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

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Outline

- Assessment Project Team
- Motivation
- Project statement of work
- Project goals and impact definition
- Approach
  - Resource
  - Technology
  - Economics
- Project timeline and documentation plans
- Key findings
- Major recommendations

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, geotechical engineer
- David Blackwell, Southern Methodist University, geophysicist
- Ronald DiPippo, power conversion consultant, mechanical engineer
- Elisabeth Drake, MIT, energy systems specialist, chemical engineer
- John Garnish, EU Energy Commission (retired)
- Bill Livesay, Drilling 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

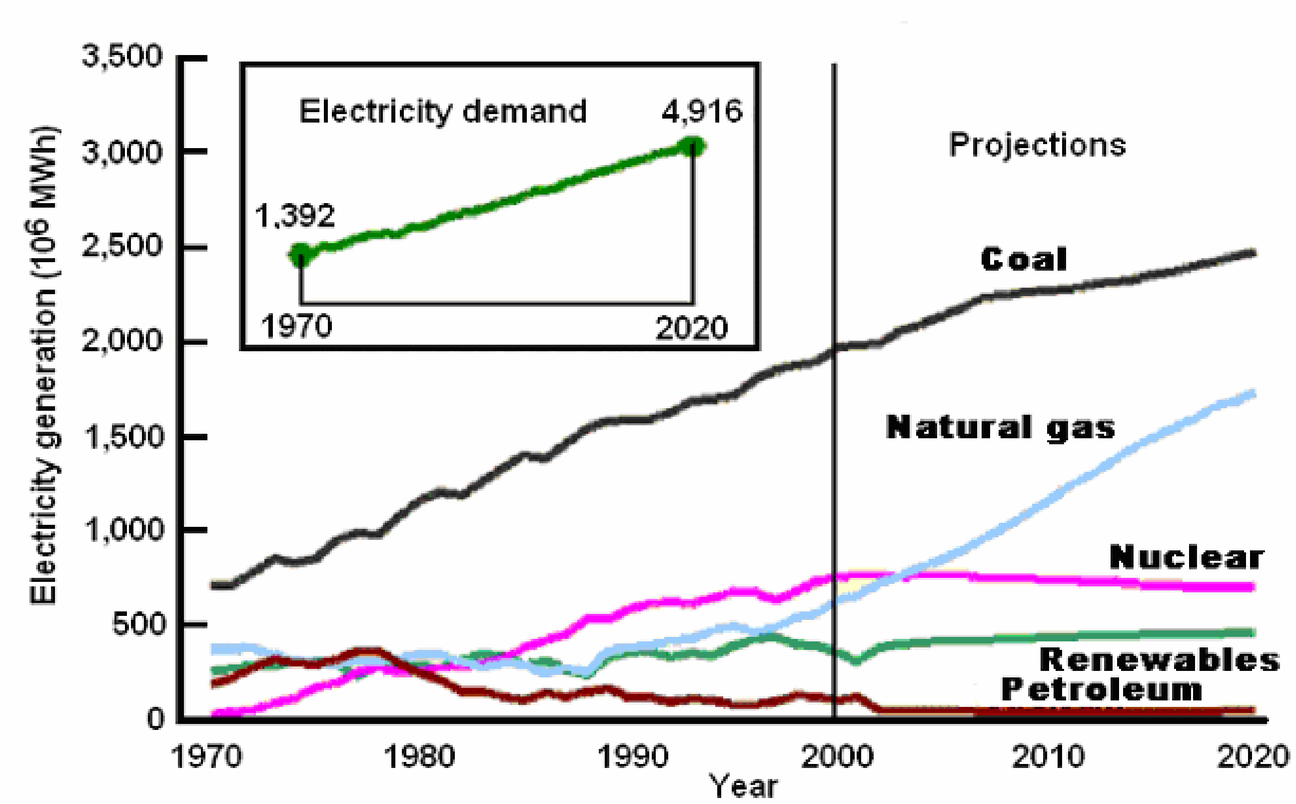
Associate Panel Members

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

Support Staff

- Gwen Wilcox, MIT

A key motivation - US Electricity Supply for the long term



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

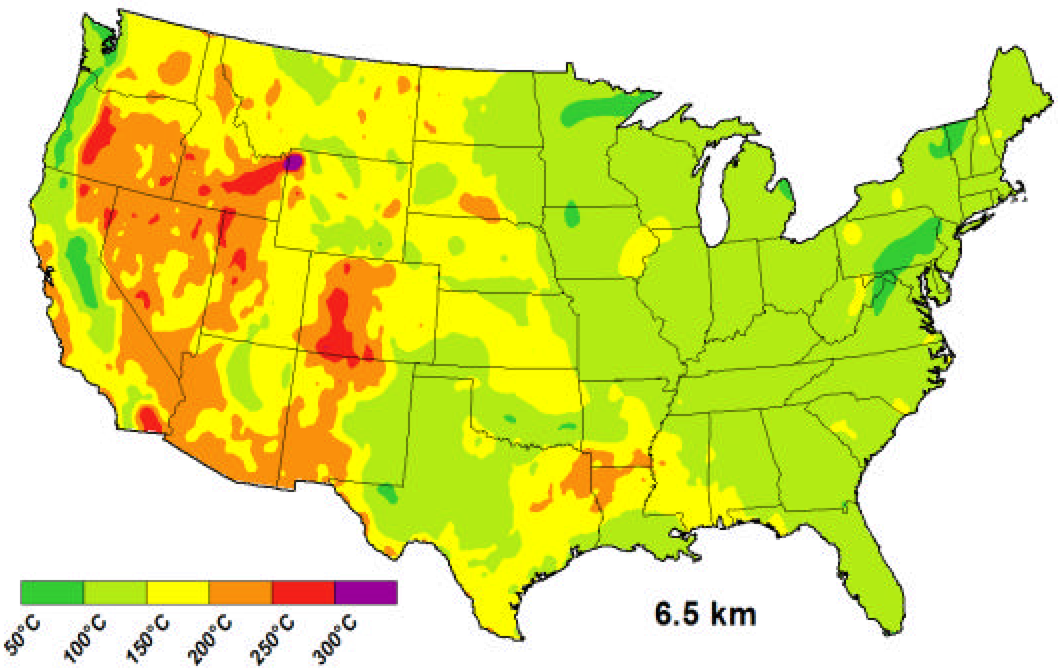
Current US generating capacity is about 1,000,000 MWe or 1 TWe

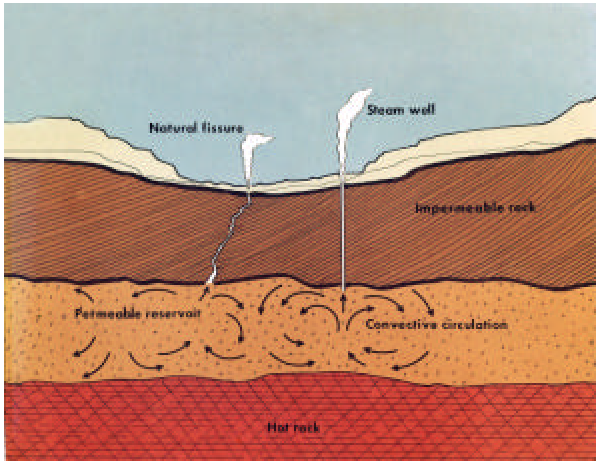
A key motivation - US Electricity Supply for the long term

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 because of a failure to meet emissions standards
   - In the next 25 years, over 40 GWe of existing nuclear capacity will be beyond even generous re-licensing procedures
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. The costs of a new generation of clean coal plants will be significant as they have to meet tightening emission standards and may have to deal with carbon sequestration.
5. The changes in infrastructure needed for interruptible renewables including storage, inter-connections, and new T&D are large

The Geothermal Option – "Back to the Future" -- 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 ?





Project Statement of Work

The MIT-led team will address several major questions affecting the future development of EGS:

1. What are quality, grade and distribution of the EGS resource nationally?
2. What remains to be done technically to achieve complete EGS system feasibility?
3. What are the key technical and economic issues that must be resolved for EGS to have national impact in US energy supply by 2050?

EGS Assessment Project Goals

Primary goal – to provide an in-depth 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

Major impact was defined as enabling 100,000 MWe of an economically viable EGS resource on line or as a true reserve by 2050

Other important "products"

Supply curve predictions -- A key product of this study will be the generation of supply curves for electricity and thermal energy for the US. These will be expressed quantitatively as energy recovered as a function of energy price reflecting variation in the quality and grade of the EGS resource, evolution of EGS technology and the uncertainties that are inherent as one projects forward in time.

