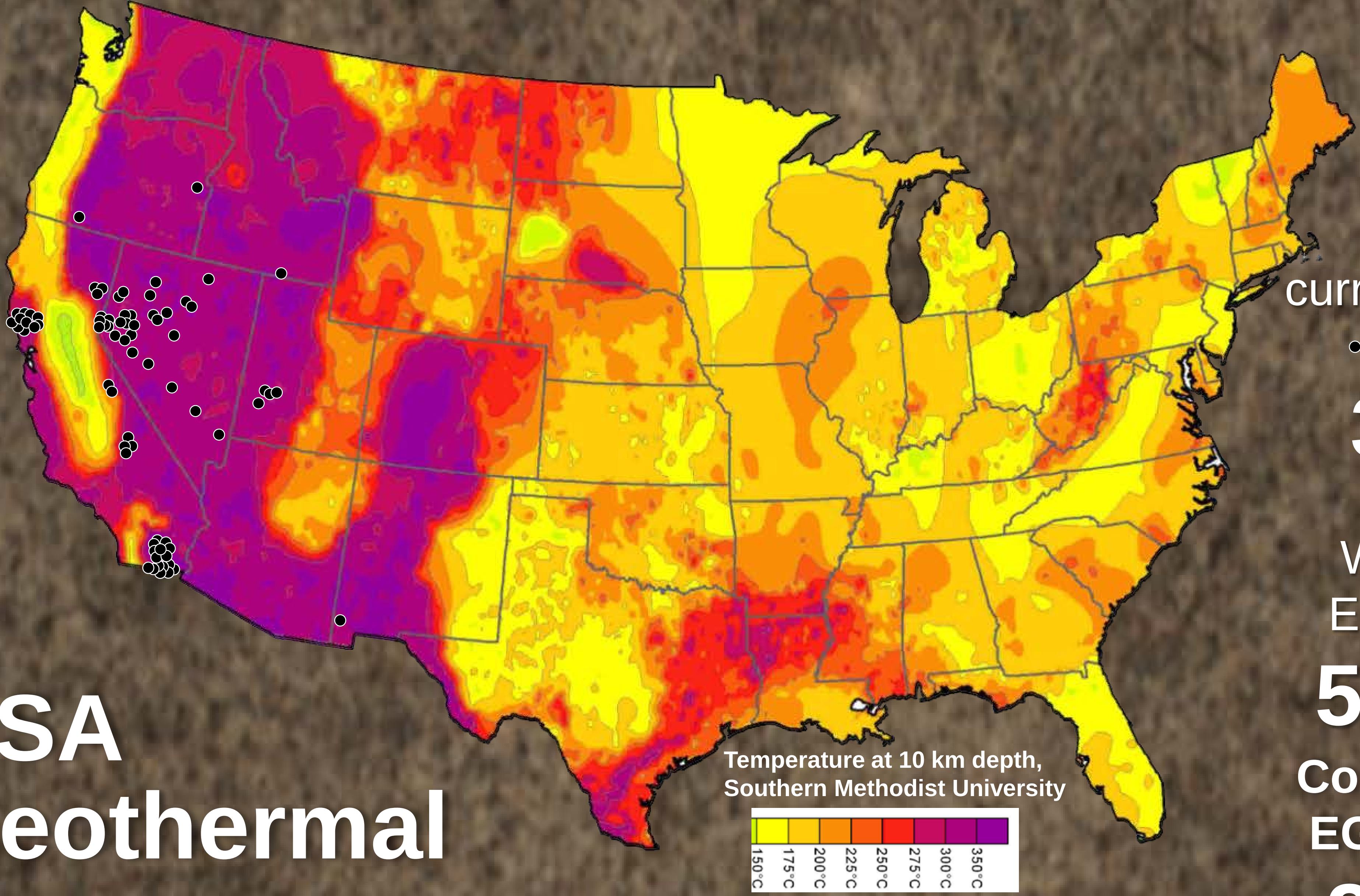
USA Geothermal Resources



Temperature at 10 km depth, Southern Methodist University

current conventional
• geothermal

