# The Future of Geothermal Energy in the US

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- ☐ Motivation and scope of assessment
- ☐ Geothermal resource
- ☐ Technology status for heat extraction and conversion
- ☐ Environmental attributes and constraints
- ☐ Economics projections
- ☐ Summary of findings and recommendations

# Multidisciplinary EGS Assessment Team

**Panel Members**

- Jefferson Tester, chair, MIT, energy systems specialist, chemical engineer
- Brian Anderson, University of West Virginia, chemical engineer
- Anthony S. Batchelor, GeoScience, Ltd, rock mechanics and geotechnical engineer
- David Blackwell, Southern Methodist University, geophysicist
- Ronald DiPippo, power conversion consultant, mechanical engineer
- Elisabeth Drake, MIT, energy systems specialist, chemical engineer
- John Garnish, physical chemist, EU Energy Commission (retired)
- Bill Livesay, Drilling engineer and consultant
- Michal Moore, University of Calgary, resource economist
- Kenneth Nichols, Barber-Nichols, CEO (retired), power conversion specialist
- Susan Petty, Black Mountain Technology, reservoir engineer
- Nafi Toksoz, MIT, seismologist
- Ralph Veatch, reservoir stimulation consultant, petroleum engineer

**Associate Panel Members**

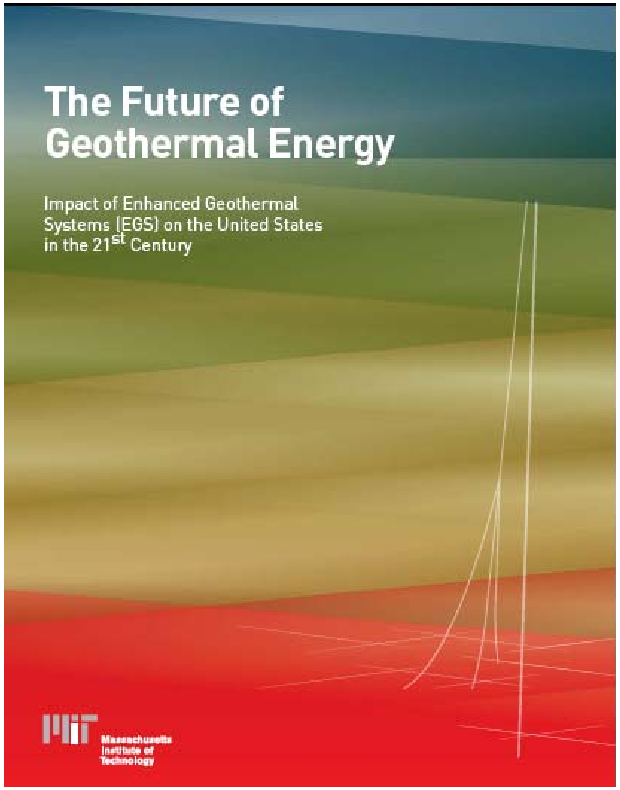
- Roy Baria, former Project Director of the EU EGS Soultz Project , geophysicist
- Enda Murphy and Chad Augustine, MIT chemical engineering research staff
- Maria Richards and Petru Negraru, geophysists, SMU Research Staff

**Support Staff**

- Gwen Wilcox, MIT

# The Future of Geothermal Energy

## Energy Recovery from Enhanced/Engineered Geothermal Systems (EGS) – Assessment of Impact for the US by 2050



The Future of Geothermal Energy

Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century

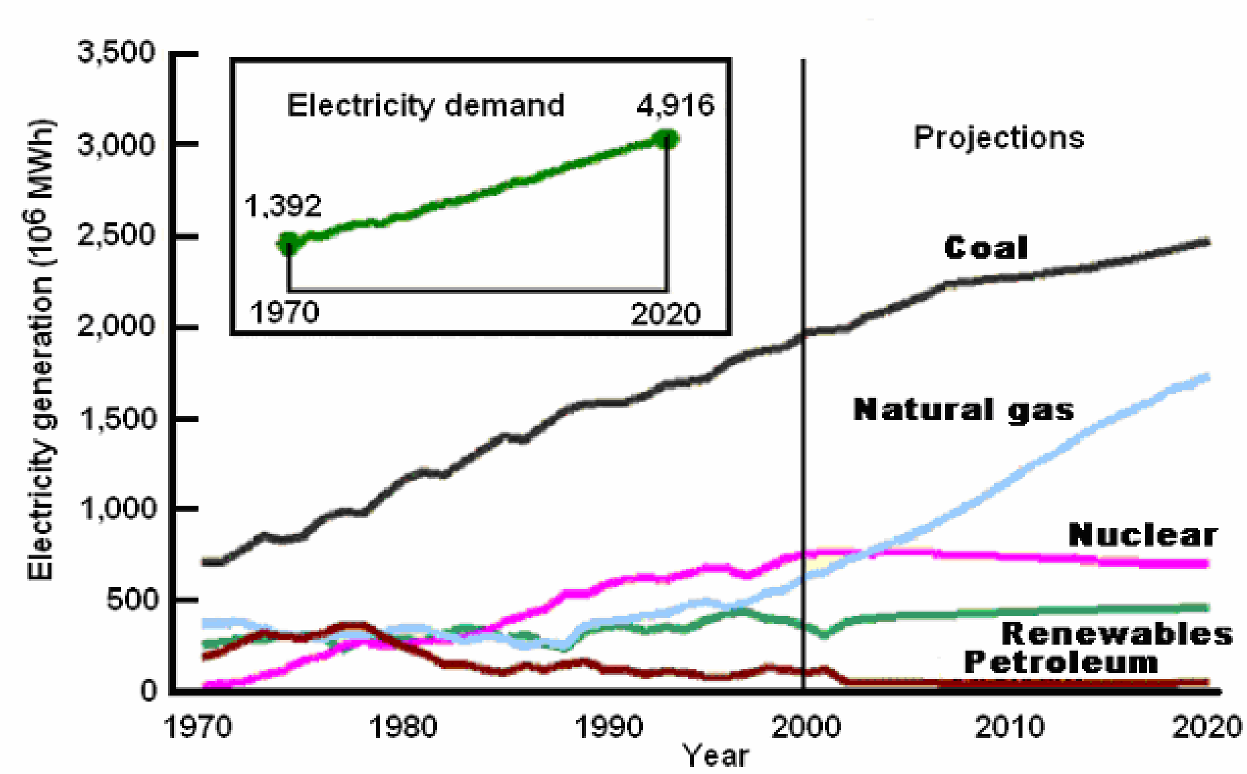
Massachusetts Institute of Technology

**An MIT– led study by an 18- member international panel**

Primary goal – to provide an independent and comprehensive evaluation of EGS as a major US primary energy supplier

Secondary goal – to provide a framework for informing policy makers of what R&D support and policies are needed for EGS to have a major impact

# Projected growth in US electricity demand and supply



US electricity generation by energy source 1970-2020 in millions of MWe-hr. Source: EIA (2005)

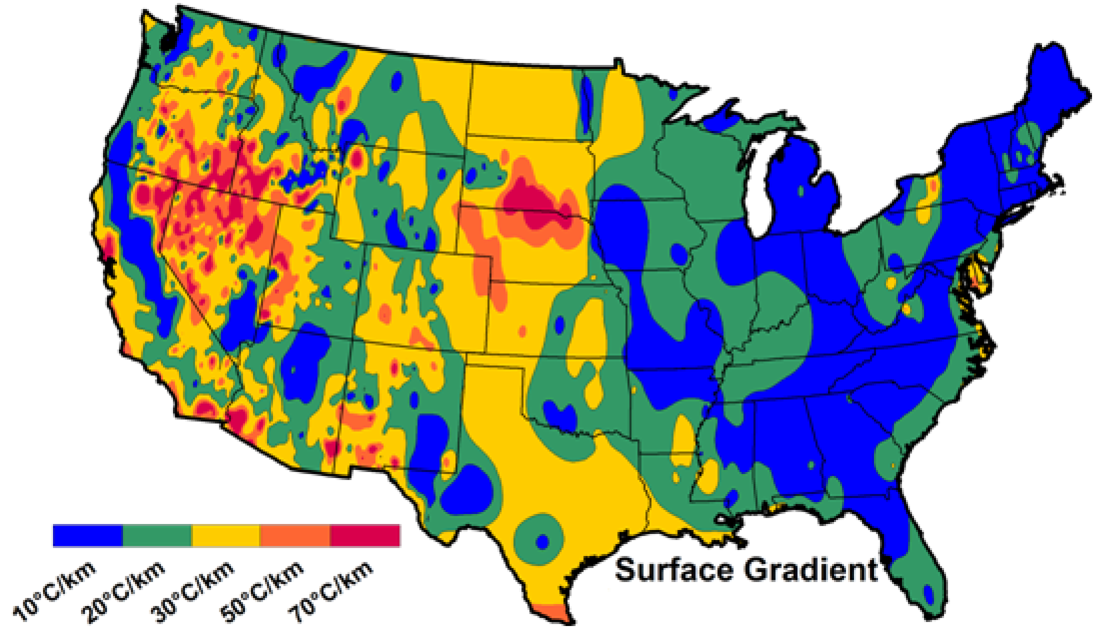
**Current US generating capacity is now about 1,000,000 MWe or 1 TWe**

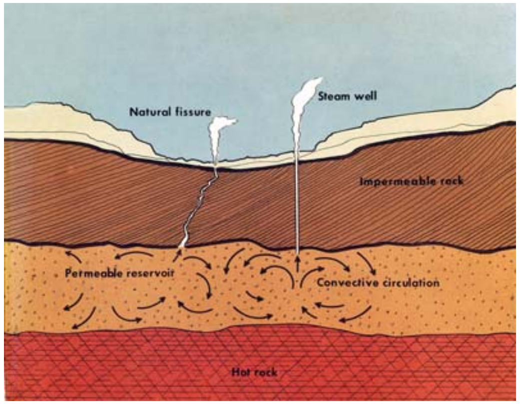
# Key motivations for finding more sustainable options for supplying U.S. electricity for the long term