Near term -- Technology R&D recommendations and suggested targets for EGS field testing and demonstration

Long term -- Anticipated impacts of technology developments, learning curve cost reductions and investments needed for having EGS become a major supplier of US energy

Approach – 4 key elements of the assessment

1. **Resource**
   - defining EGS within the geothermal continuum
   - quantitative, national scale evaluation of current state of knowledge regarding geothermal resources
   - estimation of EGS Resource Base and recoverable resource
2. **Technology**
   - specification of requirements for **subsurface** and surface system components, including drilling, reservoir design and stimulation, energy conversion
   - retrospective review, analysis and lessons learned from 30+ years of field testing
3. **Environmental attributes and constraints**
4. **Economics**
   - evaluation and analysis of drilling and completion costs
   - update drilling indices for cost normalization
   - evaluation of costs for energy conversion options for utilization
   - economic modeling for prediction of costs using GETEM and MITEGS models
   - base case parameters and sensitivity to technology and financial parameter variations
   - learning curves, supply curves and R&D projections for a national program

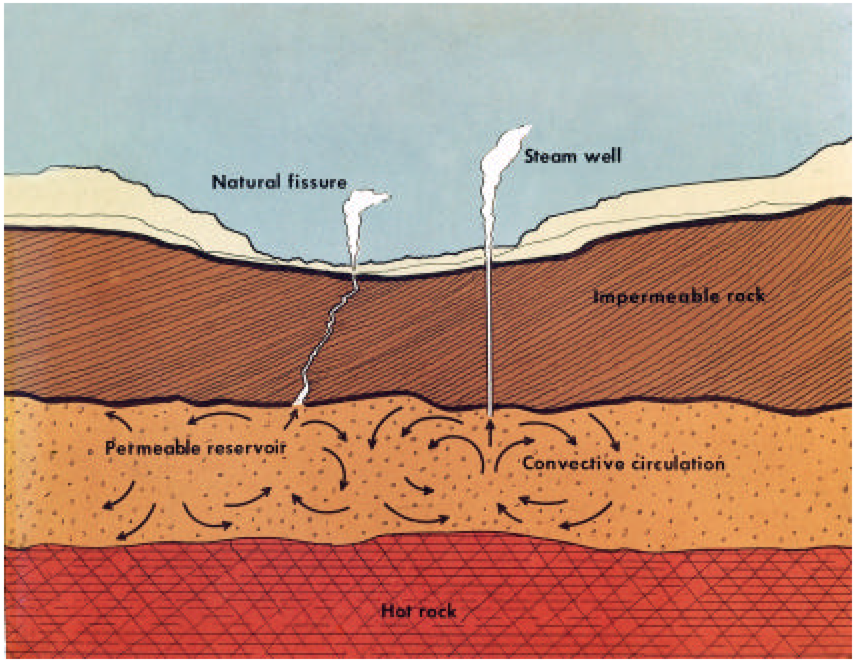
Project timeline and documentation schedule

- Sept.1 2006 -- Project start – assembly of panel
- Sept. 2005 – Jan 2006 -- Series of meetings/workshops involving specific discussion topics and invited speakers
- Jan. 2006– Open meeting at the Stanford Reservoir Engineering Workshop
- April 2006 - First draft of report for internal review
- May 2006 - Second draft of report for external peer review
- May – June report under external peer review
- July -- Panel's response to peer review and revision of report
- July 15 2006 – submission of revised report for copy editing
- August 1 – Sept 8 2006 - final revision and production of the report
- Sept. 13 – GRC forum on EGS Assessment Panel findings and recommendations, distribute synopsis and executive summary
- Oct. 2006 - Release of complete final report (9 chapters, 350 pages)

Hydrothermal Resource

Although the hydrothermal resource is large and underutilized, it is very localized to a few regions of the world – for T > 100°C to depths of 6 km the Resource base is:

- **World – 130,000 EJ (10^{+18}J)**
- **US – 9600 EJ**



Electric capacity from hydrothermal resources

On a worldwide basis (USDOE and GEA est.):

- Proven reserves today 55,000 MWe

-"Probable" resource 100,000 MWe

For the US (USGS est.)

- Proven reserves 10,000 MWe

- Undiscovered resource 20,000 MWe

So what is left ??

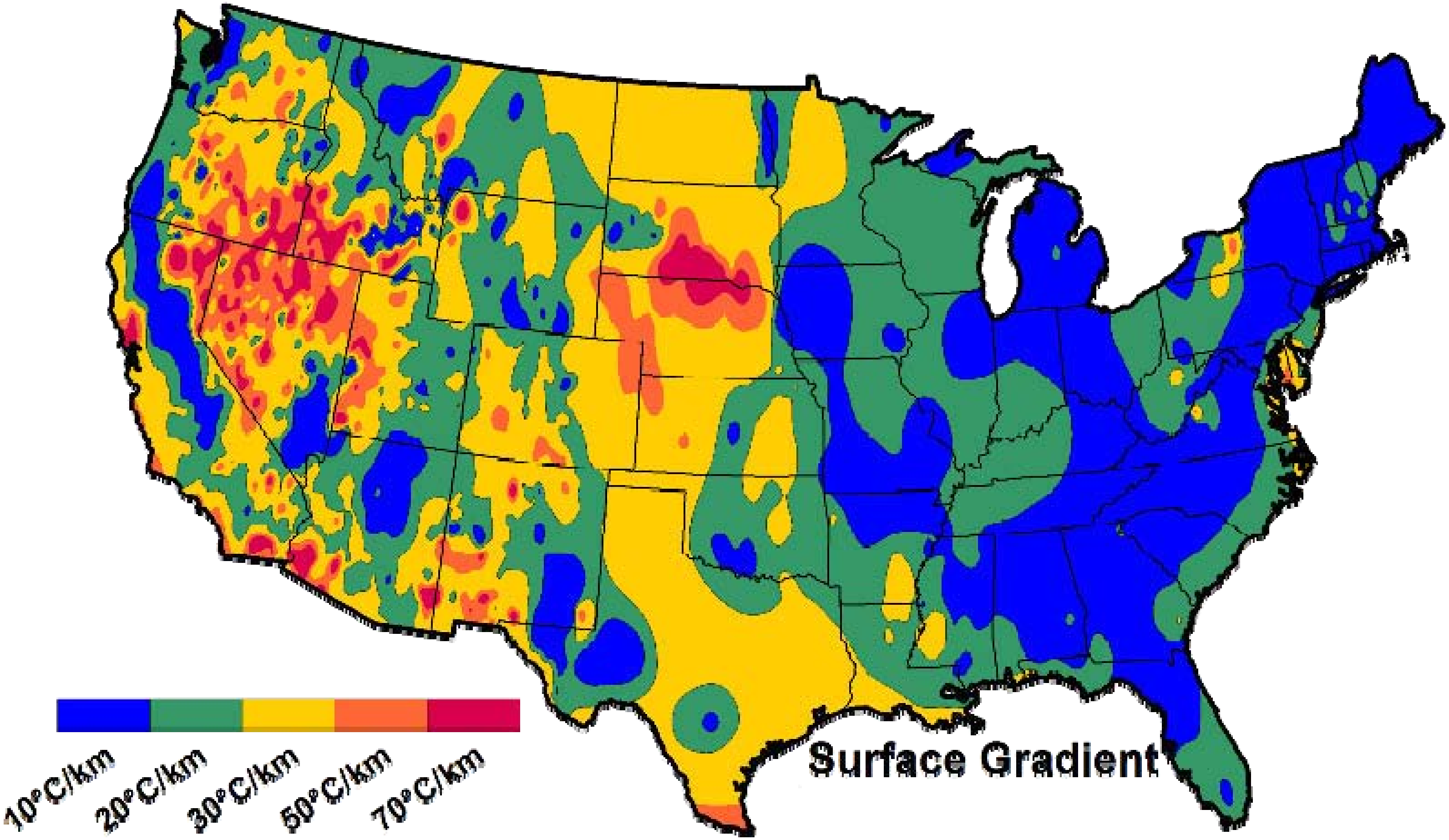
Part 1. EGS Resource

About 100,000,000 EJ worldwide / 14,000,000 EJ for the US of accessible stored thermal energy -- enough energy to meet our needs for sustainable future!