3.5 GW

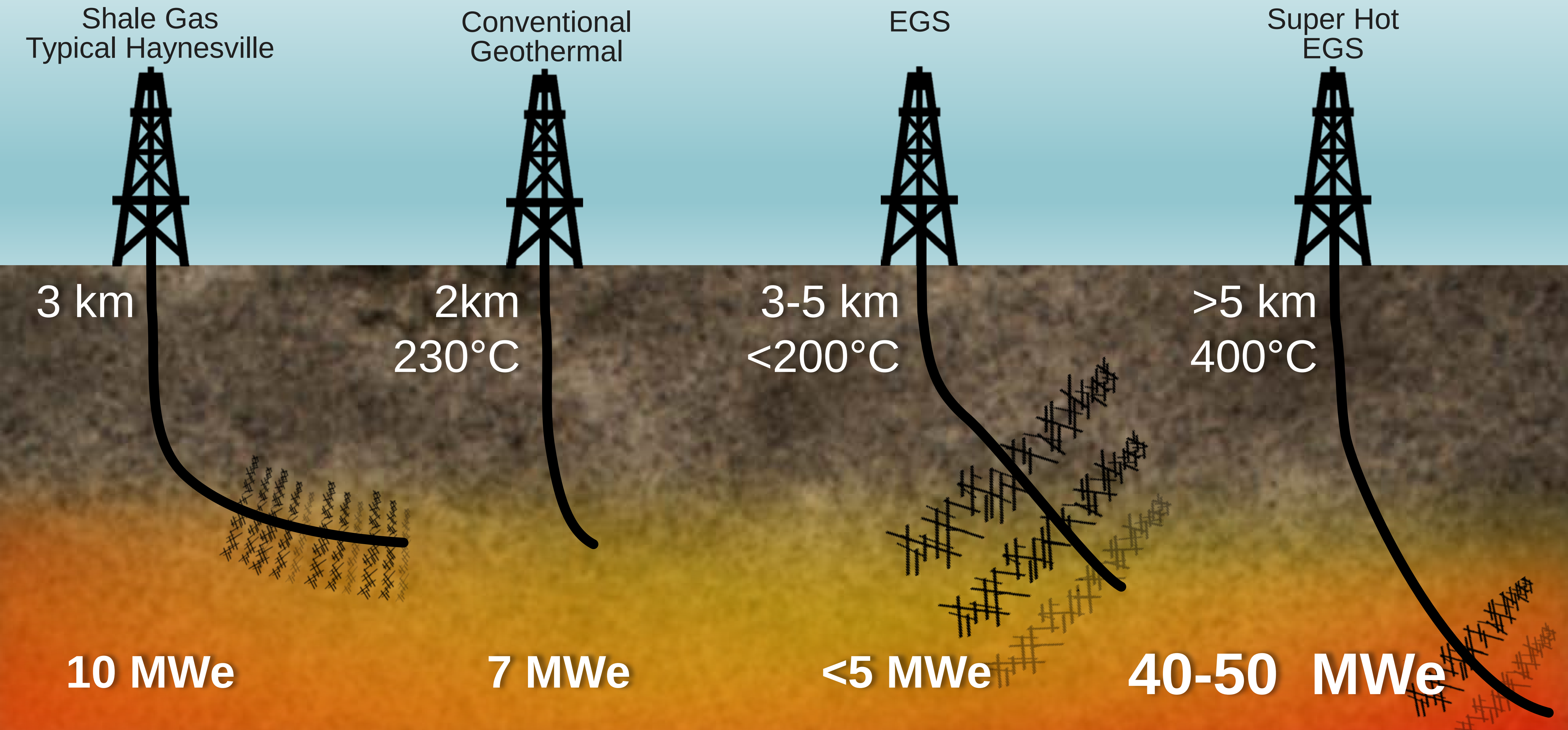
Western US
EGS potential

500 GW

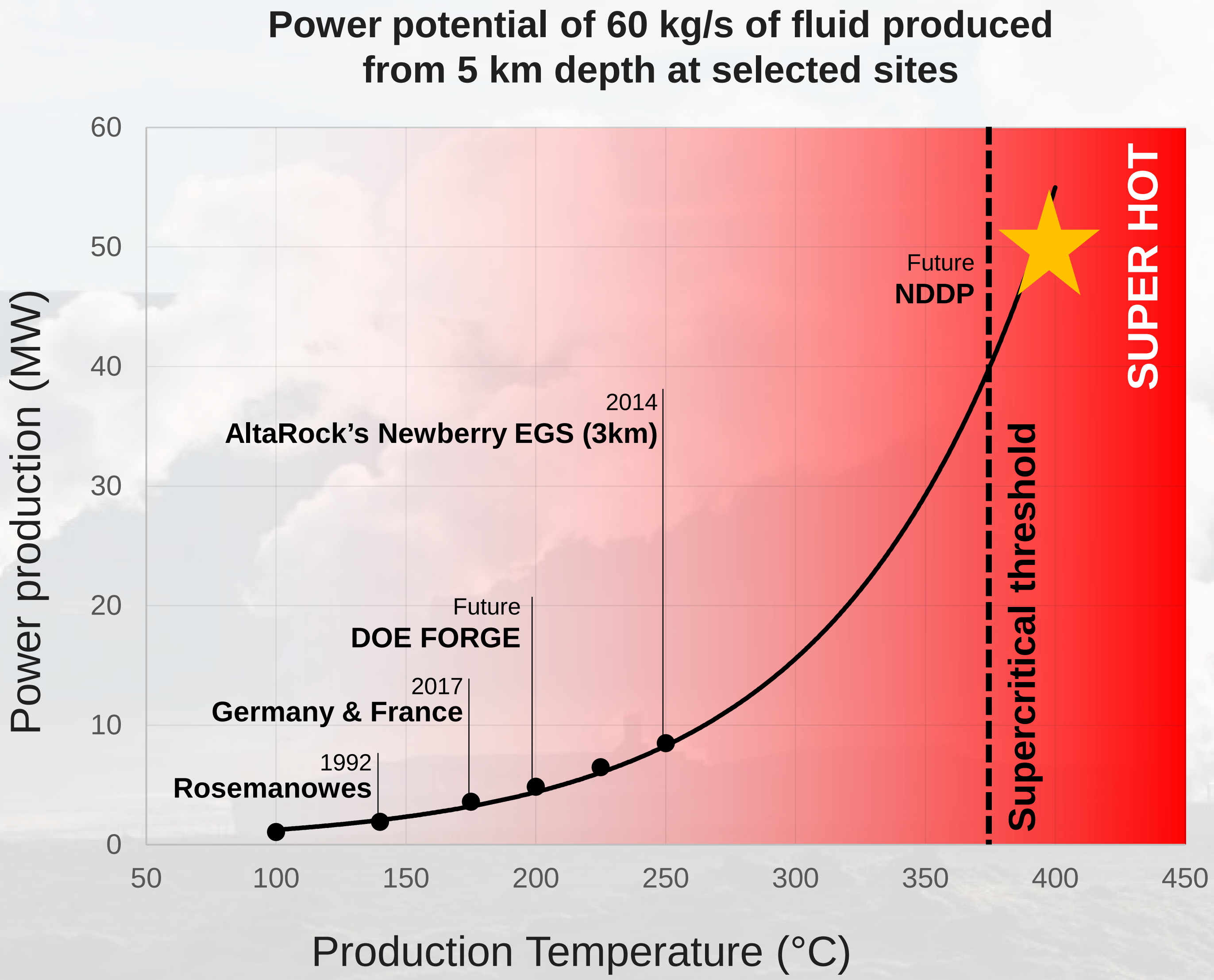
Continental US EGS Potential