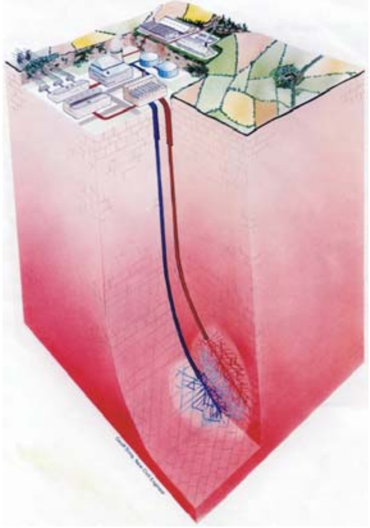
1. **The US energy supply system is threatened** for the long term with demand for electricity outstripping supplies in the next 15 to 25 years
    - ☐ In the next 15 to 20 years 40 GWe of “old” coal-fired capacity will need to be retired or updated because of a failure to meet emissions standards
    - ☐ In the next 25 years, over 40 GWe of existing nuclear capacity will be beyond even the most generous re-licensing accommodations
2. **Projected availability limitations and increasing prices for natural gas** are not favorable for large increases in electric generation capacity for the foreseeable future
3. **Public resistance to expanding nuclear power** is not likely to change in the foreseeable future due to concerns about waste and proliferation. Other environmental concerns will limit hydropower growth as well
4. **High costs of new clean coal plants** as they have to meet tightening emission standards and may have to deal with carbon sequestration.
5. **Infrastructure improvements needed** for interruptible renewables including storage, inter-connections, and new T&D are large

# The Geothermal Option – a missed opportunity for the US ?

Is there a feasible path from today's hydrothermal systems with 3000 MWe capacity to tomorrow's Enhanced Geothermal Systems (EGS) with 100,000 MWe or more capacity by 2050 ?

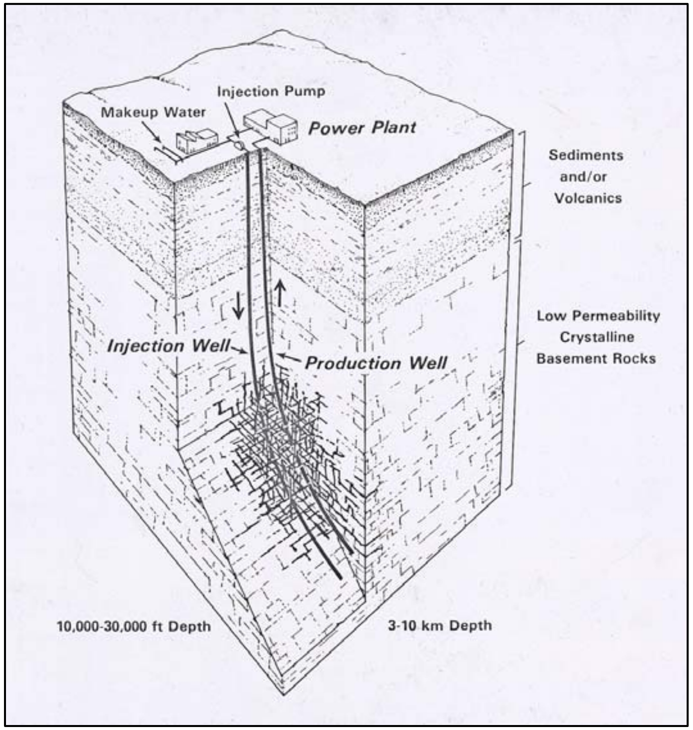


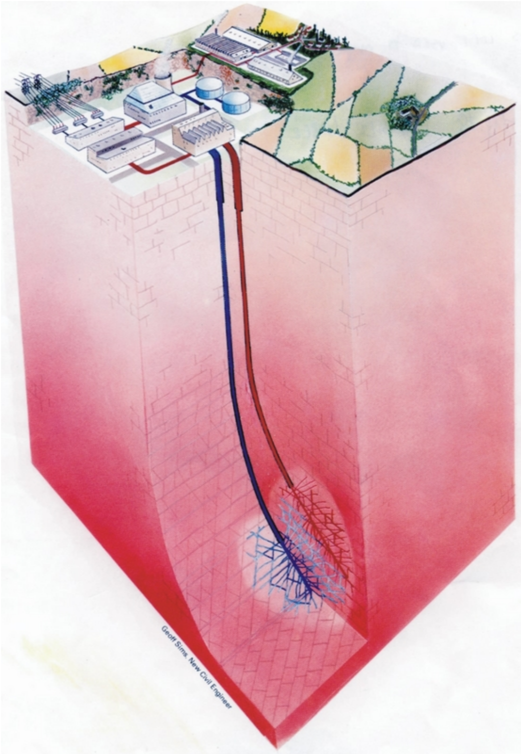




**Geothermal resources within a continuum from high-grade hydrothermal to high and low grades of EGS**

# Enhanced/Engineered Geothermal Systems (EGS)





**EGS defined broadly as engineered reservoirs that have been stimulated to extract economical amounts of heat from unproductive geothermal resources.**

# Approach – 4 key elements of the assessment

1. EGS resource within the geothermal continuum

2. Technology status for heat extraction and conversion

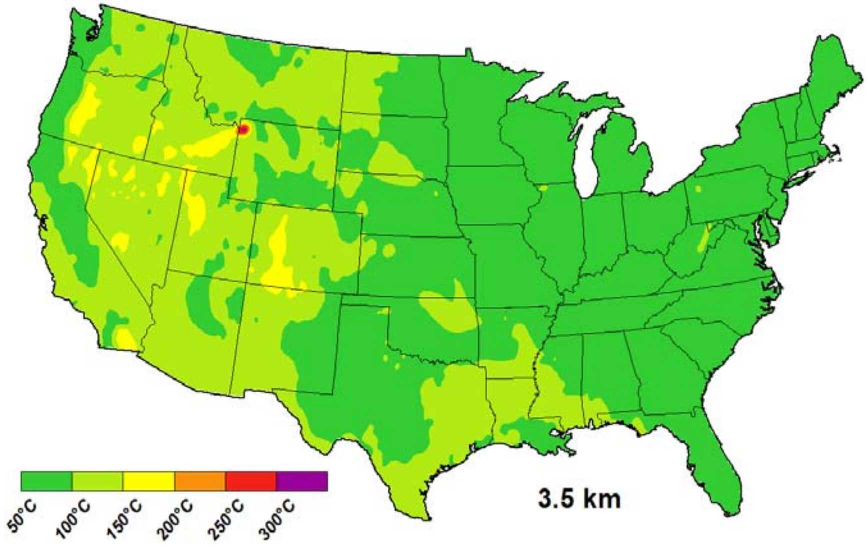
3. Environmental attributes and constraints

4. Economic projections

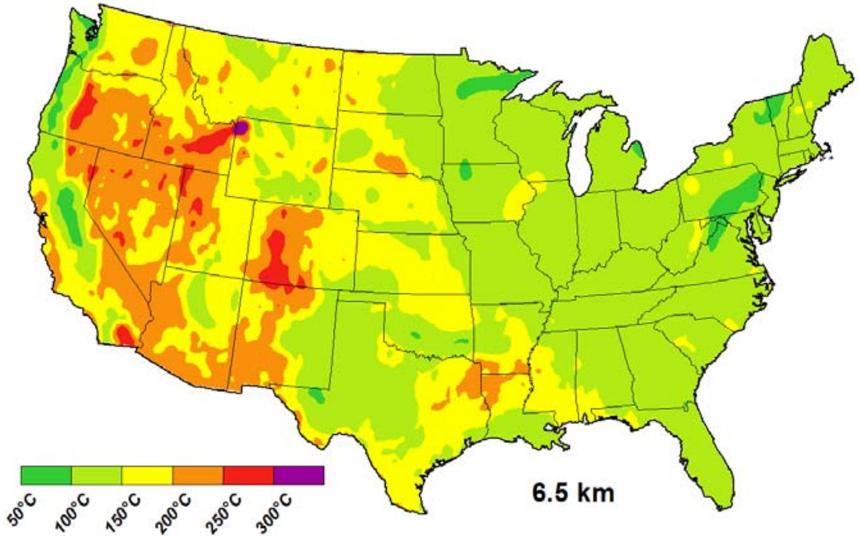
# Part 1 EGS resource within the geothermal continuum

- Quantitative, regional evaluation of current state of knowledge of EGS resources for the US
- The total resource base within the geothermal continuum from hydrothermal to EGS
- Estimation of recoverable EGS resource