- defining EGS within the geothermal continuum
- quantitative, national scale evaluation of current state of knowledge regarding geothermal resources
- estimation of EGS Resource Base and recoverable resource

Keep in mind that the length scale of this assessment is of the order 10 -100 km – specific sites only considered as representative "targets" for near term field demonstrations

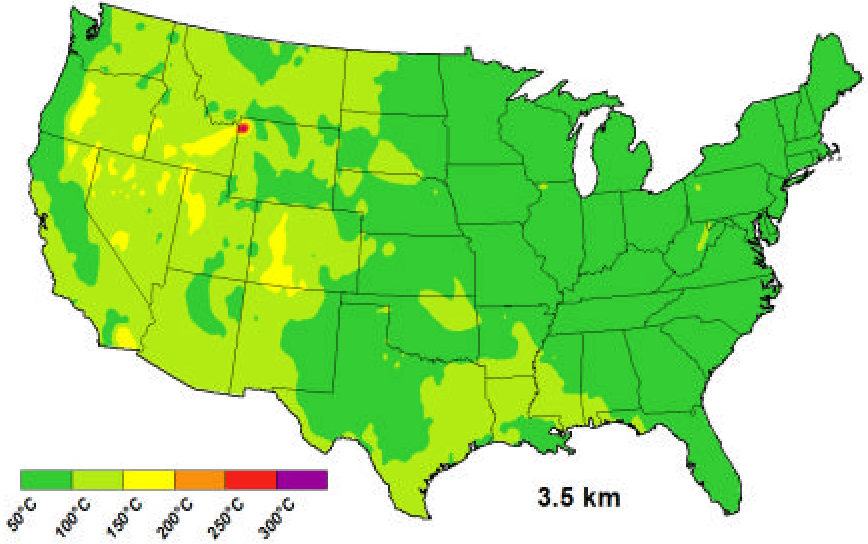
US EGS Resource Assessment

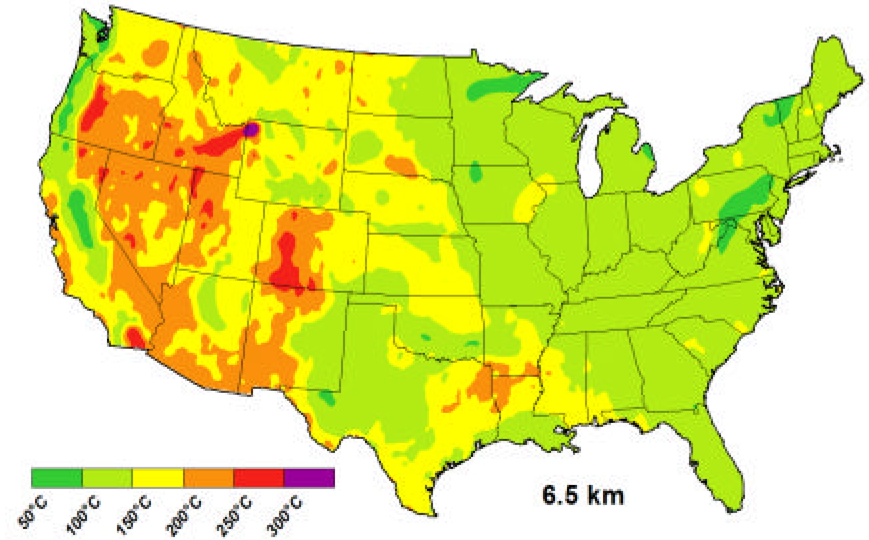


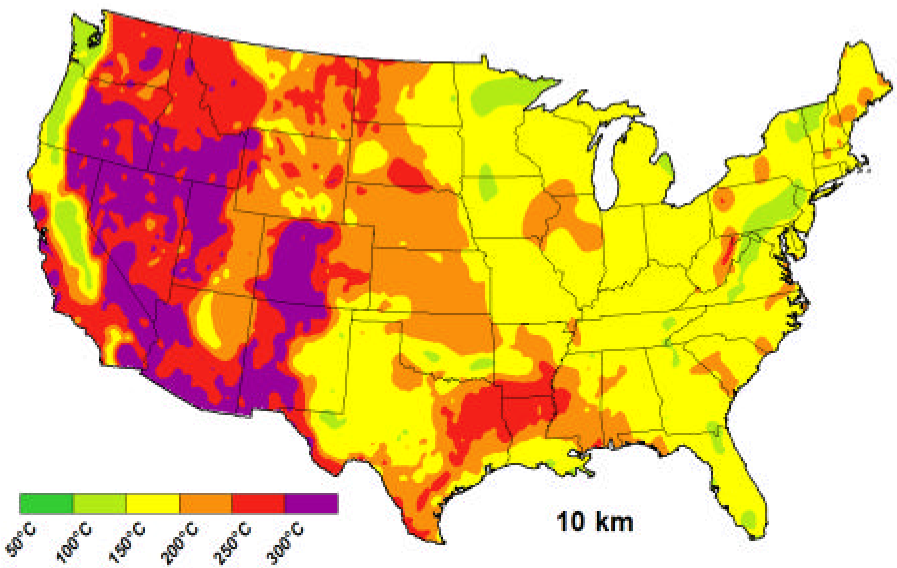
Average surface geothermal gradient

from Blackwell and Richards, SMU (2006)