2.3 TW

Energy per Well



Performance Moonshot

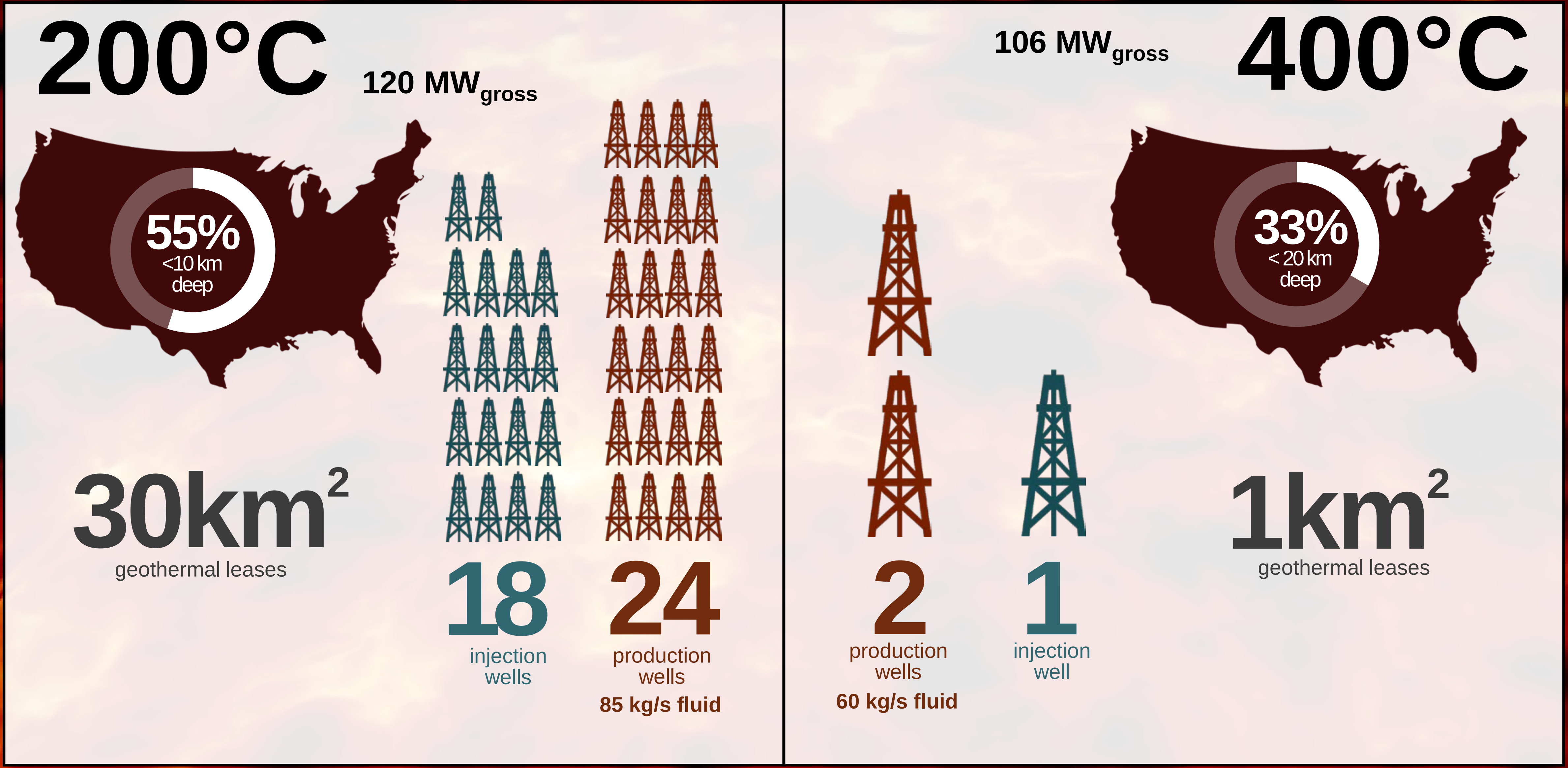


50 MWe/well

compared to 5 MWe/well at 200°C

10x output/well