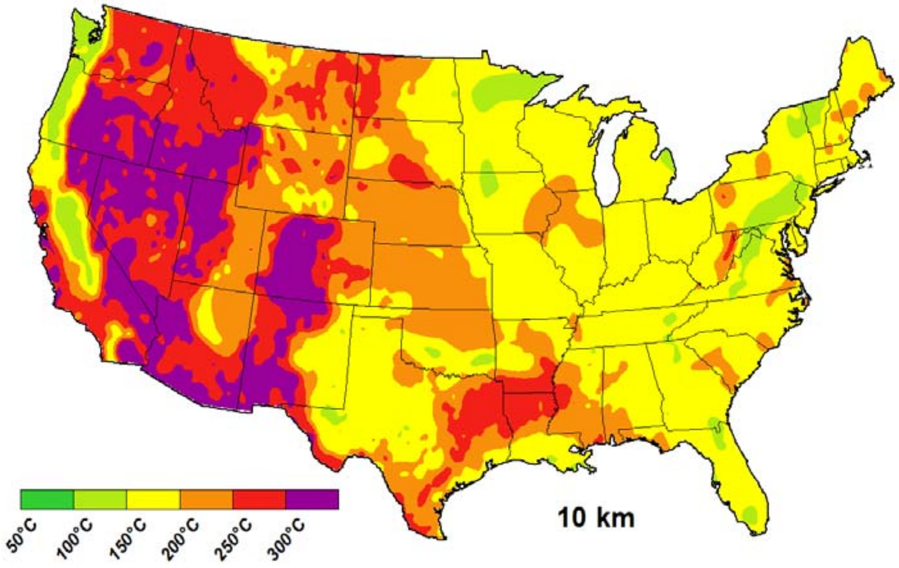
# Rock temperatures at particular depths



3.5 km

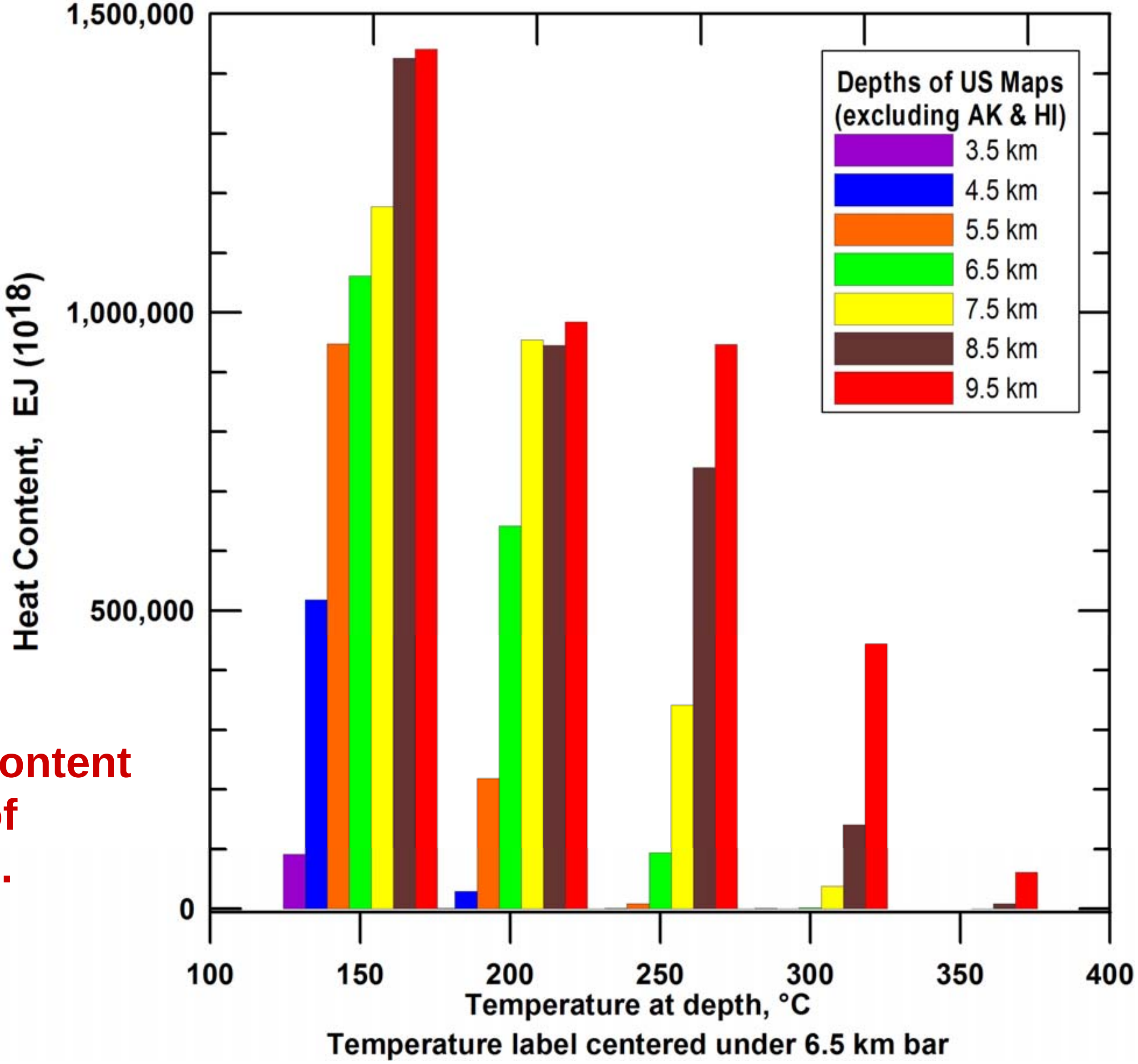


6.5 km



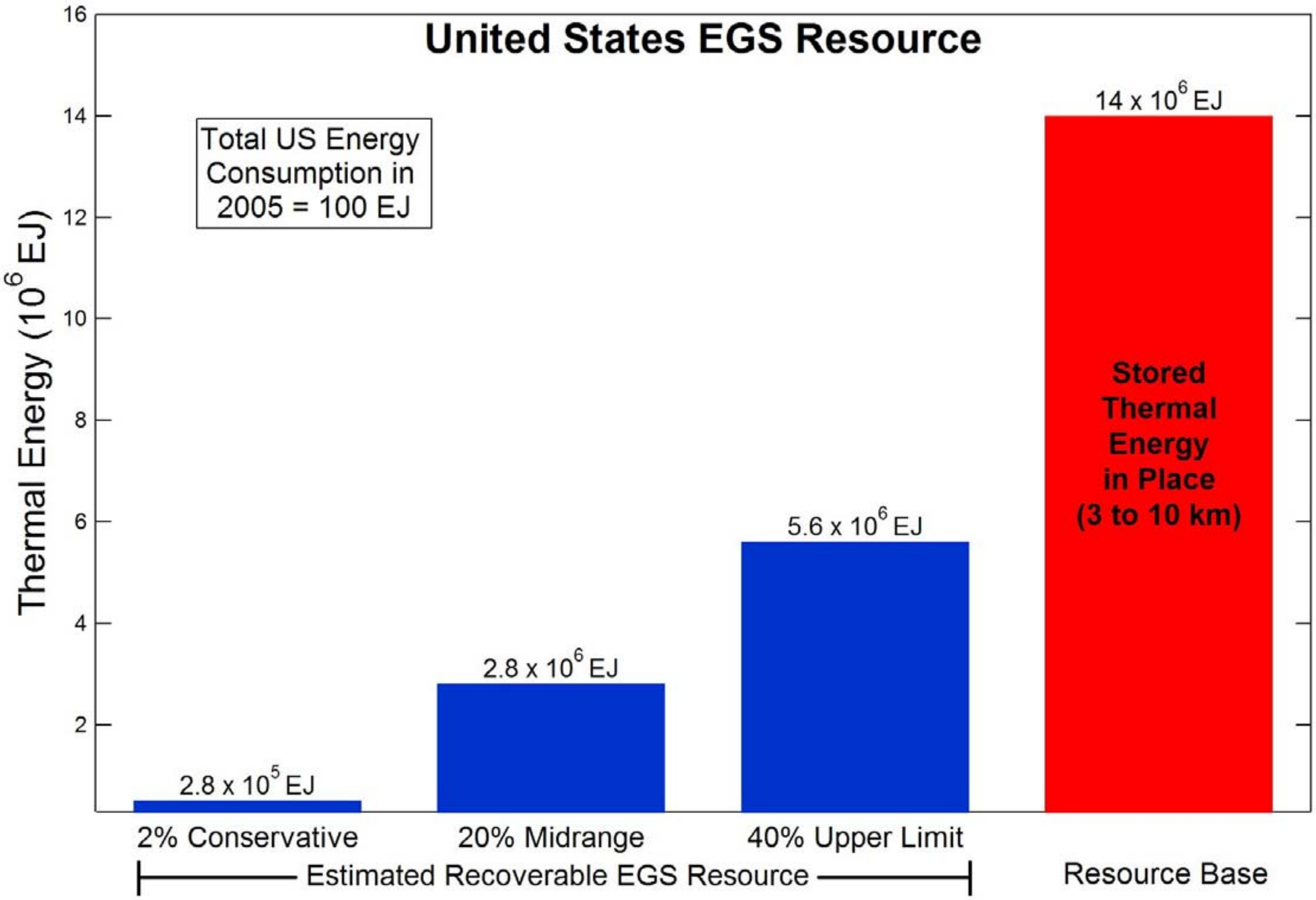
10 km

Source – Blackwell and co-workers, Southern Methodist University, Texas



**Histograms of heat content in EJ, as a function of depth for 1 km slices.**

# Estimated total geothermal resource base and recoverable resource in EJ or $10^{+18}$ Joules.



The amount of recoverable energy from EGS will not be constrained by the size and location of the resource