Rock temperatures at particular depths

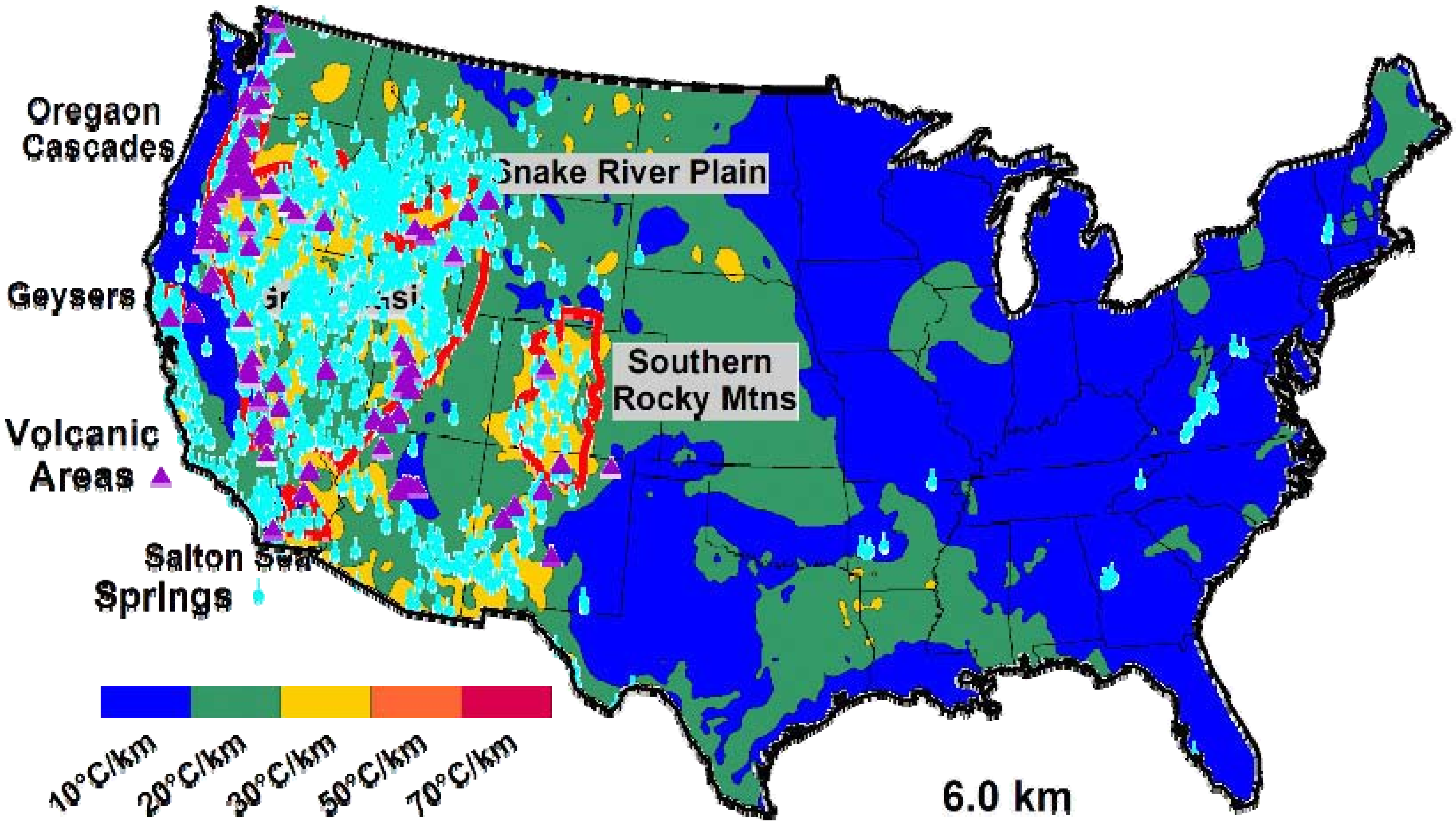






Source – Blackwell and co-workers, Southern Methodist University, Texas

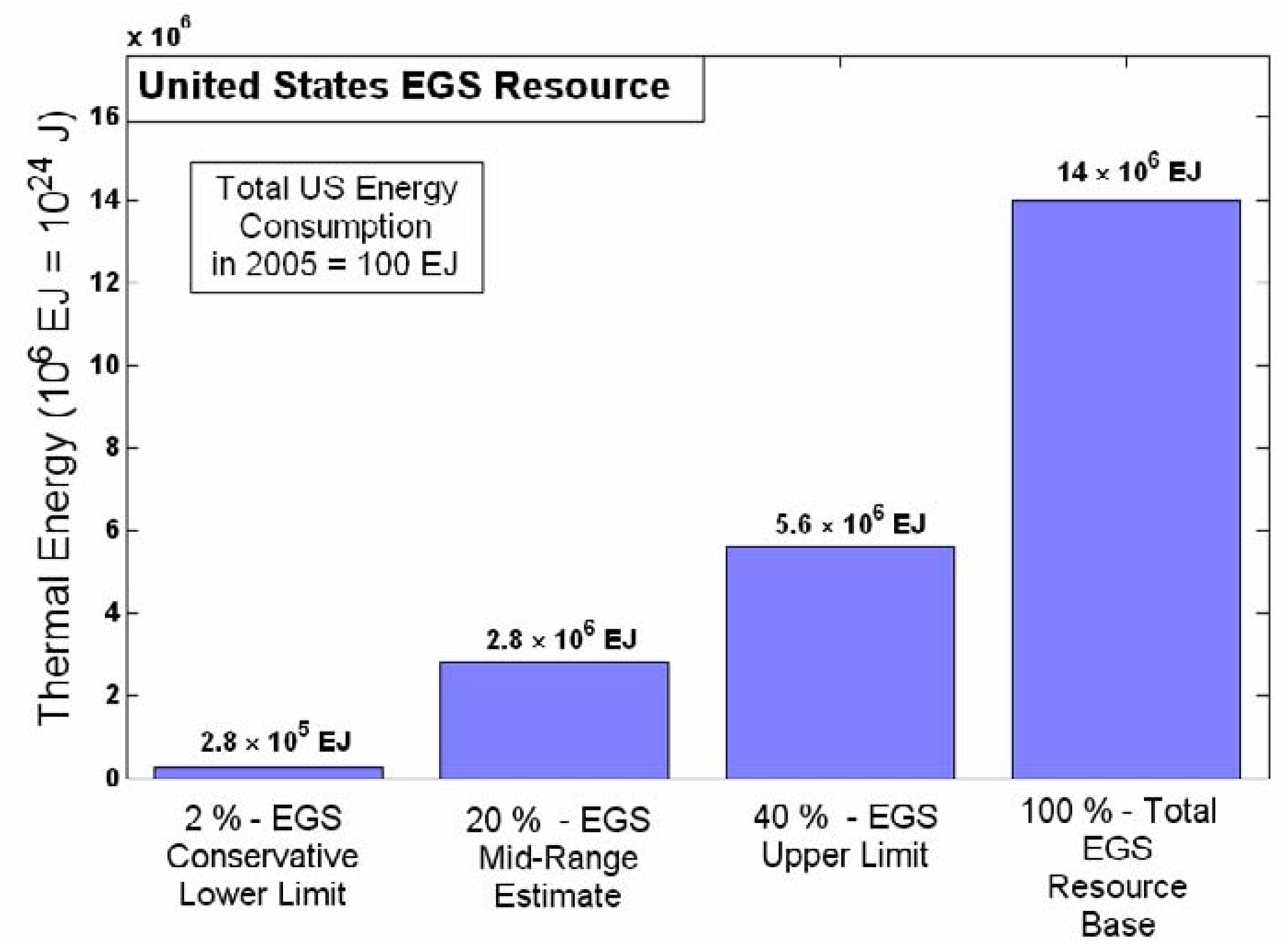
Average US geothermal gradient to 6 km



from Blackwell and Richards, SMU (2006)

EGS grades vary widely in the US

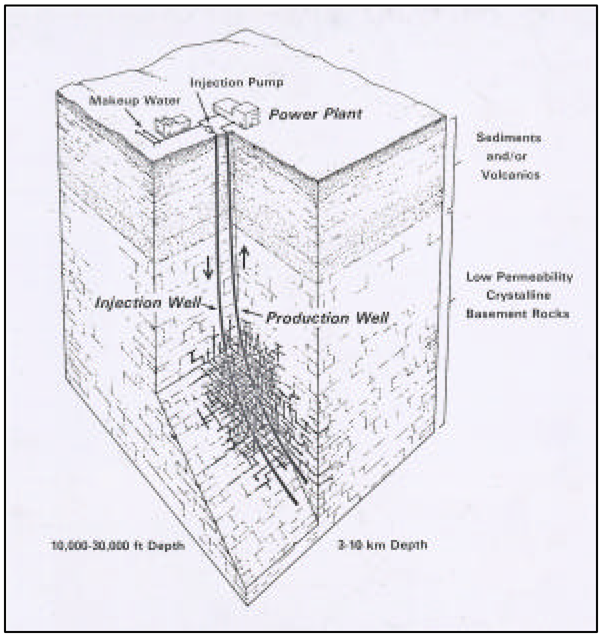
Speculation on the recoverable fraction of the EGS resource

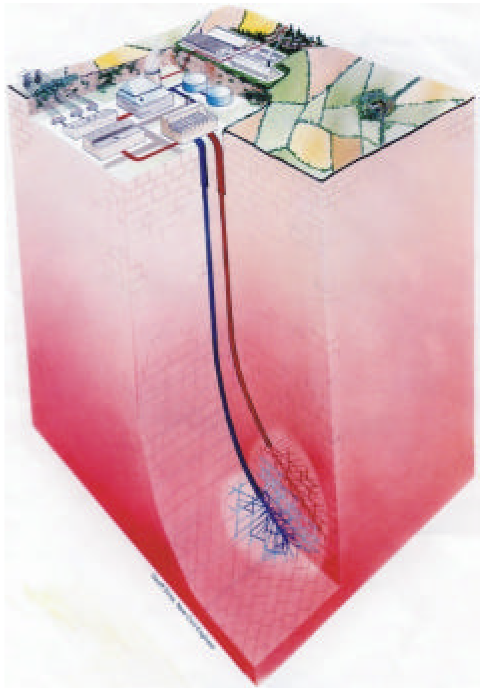


The amount of recoverable energy from EGS will not be constrained by the size and location of the resource

To achieve these levels of energy recovery

All we need is a technology to create reservoirs that emulate what nature has provided in high-grade, hydrothermal systems





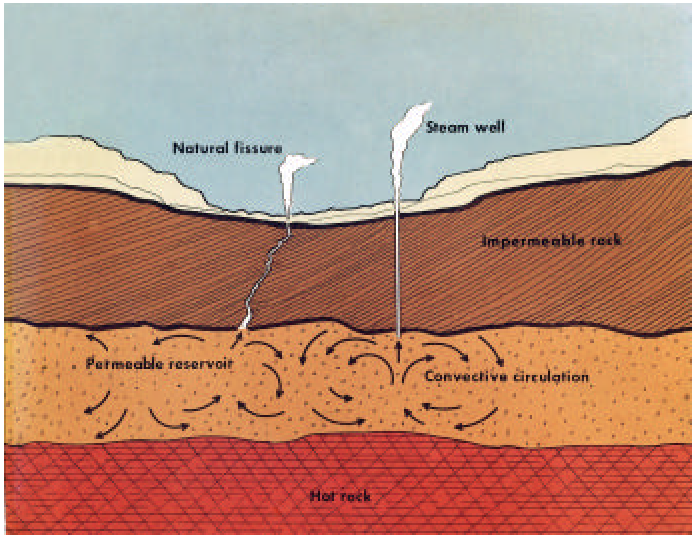
Enhanced/Engineered Geothermal Systems (EGS)

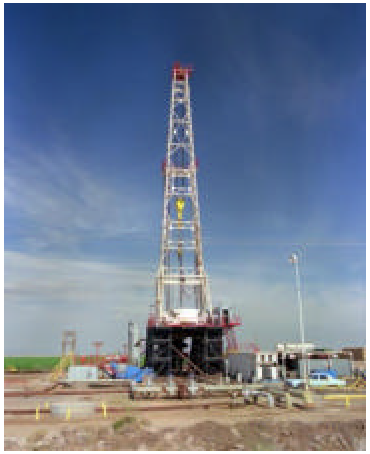
Part 2 – Technology

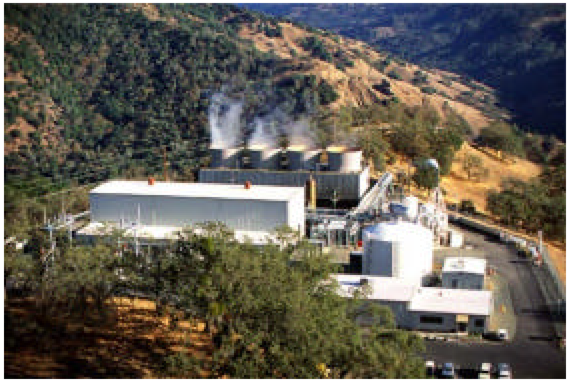
- specification of requirements for subsurface and surface system components, including drilling, reservoir design and stimulation, energy conversion
- retrospective review, analysis and lessons learned from 30+ years of field testing