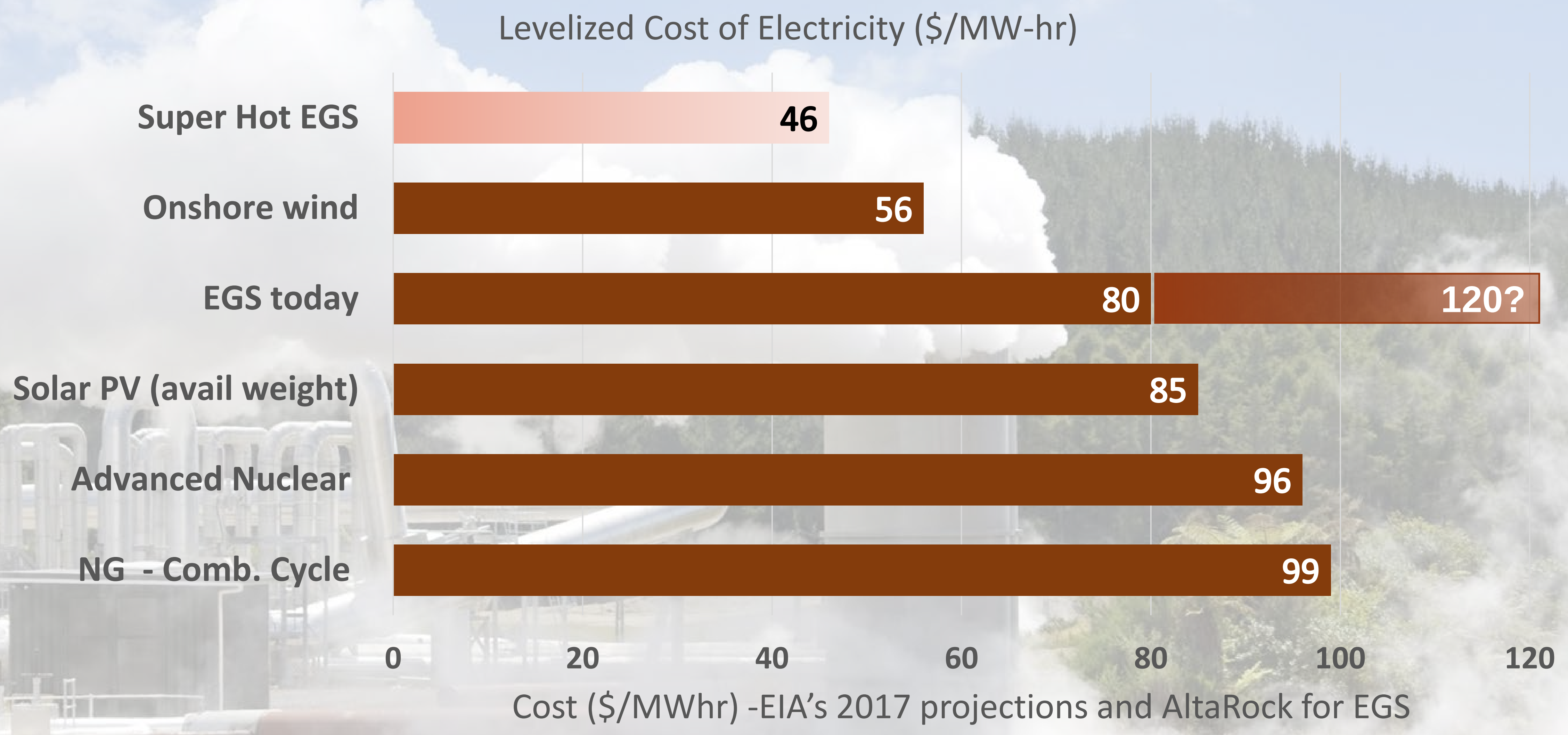
- 5x producing potential compared to liquid water at 200°C
- 2x higher conversion efficiency of thermal heat to electricity