# Geothermal resources within a continuum from high-grade hydrothermal to high and low grades of EGS

**Table 1.1 Estimated U.S. geothermal resource base to 10 km depth by category**

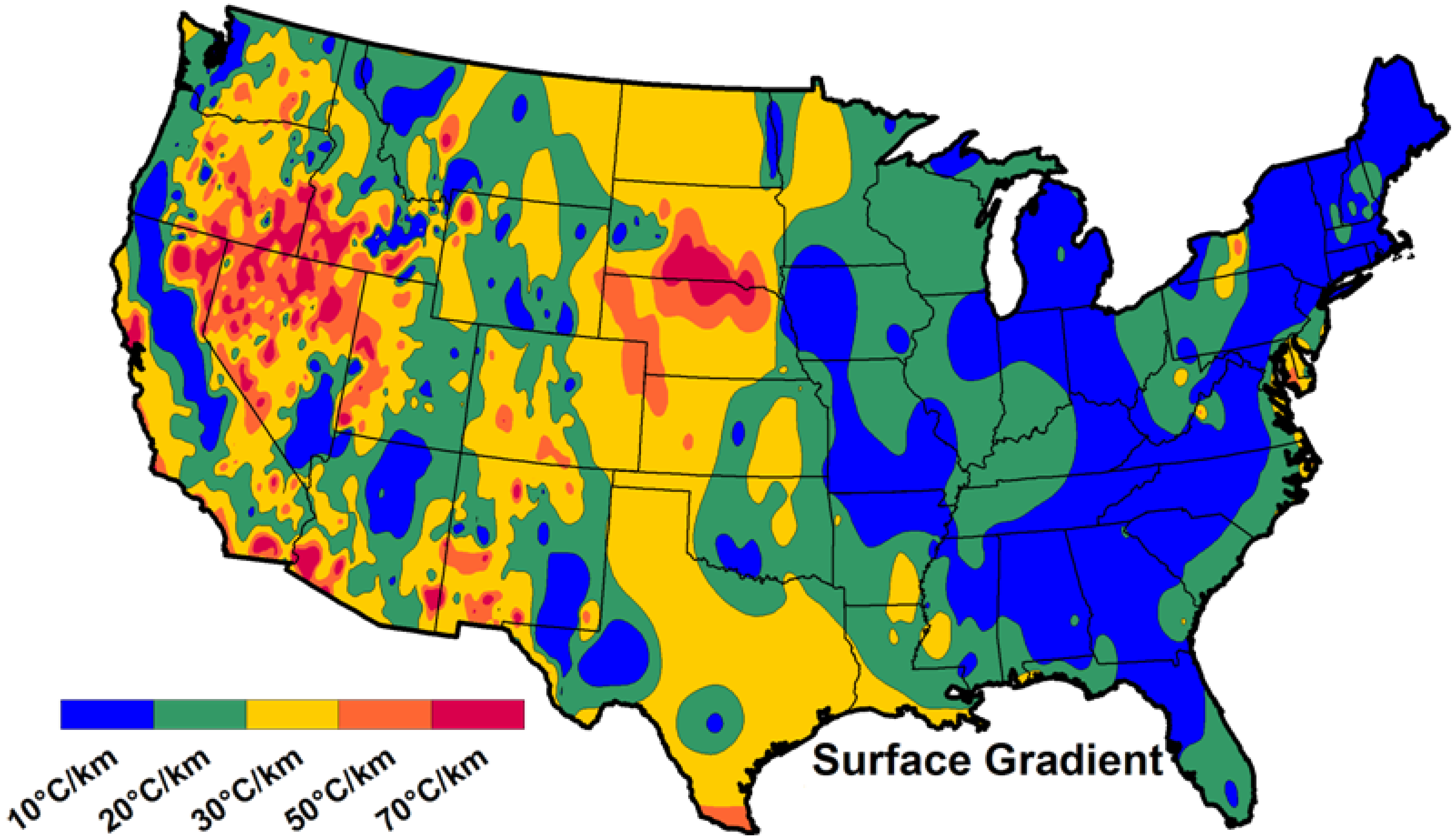
| Category of Resource | Thermal Energy, in Exajoules (1EJ = $10^{18}$ J) | Reference |
|---|---|---|
| **Conduction-dominated EGS** | | |
| Sedimentary rock formations | >100,000 | This study |
| Crystalline basement rock formations | 13,900,000 | This study |
| Supercritical Volcanic EGS* | 74,100 | USGS Circular 790 |
| **Hydrothermal** | 2,400 – 9,600 | USGS Circulars 726 and 790 |
| **Coproduced fluids** | 0.0944 – 0.4510 | McKenna, et al. (2005) |
| **Geopressured systems** | 71,000 – 170,000** | USGS Circulars 726 and 790 |

* **Excludes Yellowstone National Park and Hawaii**

** **Includes methane content**

**Remember 100 EJ = 1 year use of primary energy in the U.S.**

# Geothermal resources within a continuum from high-grade hydrothermal to high and low grades of EGS



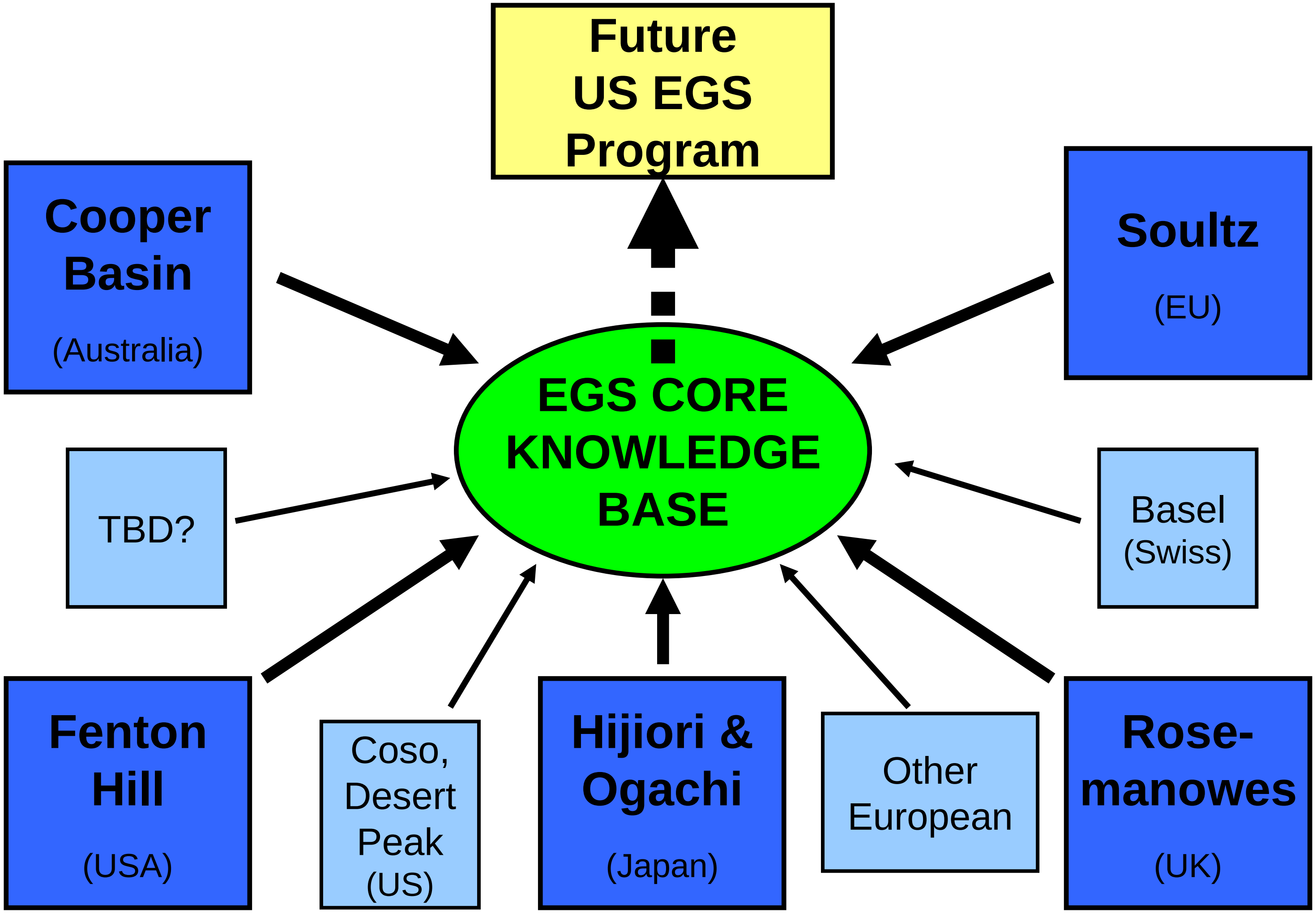
*The ultimate challenge for universal heat mining is to be able to develop lower grade geothermal resources – primarily in the eastern US.*

*To do this lower drilling costs are needed!!*

# 2. Technology status for heat extraction and conversion

- ☐ Retrospective review, analysis and lessons learned from 30+ years of field testing
- ☐ Specification of subsurface requirements for drilling and reservoir stimulation
- ☐ Surface system components for conversion to electric power

# 30+ Year History of EGS Research



**Future US EGS Program**

**Cooper Basin**
(Australia)

**Soultz**
(EU)

**EGS CORE KNOWLEDGE BASE**

TBD?