Hydrothermal systems – common characteristics

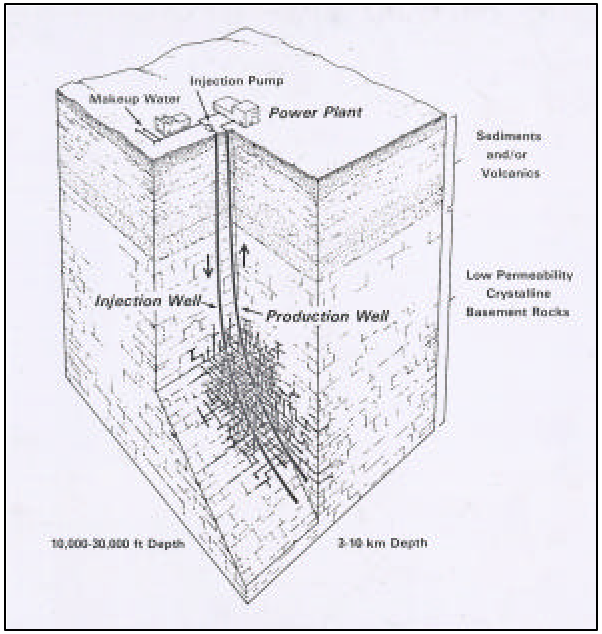
- An accessible, sufficiently high temperature rock mass underground
- Connected well system with ability for water to circulate through the rock mass to extract energy
- Production of hot water or steam at a sufficient rate and for long enough period of time to justify financial investment
- Means of directly utilizing or converting the thermal energy to electricity

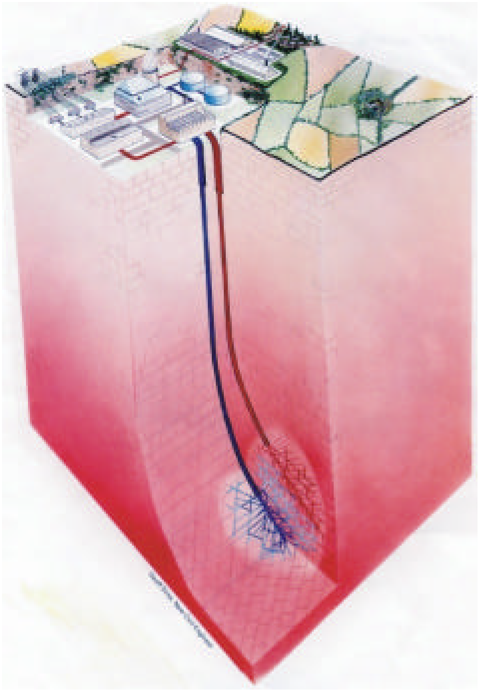






Enhanced/Engineered Geothermal Systems (EGS)





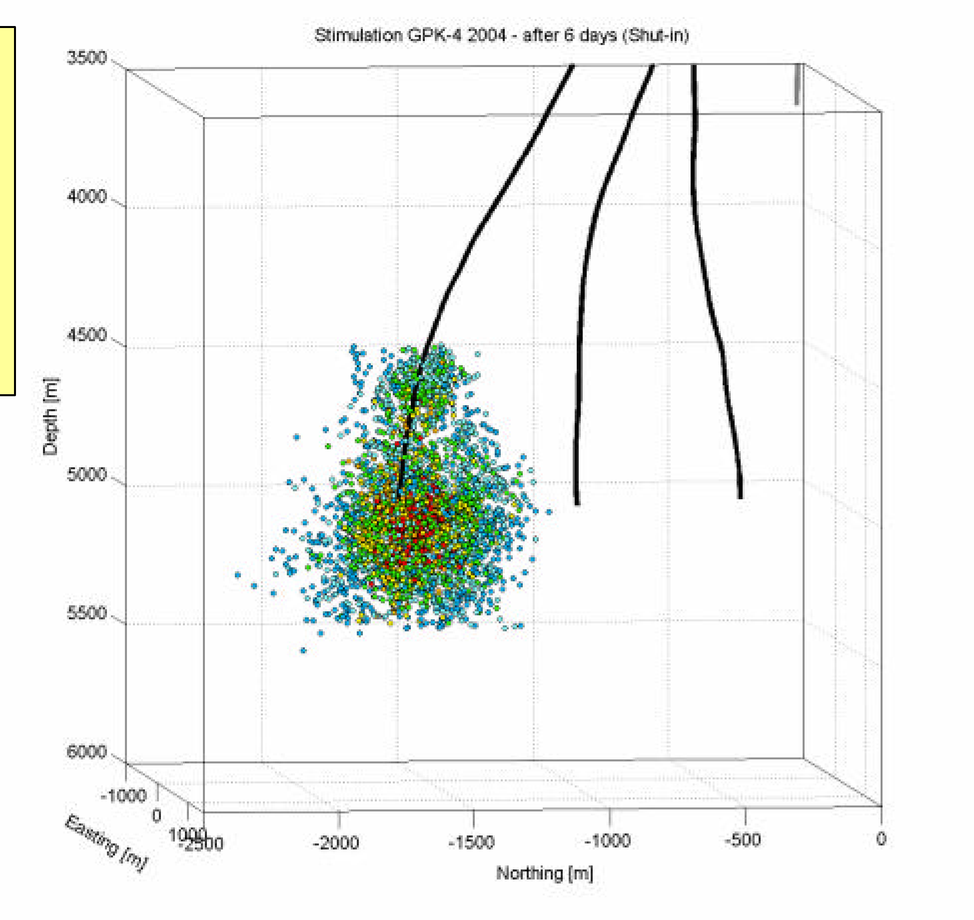
Engineered reservoirs that have been created to extract economical amounts of heat from unproductive geothermal resources.

Multi-scale R&D needs to focus on developing subsurface science and technology to create reservoirs that emulate what nature has provided in high-grade, hydrothermal systems

Stimulation to create a well-connected reservoir system

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



Animation of microseismic events during hydraulic fracturing at Soultz from Roy Baria

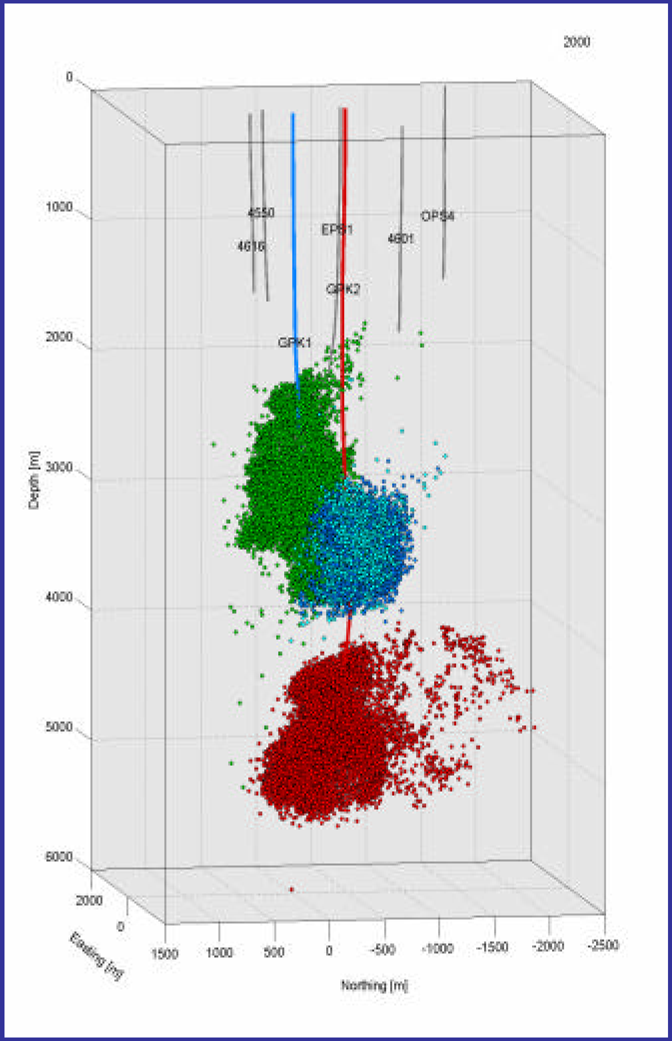
R&D focused on developing technology to create reservoirs that emulate high-grade, hydrothermal systems