Temperature Matters

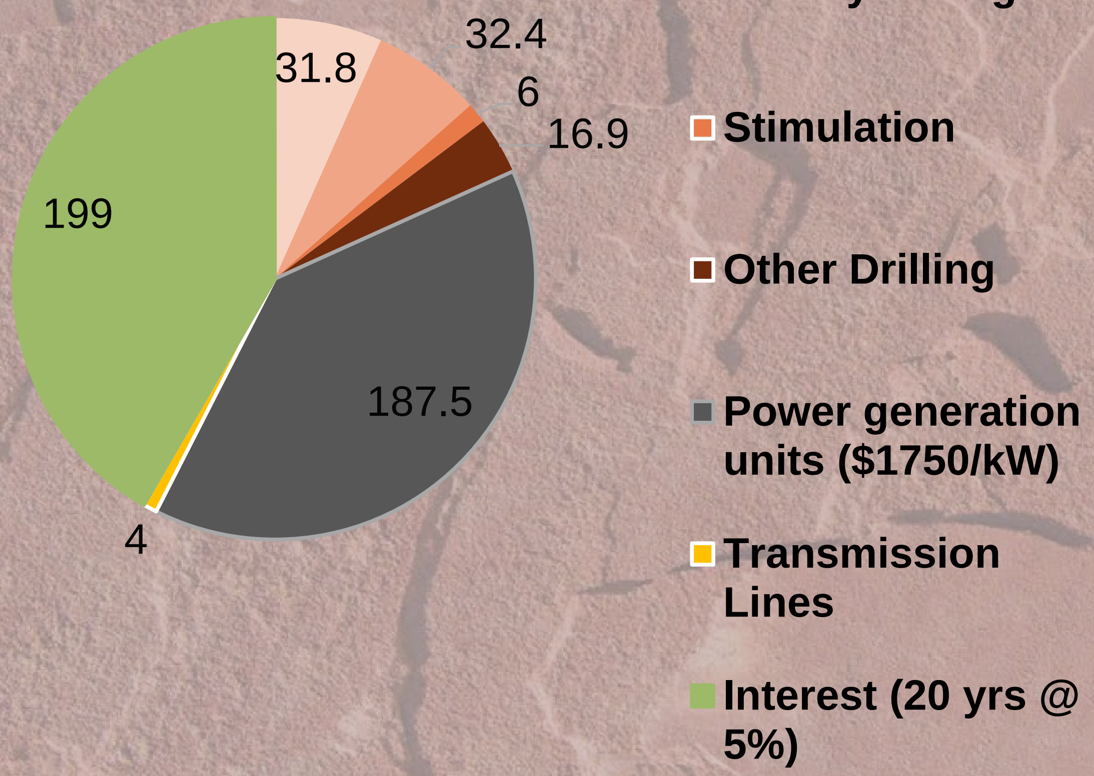
100 MW utility-scale plant

Economic Advantage – plants online in 2022



LCOE for 100 MW Super-hot project

Capital and Interest Cost (million dollars)