Basel (Swiss)

**Fenton Hill**
(USA)

Coso, Desert Peak (US)

**Hijiori & Ogachi**
(Japan)

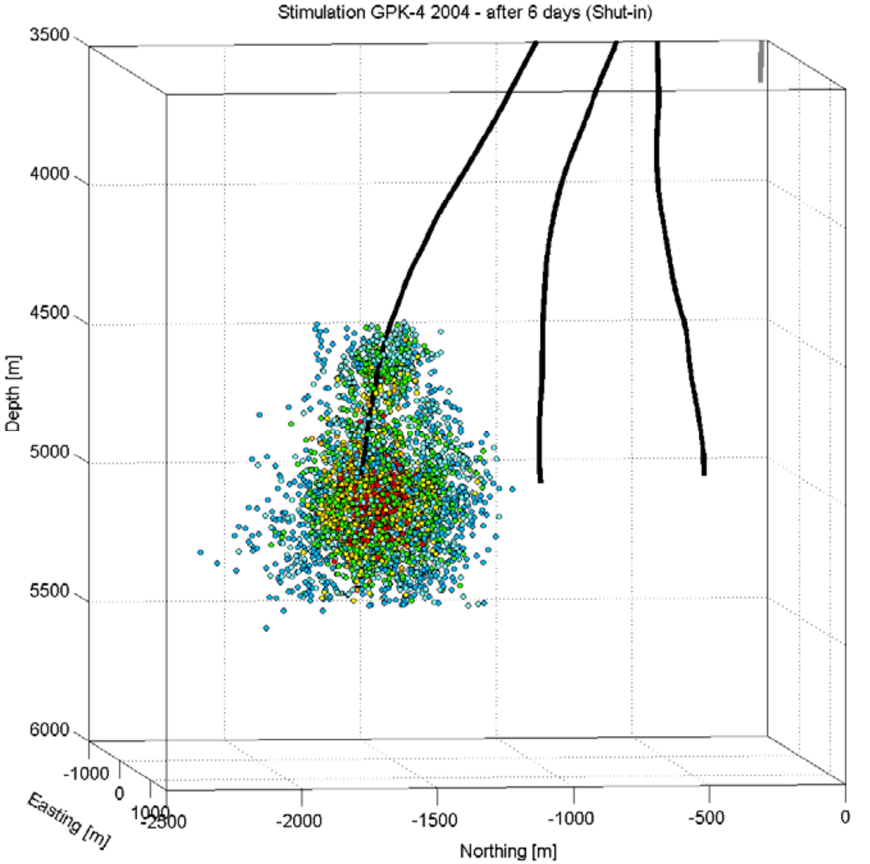
Other European

**Rose-manowes**
(UK)

# Developing stimulation methods to create a well-connected reservoir

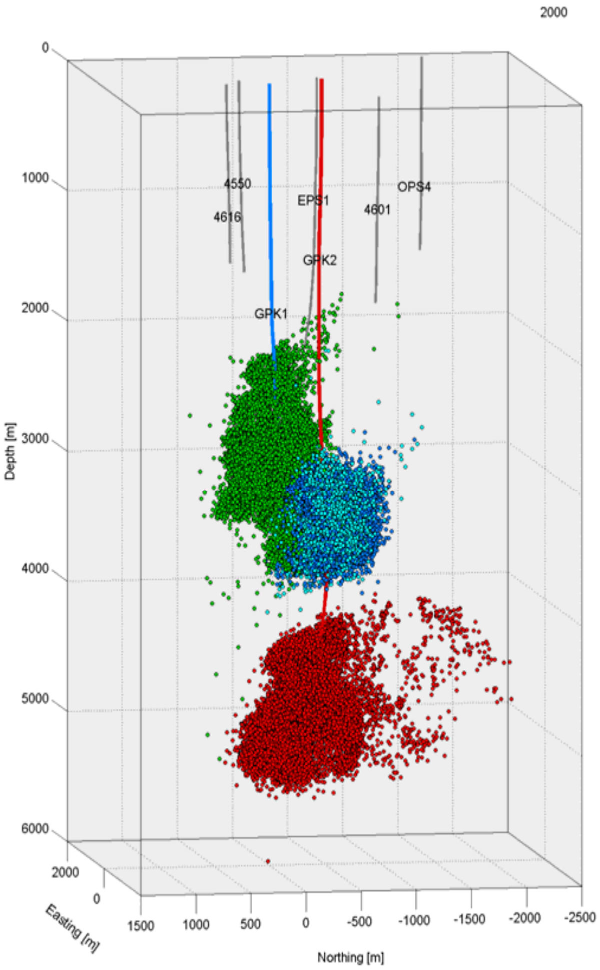
**The critical challenge technically is how to engineer the system to emulate the productivity of a good hydrothermal reservoir**

**Connectivity is achieved between injection and production wells by hydraulic pressurization and fracturing**



“snap shot” of microseismic events during hydraulic fracturing at Soultz from Roy Baria

# R&D focused on developing technology to create reservoirs that emulate high-grade, hydrothermal systems



Soultz, France from Baria, et al.

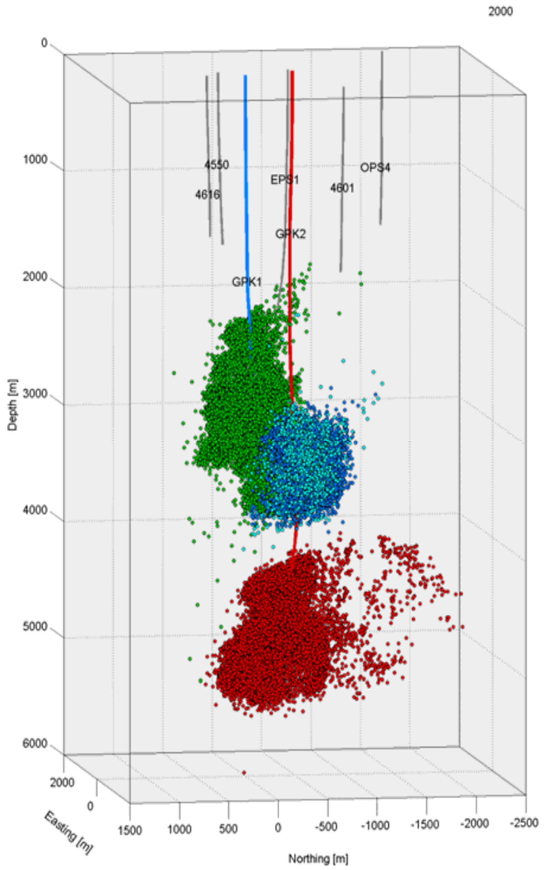
30+ years of field testing at

- Fenton Hill, Los Alamos US project
- Rosemanowes, Cornwall, UK Project
- Hijori, et al , Japanese Project
- Soultz, France EU Project
- Cooper Basin, Australia Project, et al.

has resulted in much progress and many lessons learned

- directional drilling to depths of 5+ km & 300+$^o$C
- diagnostics and models for characterizing size and thermal hydraulic behavior of EGS reservoirs
- hydraulically stimulate large >1km$^3$ regions of rock
- established injection/production well connectivity within a factor of 2 to 3 of commercial levels
- controlled/manageable water losses
- manageable induced seismic and subsidence effects
- net heat extraction achieved

# Although EGS is technically feasible, there are a few things left to do



1. **Commercial level of fluid production with an acceptable flow impedance thru the reservoir**
2. **Establish modularity and repeatability of the technology over a range of US sites**
3. **Lower development costs for low grade EGS systems**

Our analysis shows that significant reductions in risks and cost will result from a modest investment of federal R&D in the next 15 years to demonstrate EGS at several high grade sites in the US

# 3. Environmental attributes and constraints

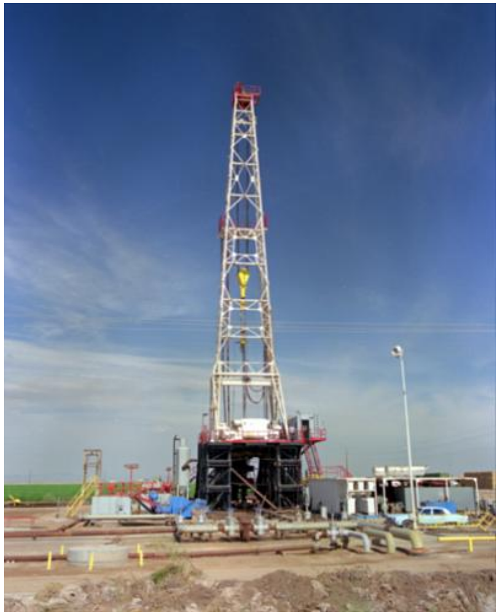
- Water use – will require effective control and management, especially in arid regions
- Land use – small “footprint” compared to alternatives
- Induced seismicity must be monitored and managed
- Low emissions, carbon-free base load energy
- No storage or backup generation needed
- Adaptable for district heating and co-gen / CHP applications to increase use efficiency