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

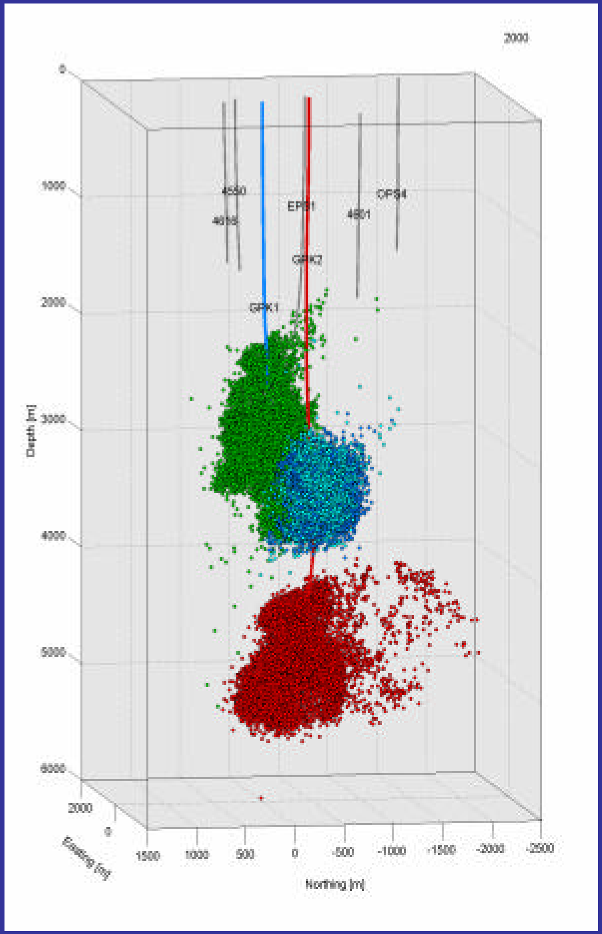
has resulted in much progress and many lessons learned

- directional drilling to depths of 5+ km & 300+°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



Soultz, France from Baria, et al.

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



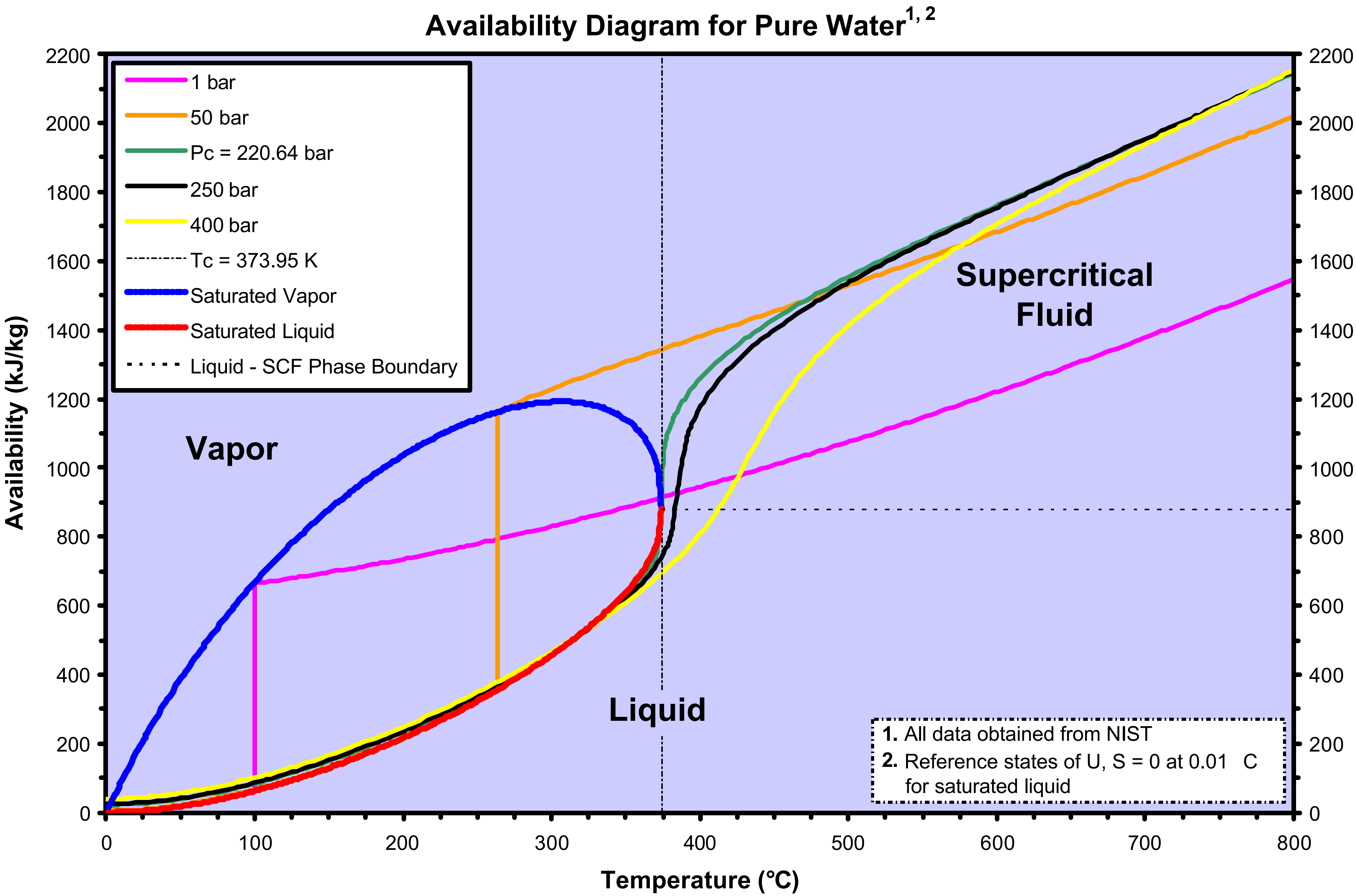
1. Commercial level of fluid production with an acceptable flow impedance thru the reservoir
2. Establish modularity and repeatability of the technology over a range of US sites
3. Lower development costs for low grade EGS systems