Revenue

100-83 MW for 20 years

2% annual resource decline

With redrills at 10 years

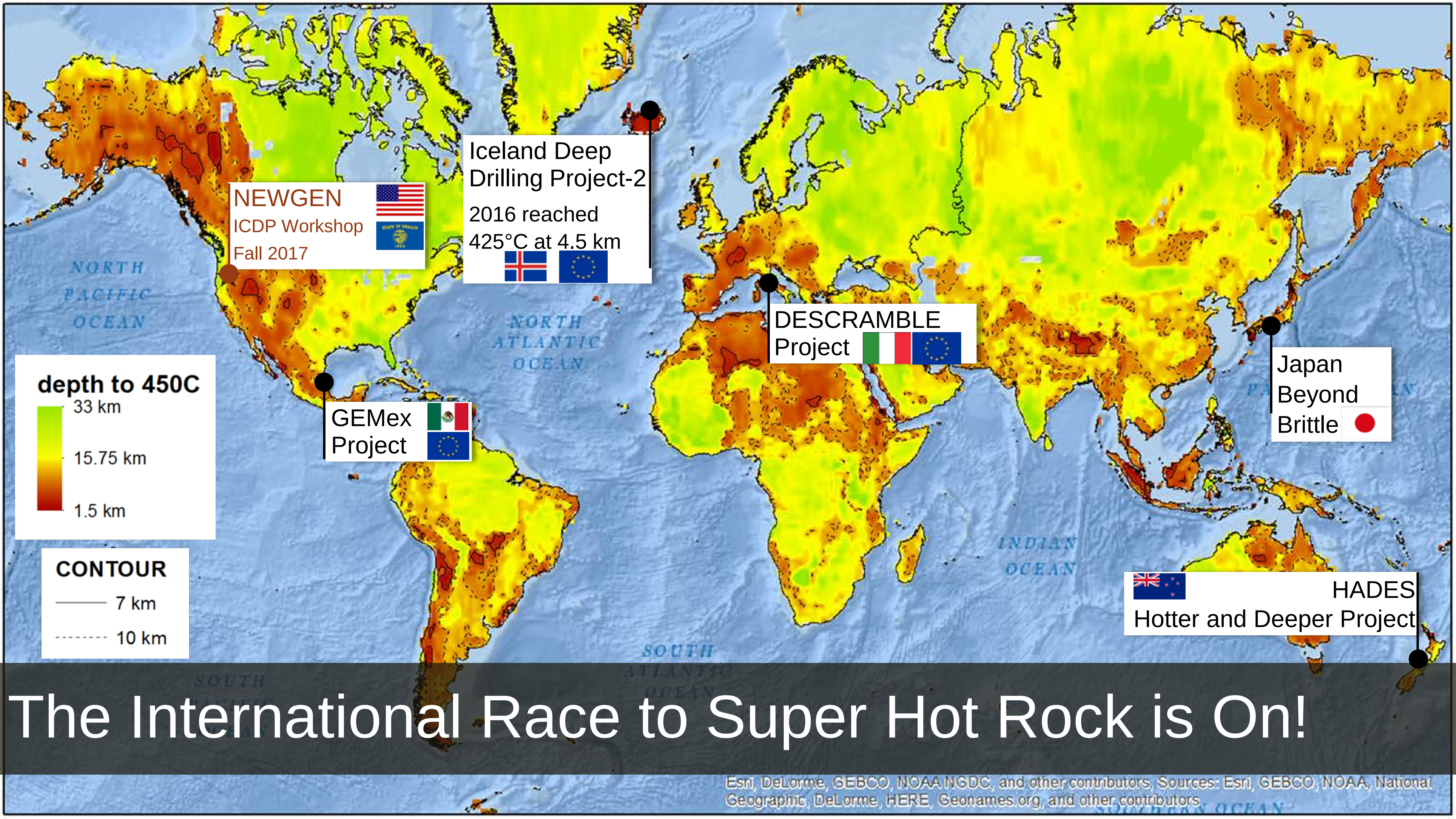
Ongoing Expenses

$6M / year O&M

$42M in year 10 for redrills

6% discount rate

LCOE = $46/MWh



NEWGEN
ICDP Workshop
Fall 2017
Iceland Deep
Drilling Project-2
2016 reached
425°C at 4.5 km
DESCRAMBLE
Project
GEMex
Project
Japan
Beyond
Brittle
HADES
Hotter and Deeper Project
depth to 450C
33 km
15.75 km
1.5 km
CONTOUR
7 km
10 km
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
INDIAN OCEAN
SOUTH ATLANTIC OCEAN
The International Race to Super Hot Rock is On!
Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors, Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Super Hot EGS *is* the ideal energy source

Dependable

95% available

Flexible

Peaking available

Widely Deployable

16% world pop. at <10 km

81%world pop. at <20 km

High Energy Density

100 MW/km^2

Free Fuel

400°C fluid

Low Cost

$46/MW-hr

Innovations needed: Temperature

Improvement in drilling equipment and techniques at >400°C:

bits, coring, & mud

Advanced well construction materials:

casing, couplings, & cement

Reservoir creation and maintenance techniques in super hot rock:

hydraulic, thermal, & chemical

Characterization:

Sonic & image logs, fiber optic, stress measures, seismic calibration and sensors

Start in Magmatic Areas

Improvement:
Drilling Equipment and Techniques at >400°C:

Current Technology

- Cool well with water/aerated water
- Underbalanced drilling for hole cleaning
- Pressure control through cooling
- Maintain cooling throughout drilling and completion process. Prevent thermal cycling.
- HT mudmotors for directional control cooled with water/aerated water
- Logging while tripping for directional/T/P data
- Roller cone bits with metal/metal seals

Technology Improvement

- Cooling through water/aerated water/liquid nitrogen
- Pressure controlled drilling with HT stable polymer sweeps
- Well casing and cement design to withstand thermal cycling
- HT mudmotors with very HT electronics for directional control cooled with liquid nitrogen
- Solid body bits with cavitation

Improvement: Advanced Well Construction Materials

Technology

Current Technology

- Foamed reverse circulation cementing with HT stable cement formulations up to 325C
  - Brittle noncompliant cement can fail with thermal cycling. Foamed cement is compliant
  - At very high temperatures, cement systems will not crystallize
  - Gaps in cement fatal flaw. Foamed cement expands
- Well designs for very HT from thermal heavy oil recovery used with success in geothermal
- Casing connections
  - Connections that seal in compression and tension withstand thermal cycling with foamed complete cement job work
  - Casing connection failures still a large problem
  - Testing at very high temperature has been limited
  - Most connections tested by modeling
- Casing materials
  - Titanium works but is very high cost
  - High strength alloys may not last through thermal cycles
  - Supercritical fluids can be highly corrosive