# 4. Economic projections

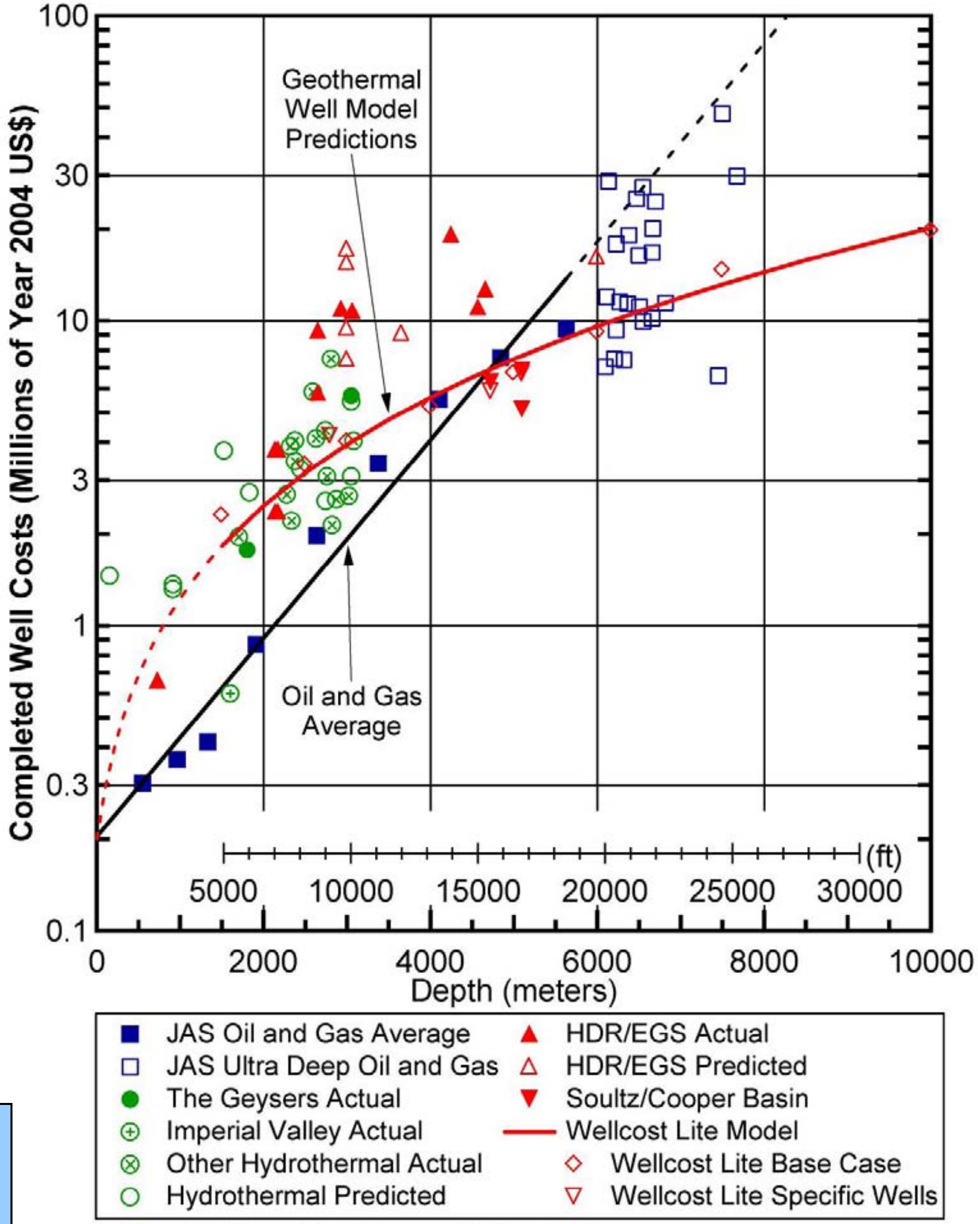
- ☐ Review and evaluation of earlier economic modeling
- ☐ Analysis and modeling of drilling and completion costs
- ☐ Update drilling indices for cost normalization
- ☐ Evaluation of capital costs for energy conversion options for utilization
- ☐ Economic modeling for prediction of costs using GETEM and MITEGS models
- ☐ Set base case parameters and analyzed sensitivity to technology and financial parameter variations
- ☐ Compared predicted LECs for 6 representative sites
- ☐ Developed learning curves and supply curves
- ☐ Estimated R&D support and deployment cost offset needs

# Well costs are strongly dependent on depth

**For depths < 6 km geothermal wells cost more than oil and gas wells, but costs vary less strongly with depth**

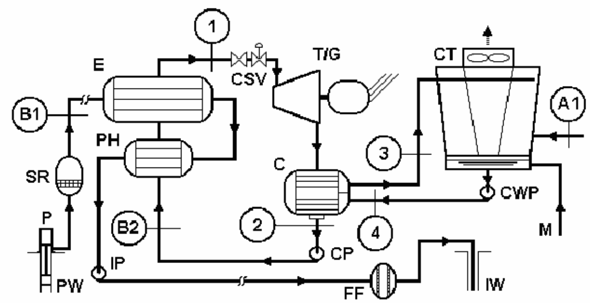


**Wellcost Lite – comprehensive model, details for bit performance, casing design, tangible and intangible costs, etc.**

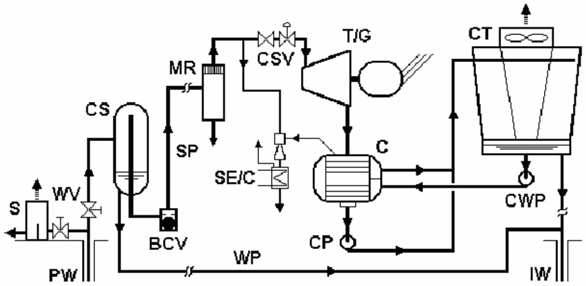


1. JAS = *Joint Association Survey on Drilling Costs.*
2. Well costs updated to US$ (yr. 2004) using index made from 3-year moving average for each depth interval listed in JAS (1976-2004) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Ultra deep well data points for depths greater than 6 km are either individual wells or averages from a small number of wells listed in JAS (1994-2000).
4. "Other Hydrothermal Actual" data include some non-US wells (Mansure 2004).

# Detailed analysis of energy conversion options was carried out for a range of EGS temperature and pressure conditions

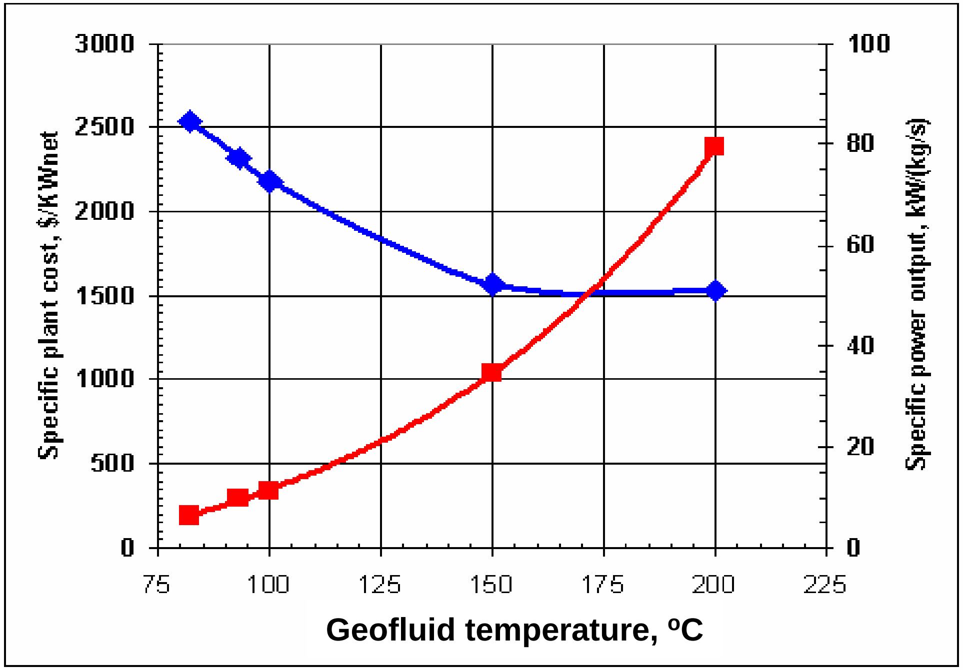


(a)



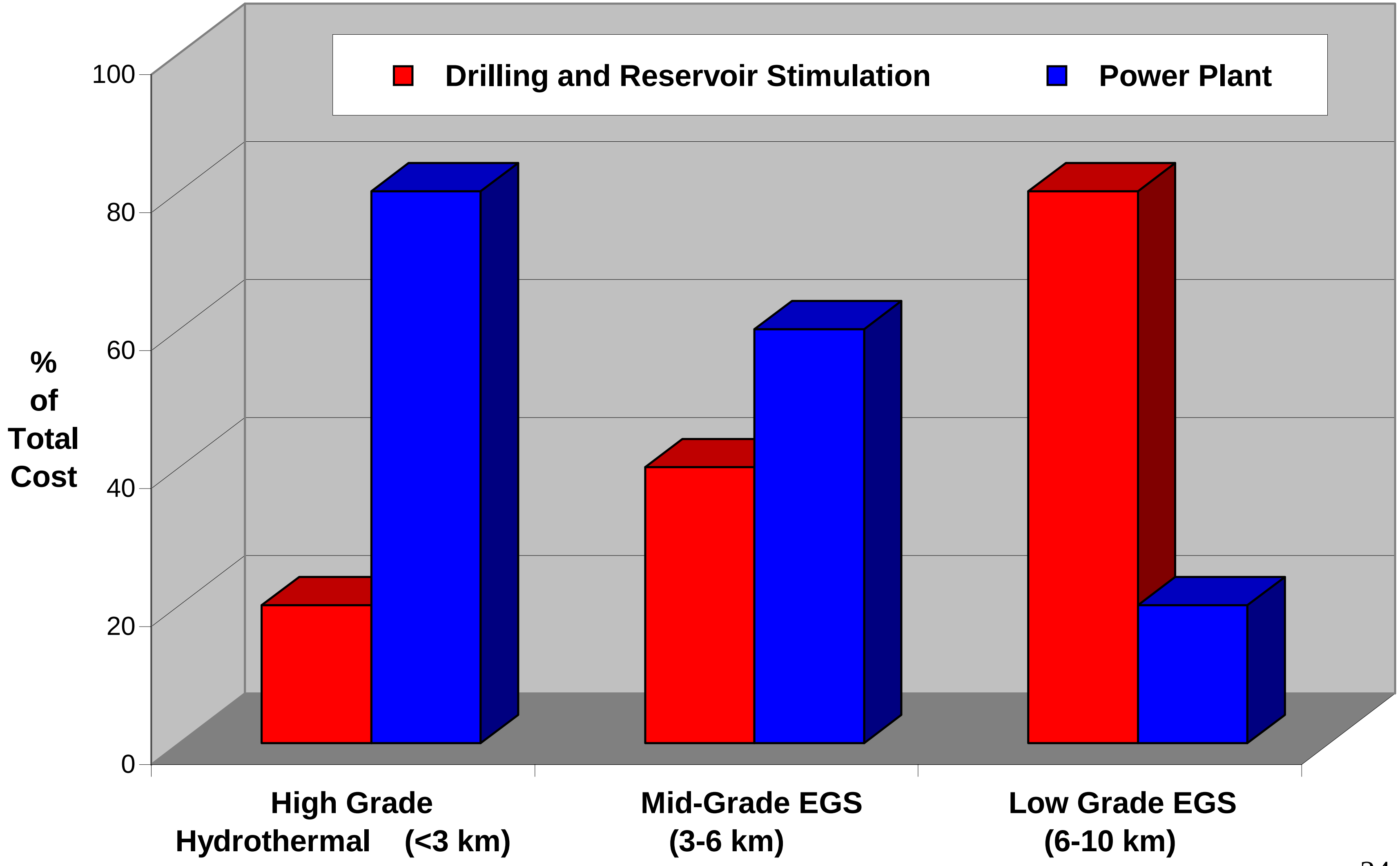
(b)