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

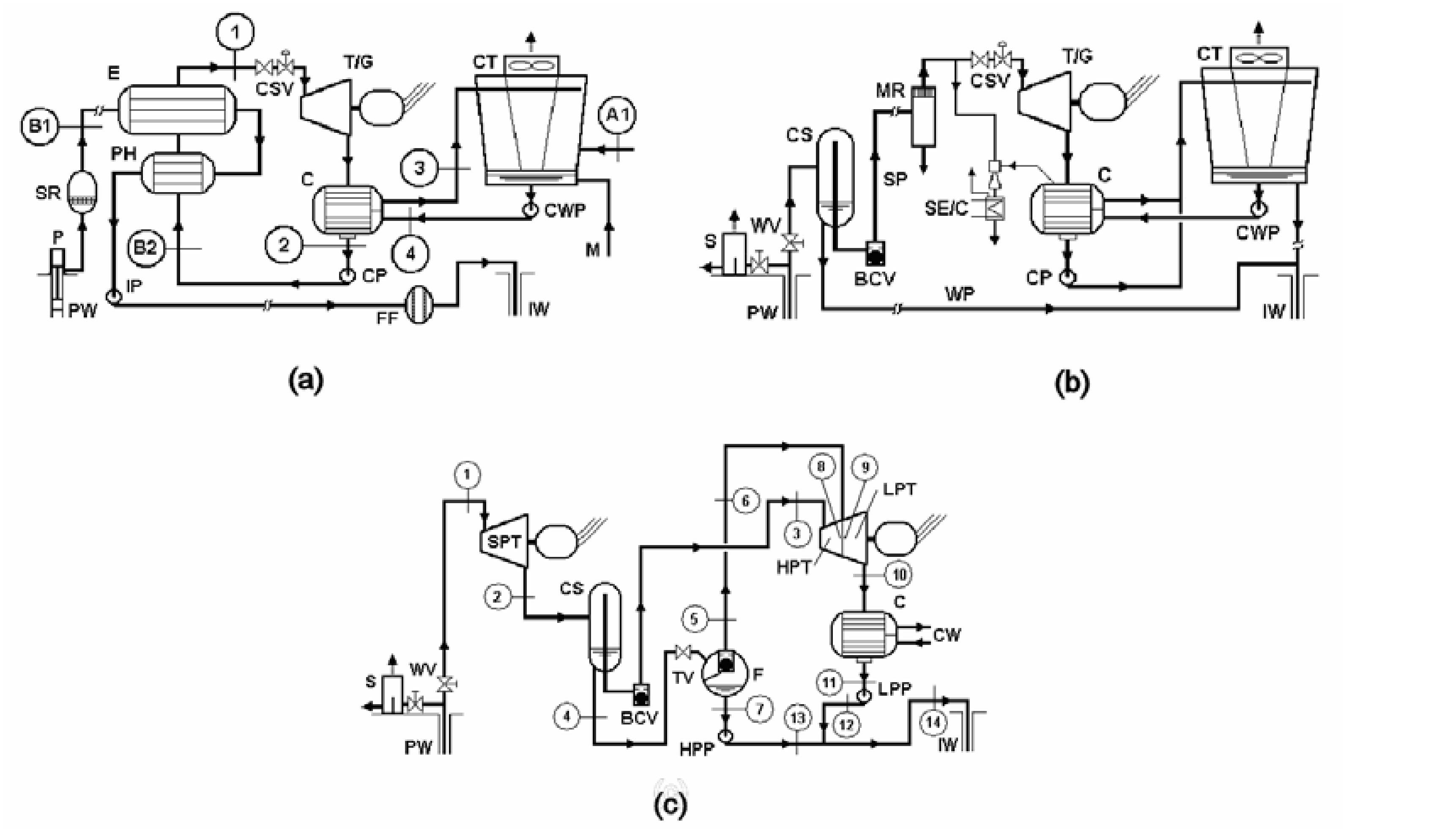
EGS Drilling

- a critical cost component, particularly for low-grade EGS requiring deep wells
- carries large risk and uncertainty
- limited experience in deep systems >3 km
- no experience beyond 6 km depths
- Wellcost Lite model was validated to 6 km and used to predict EGS well costs for base case conditions up to 10 km
- multilaterial completions and advanced casing designs considered
- actual drilling costs for geothermal and oil and gas wells were normalized to 2003 $ and compared
- sensitivity analysis was used to show relative importance of drilling on LEC
- evolutionary progress of technology and learning play critical and interactive roles in reducing costs
- revolutionary technologies will be needed for universal heat mining

Power producing potential of geothermal heat depends strongly on resource temperature and pressure



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



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

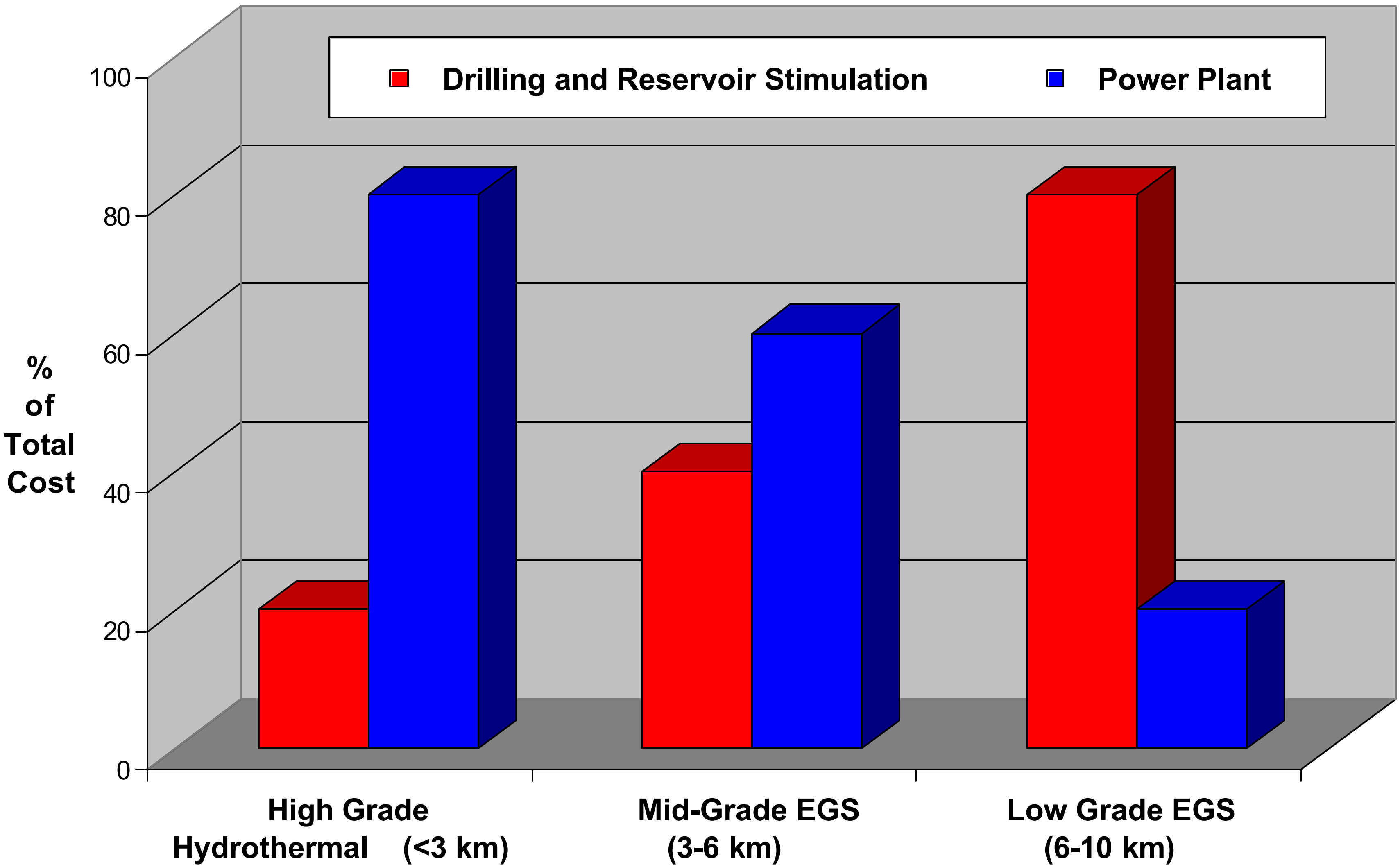
Part 3 – Environmental attributes and constraints

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

Part 4 – Economics

- evaluation and analysis of drilling and completion costs
- update drilling indices for cost normalization
- evaluation of costs for energy conversion options for utilization
- economic modeling for prediction of costs using GETEM and MITEGS models
- base case parameters and sensitivity to technology and financial parameter variations
- learning curves, supply curves and R&D projections for a national program

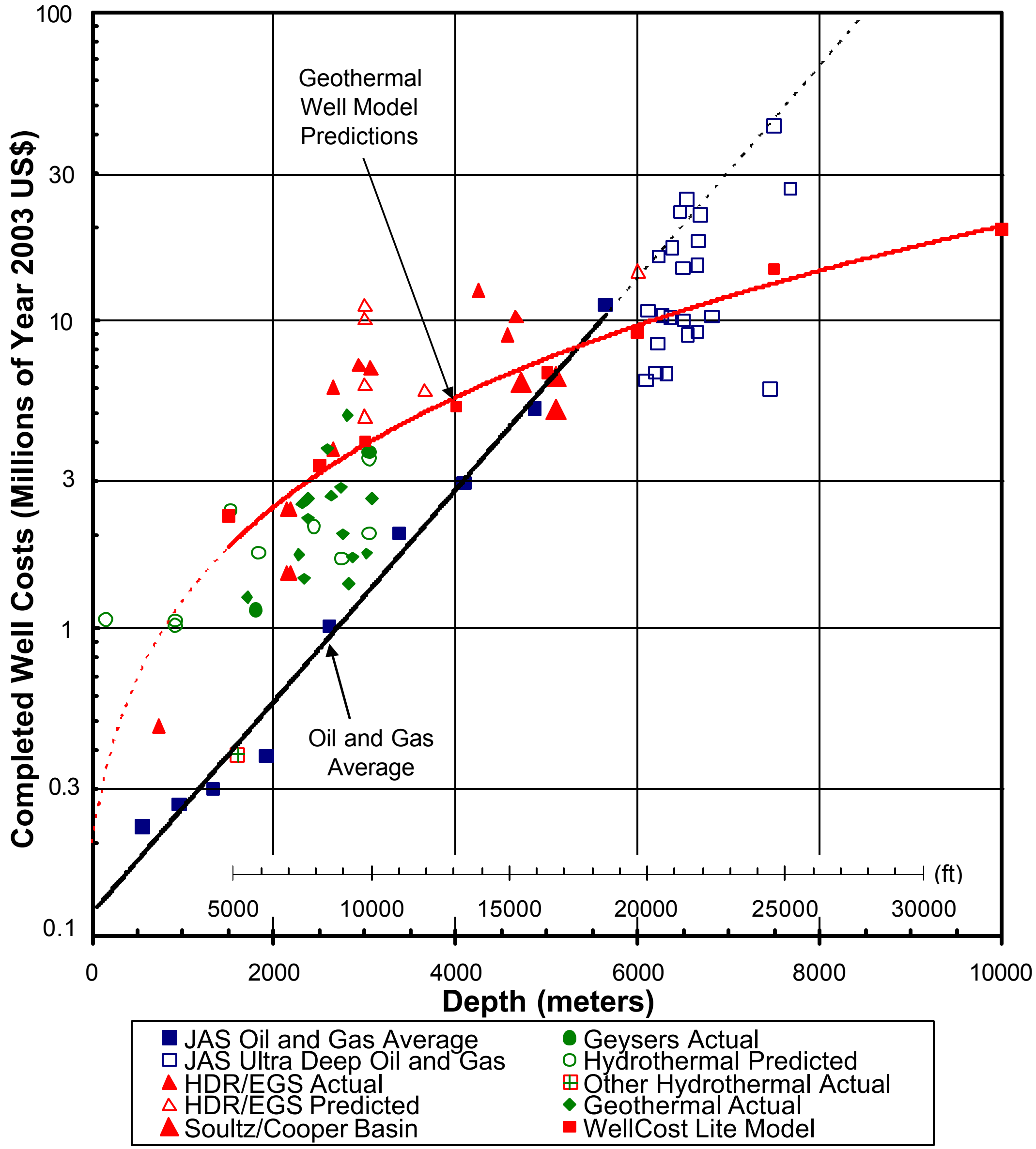
As EGS resource quality decreases, drilling and stimulation costs dominate