Technology Improvement

- Ultra high temperature stable compliant cements – very high silica content
  - Superfine sand well sealing systems
  - New very HT cements needed. Must be compliant/elastic to withstand thermal cycling
  - Materials testing facilities for very HT limited
- Well completion designs for very temperature and thermal cycling need modeling and testing
  - Most models can't handle supercritical temperatures
  - Lab facilities have limited sample size
- Casing connections designed to seal through thermal cycling need testing at scale
  - Current testing is through modeling only
  - Connection failure in IDDP-2
- Casing materials – Innovations used in space probes may be extended to very HT geothermal

Improvement: Reservoir Creation And Maintenance Techniques In Super Hot Rock

Technology

Current Technology

- Hydroshearing through pressure injection along entire open hole
- Pre-existing permeability needed for good results
- Zonal isolation through diverters in perfed liners or modified oil field packers in open hole
- Multizone stimulations limited to areas with pre-existing permeability
- Can create really large stimulated volumes
- Require large amounts of water and long stimulation times
- Stress changes with depth as brittle/ductile transition is approached a challenge for creating large stimulated volumes

Technology Improvement

- Combine tensile fractures near the wellbore with hydroshearing in the far field
- Fracture initiation in impermeable hard, brittle very hot rock
- Zonal isolation in holes with perforated liners to achieve multizone stimulation with very high flow rates
- Create large stimulated volumes with low water methods, shorter times
- CO_2 based stimulation methods
- HT stable targeted explosive fracture initiation
- Cryogenic stimulation to solidify and extend fractures in ductile rock

Improvement: Characterization

Current Technology

- Fracture imaging:
  - Wellbore cooling above ~250C
  - Ultrasonic BHTV (Sandia) temperature limit ~275C. Rotating element fails
  - Microresistivity requires cooling to about 175C
- Logging cable upper limit 300C (600F) but few available
  - Memory tools using lithium batteries for temperatures above 300C in heat shielded tools
  - Lithium batteries can explode above 165C. Must be kept cool
  - MWD/LWD requires cooling through circulation
  - Logging while tripping in cooled wellbore
- Production logging: PTS on wireline up to 300C. Over 300C using memory tools
- Sonic/neutron density/gamma/resistivity in heat shielded tool on HT cable limited to 300C
- Fiber optic DTS/DAS
  - Critical for monitor stimulation
  - Fails above ~250C

Technology Improvement

- Phased array ultrasonic borehole imager using HT electronics in heat shield avoids moving parts. In development.
- Extended HT cable limit using polyaramid for strength and water proofing/weight reduction
- HT stable batteries – recent breakthrough needs development/testing
- Ultrasonic flow measurement for no-moving-part velocity logging
- MWD/LWD needs HT batteries plus better connections on wired drill string
- Fiber optic sensors and cable for >350C needed