(a) Binary cycle plant
(b) flash steam plant
(c) supercritical triple expansion cycle



Estimated specific output and capital costs

# As EGS resource quality decreases, drilling and stimulation costs dominate



# Base case parameters for EGS economic modeling

**Major Impact with higher uncertainty and risk --**

- Flow rate per production well (20 to 80 kg/s )
- Thermal drawdown rate / redrilling-rework periods (3% per year / 5-10 years)
- Resource grade – defined by temperature or gradient = f(depth, location)
- Financial parameters
  - Debt/Equity Ratio (variable depends on EGS resource grade)
  - Debt rate of return (5.5 -8.0%)
  - Equity rate of return (17%)
- Drilling costs from model predictions using a 20% contingency factor

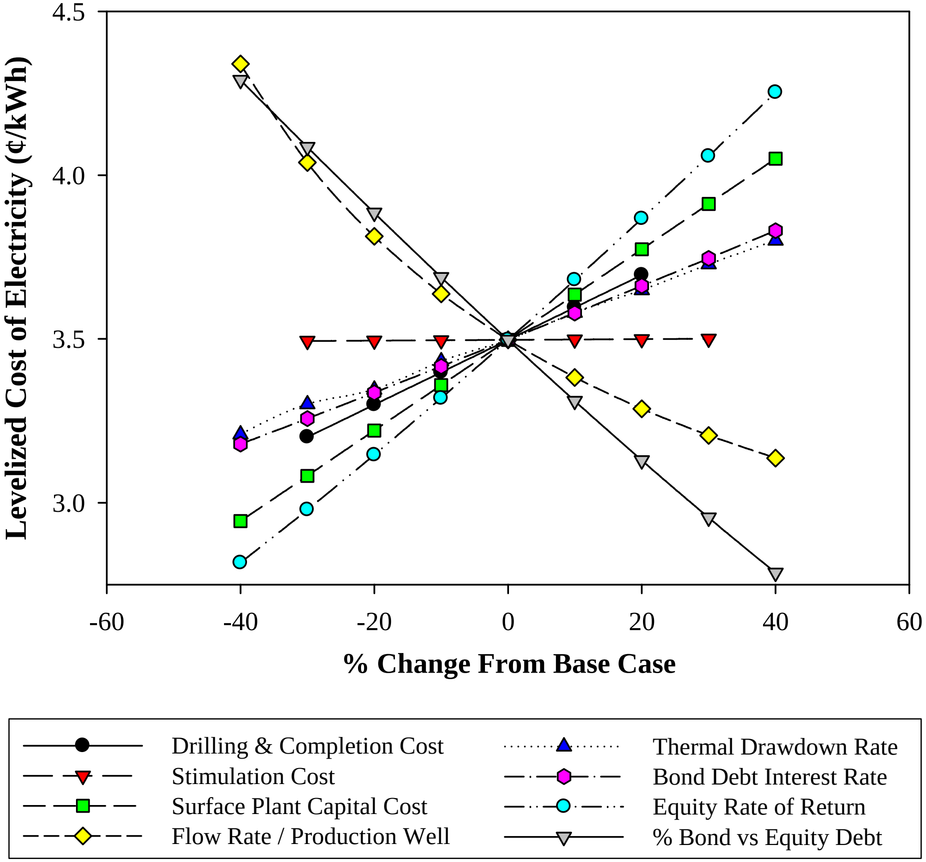
**Lesser impact but still important --**

- Surface plant capital costs
- Exploration effectiveness and costs
- Well field configuration
- Flow impedance
- Stimulation costs
- Water losses
- Taxes and other policy treatments

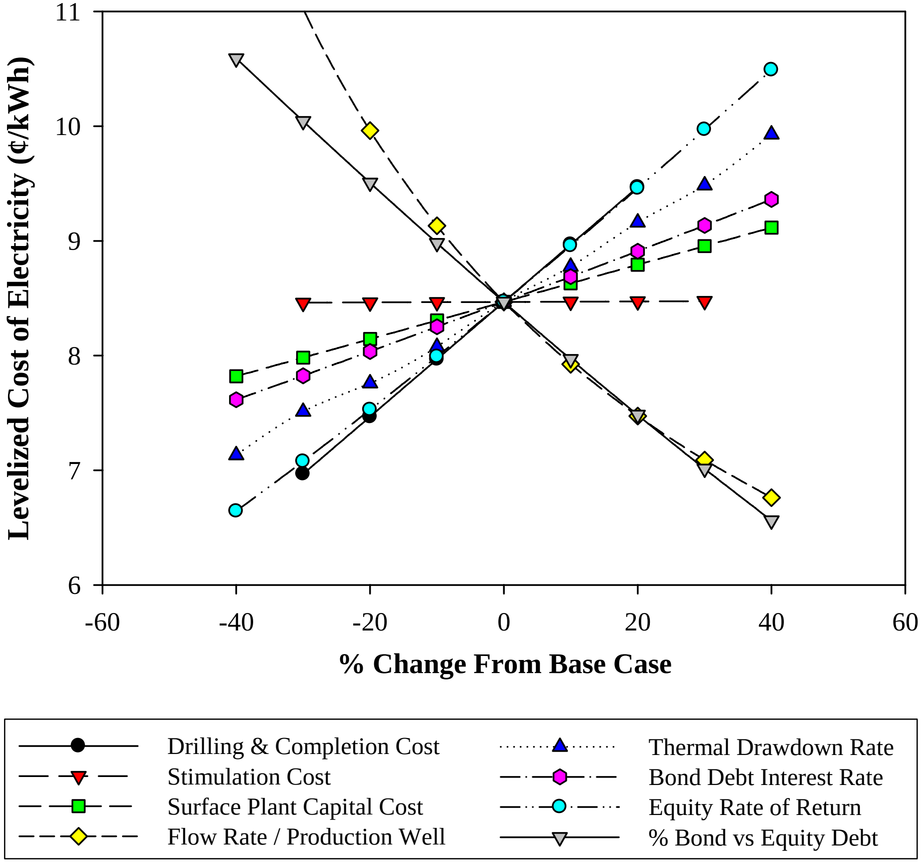
# Sensitivity analysis – assessment of factors influencing costs

**2003 US $**

**High grade EGS resource- Clear Lake conditions**

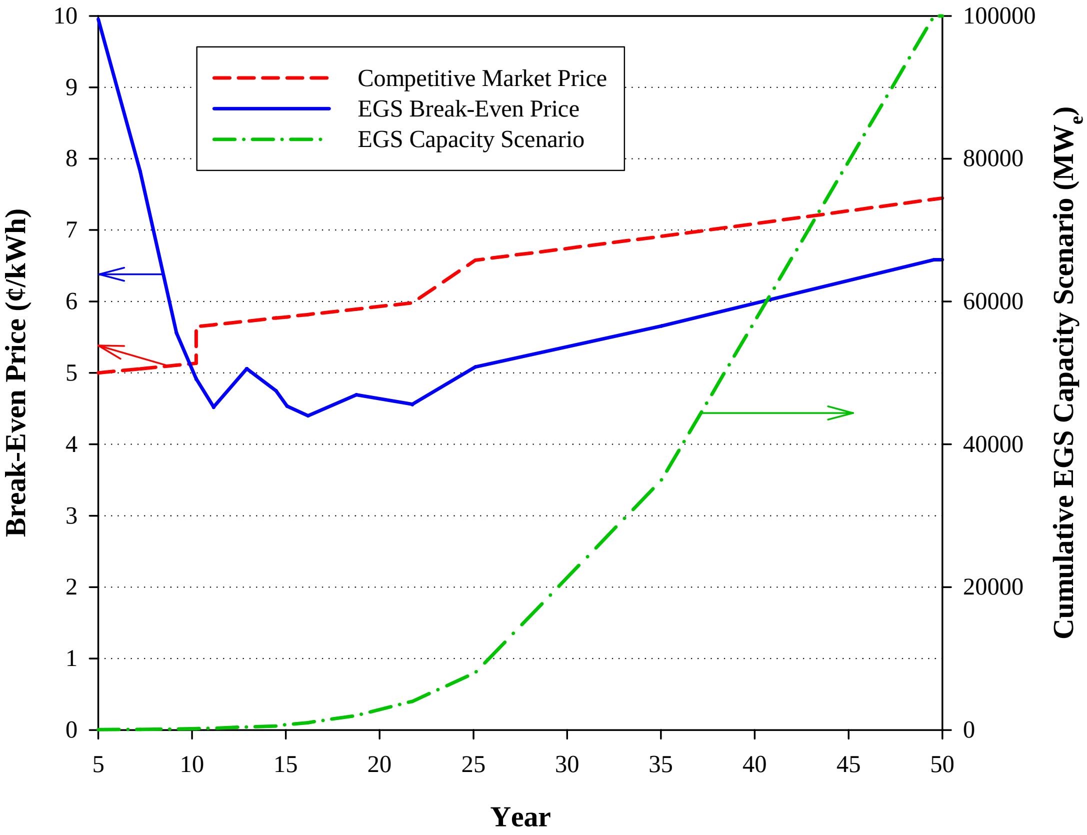


**Low grade EGS resource – Conway conditions**



**80 kg/s flow rate per production well in a quartet configuration (1 injector : 3 producers)**

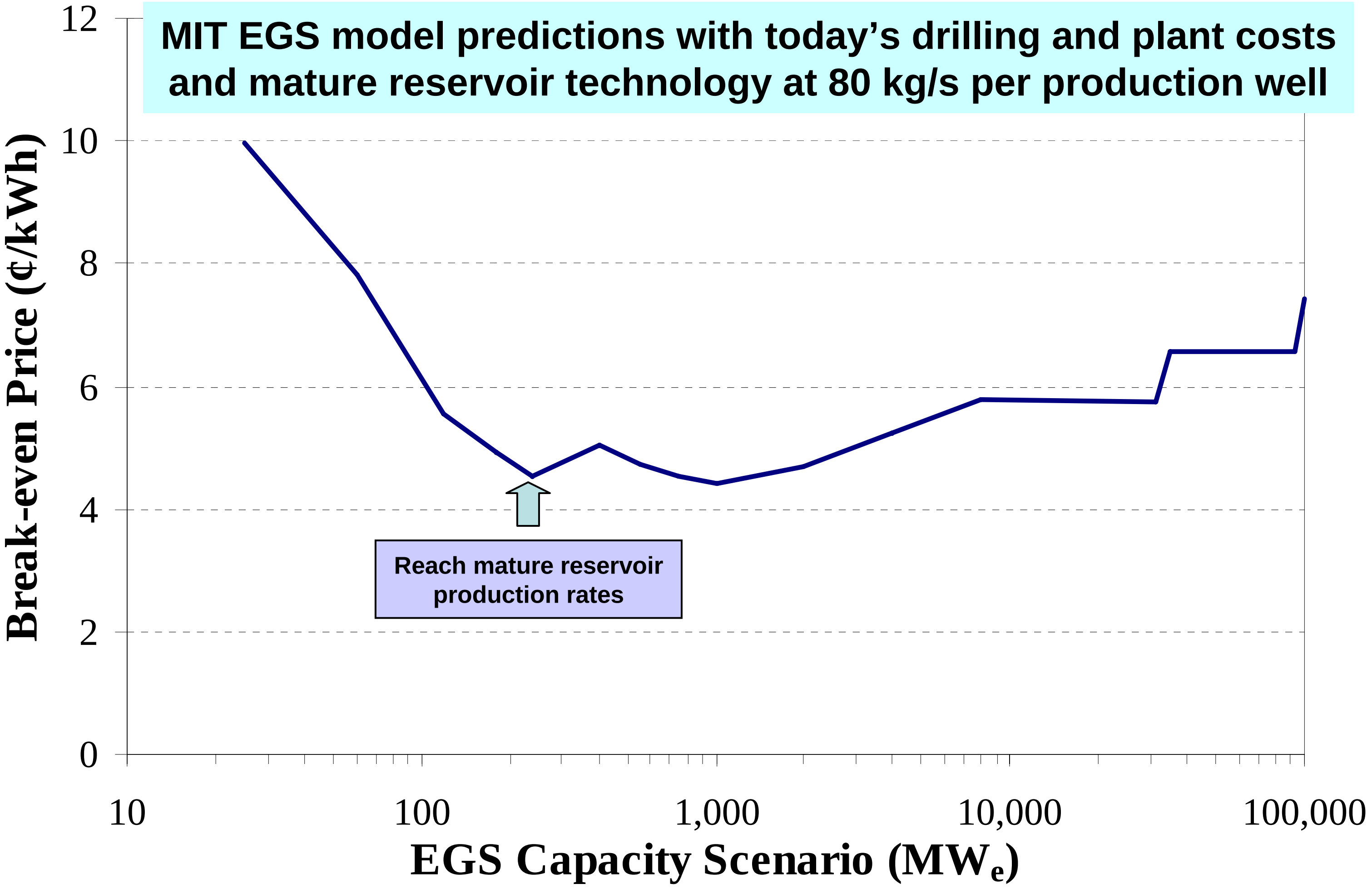
# Predicted levelized break-even price (LEC) and growth in supply using MIT EGS model



- 50 year scenario using variable debt and equity rates (VRR).
- Flow rate per production well (in a quartet configuration – 1 injector, 3 producers) follows the 80 kg/s learning curve.
- Thermal drawdown is 3%/yr resulting in wellfield rework after ~ 6 years and the vertical spacing between stacked reservoirs is 500 m.
- Resulting absorbed technology deployment cost is $216 million US (2004).

**Range in predicted absorbed deployment costs for all cases considered - $200 to 400 million over 15 years**

# Supply Curve for the US EGS resource to 100,000 MWe


MIT EGS model predictions with today's drilling and plant costs and mature reservoir technology at 80 kg/s per production well

Reach mature reservoir production rates

# Summary -- Why should the U.S. re- invest now in EGS ?

1. **Large, indigenous, accessible base load power resource** – extractable amount of energy that could be recovered is not limited by resource size.
2. **Fits portfolio of sustainable RE options** - EGS complements the DOE"s RE portfolio and does not hamper the growth of solar, biomass, and wind in their most appropriate domains.
3. **Scalable and environmentally friendly** – EGS plants have small foot prints and low emissions – carbon free and their modularity makes them easily scalable from large size plants.
4. **Technically feasible** -- Major elements of the technology to capture and extract EGS are in place. Key remaining issue is to establish inter-well connectivity at commercial production rates – only a factor of 2 to 3 greater than current levels.
5. **Economic projections -** Favorable for high grade areas now with a credible learning path to provide competitive energy from mid- and low-grade resources
6. **Deployment costs low** -- A total investment of $300-400 million over 15 years would demonstrate EGS technology at a commercial scale at several US field sites
7. **Supporting research costs are reasonable** at $20 to 40 million per year in comparison to other large impact US energy programs supported

# Recommended path for enabling 100,000 MWe from EGS by 2050

- Support more detailed and site specific resource assessment
- Support 3-5 field demonstrations in the next 15 years to refine technologies for demonstrating commercial-scale EGS
- Develop shallow, high grade EGS sites at the margins of hydrothermal reservoirs along with co-produced hot water sites as short term options
- In the longer term, develop lower gradient EGS sites requiring deeper heat mining at depths >6 km
- Implement state and federal policies that incentivize EGS
- Maintain vigorous R&D effort on subsurface science, drilling, energy conversion, and systems analysis for EGS

**Invest a total of $600 to 800 million for deployment assistance and research and development over 15 years -- $50 M/yr on average**

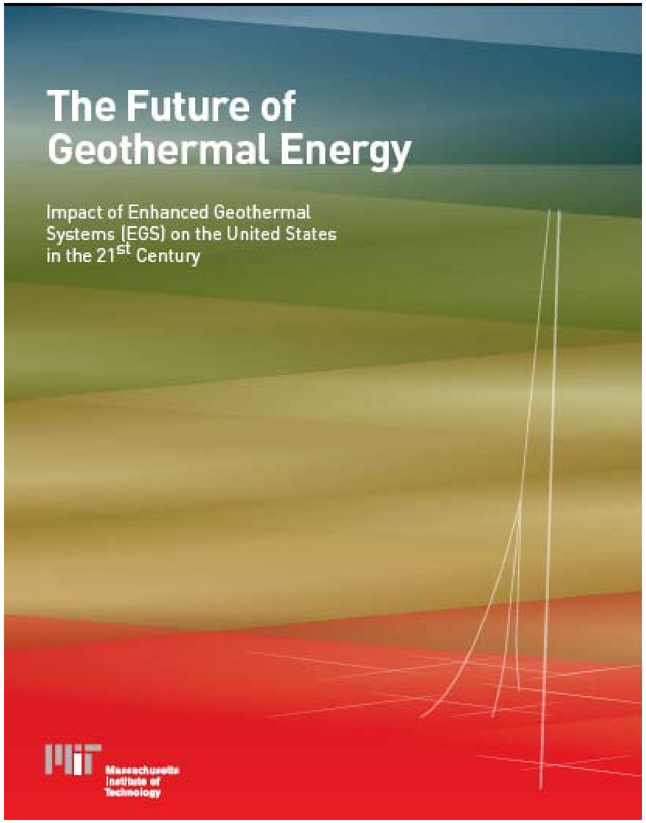
Less than the price of **one clean coal plant !**

# Australia’s Key Role in Geothermal

**Australia’s work on geothermal energy at Cooper Basin, Hunter Valley, Paralana and elsewhere is very important for developing technology and reducing uncertainties worldwide.**

**We are grateful for your leadership in recent years. We wish you much success and look forward to maintaining strong collaborations as the United States re-energizes its geothermal research and development programs.**

# Thank you and please read our report available at
http://geothermal.inel.gov/publications/future_of_geothermal_energy.pdf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Massachusetts Institute of Technology

For a hard copy of the summary and full (400-page) report please email Joel Renner at joel.renner@inl.gov

# Acknowledgements

U.S. DEPARTMENT OF ENERGY

**Acknowledge Support for the Project provided by the Geothermal Division and its Laboratories**

- ❑ Idaho National Laboratory
- ❑ National Renewable Energy Laboratory
- ❑ Sandia National Laboratories

**We are especially grateful to the US DOE for its sponsorship and to many members of US and international geothermal community for their assistance, including Roy Mink, Allan Jelacic, Joel Renner, Jay Nathwani, Greg Mines, Gerry Nix, Martin Vorum, Chip Mansure, Steve Bauer, Doone Wyborn, Ann Robertson-Tait, Pete Rose, Colin Williams, and Valgudur Stefansson**