Innovations needed: Depth

Well completion techniques and materials to economically reach 10-20 km

Next generation drilling equipment,

energetic drilling, casing while drilling

Super Hot EGS Anywhere

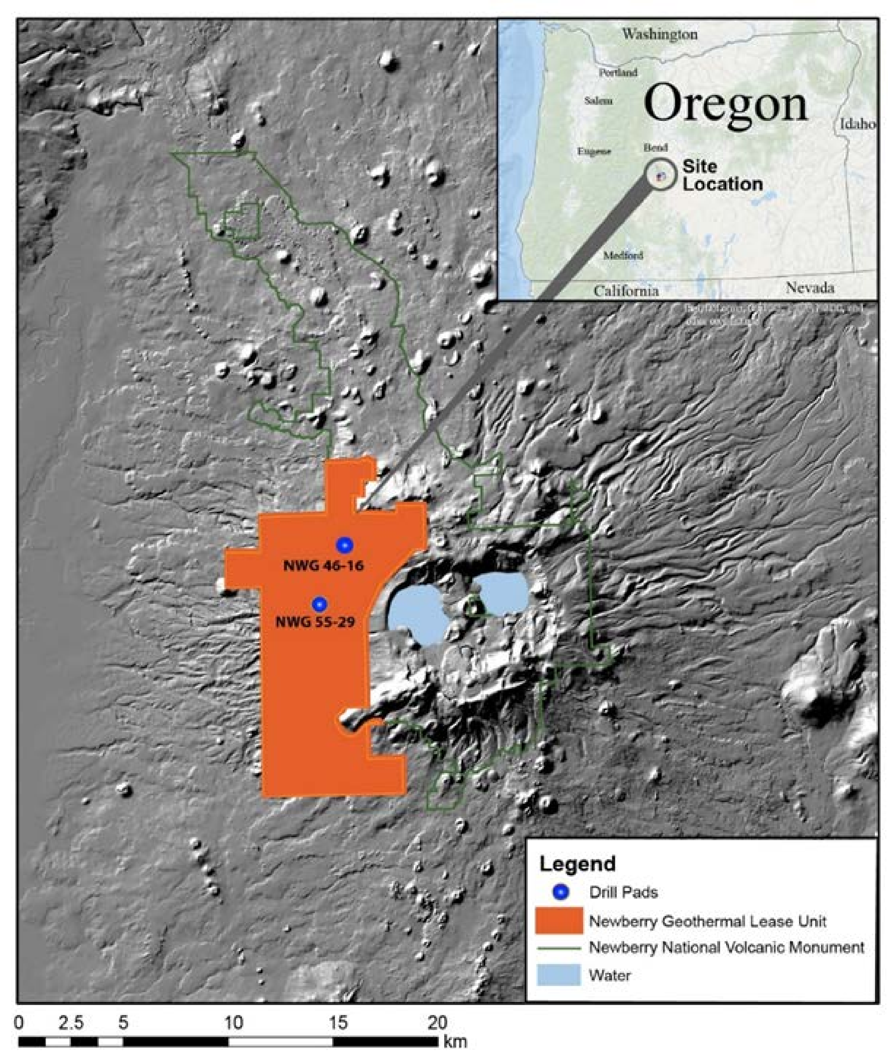
Breakthrough

Super Hot Site at Newberry

Newberry Geothermal Energy

Two Geothermal wells drilled in 2008

- 55-29 and 46-16
- Depth: 3.1 and 3.5 km
- BHT: 325 ^{0}C and 340 ^{0}C
- Gradient: 110 ^{0}C/km
- Target: 500 ^{0}C at 4.6 km



Newberry Deep Drilling Project

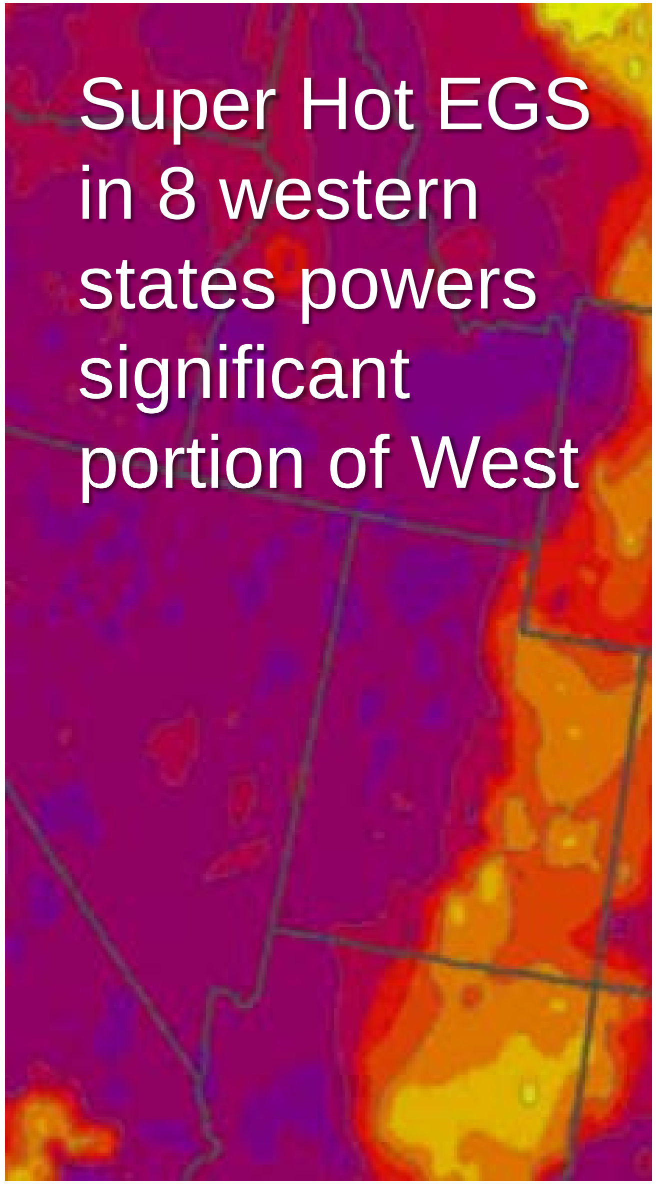
Project to deepen 46-16 to supercritical temps

ICDP Workshop, Bend, OR, Sept. 2017

55 participants from 11 countries

Goals

- test technology for drilling, well completion, and geophysical monitoring in a very high temperature environment.
- test EGS above the critical point of water
- collect samples of rocks within the tectonic brittle-ductile transition
- investigate volcanic hazards
- study magmatic geomechanics
- calibrate geophysical imaging techniques



Achievements – 10 year plan