EGS well costs vary less strongly with depth but still cost more than oil and gas wells to depths < 6 km

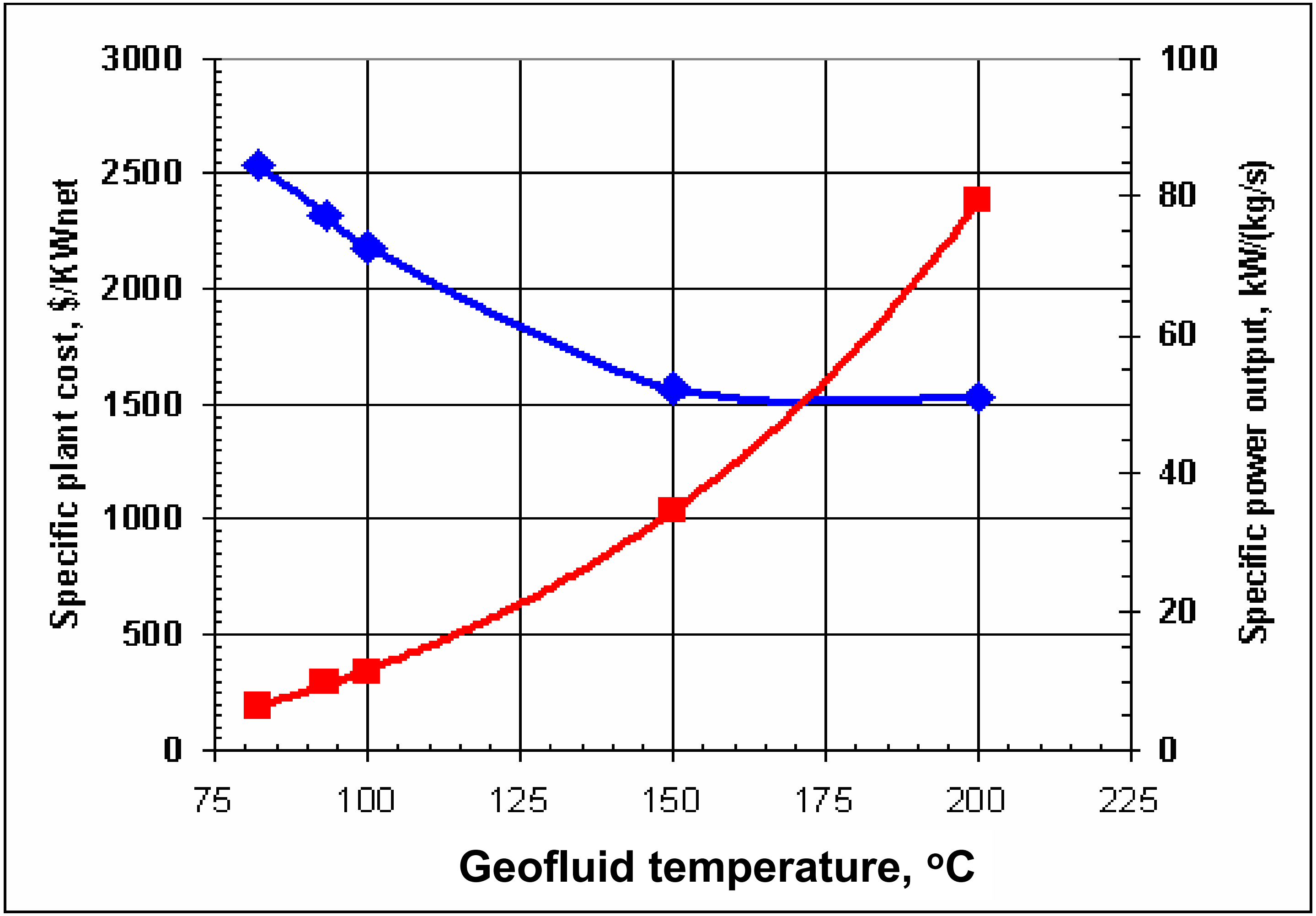
Wellcost Lite Model ------ comprehensive, details for bit performance, casing design tangible and intangible costs, etc.

High grade systems at 150 -250°C require rock at 3 to 5 km depths



1. JAS = *Joint Association Survey on Drilling Costs* .
2. Well costs updated to US$ (yr. 2003) using index made from 3-year moving average for each depth interval listed in JAS (1976-2003) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Some Soultz and Cooper Basin well costs in non-corrected Year 2004 US$.
4. Ultra deep well data points for depth greater than 6 km are either individual wells or averages from a small number of wells listed in JAS (1994-2002).
5. "Geothermal Actual" data include some non-US wells (Mansure, 2004)

Surface Plant Output and Capital Costs



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

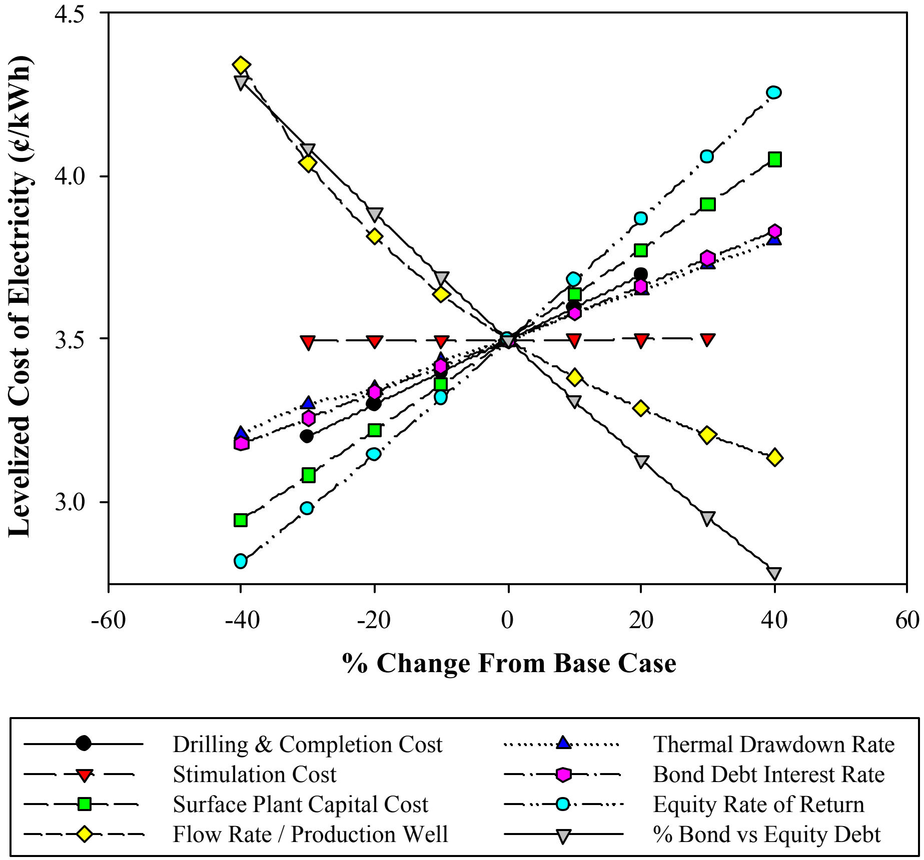
Lesser impact but still important --

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

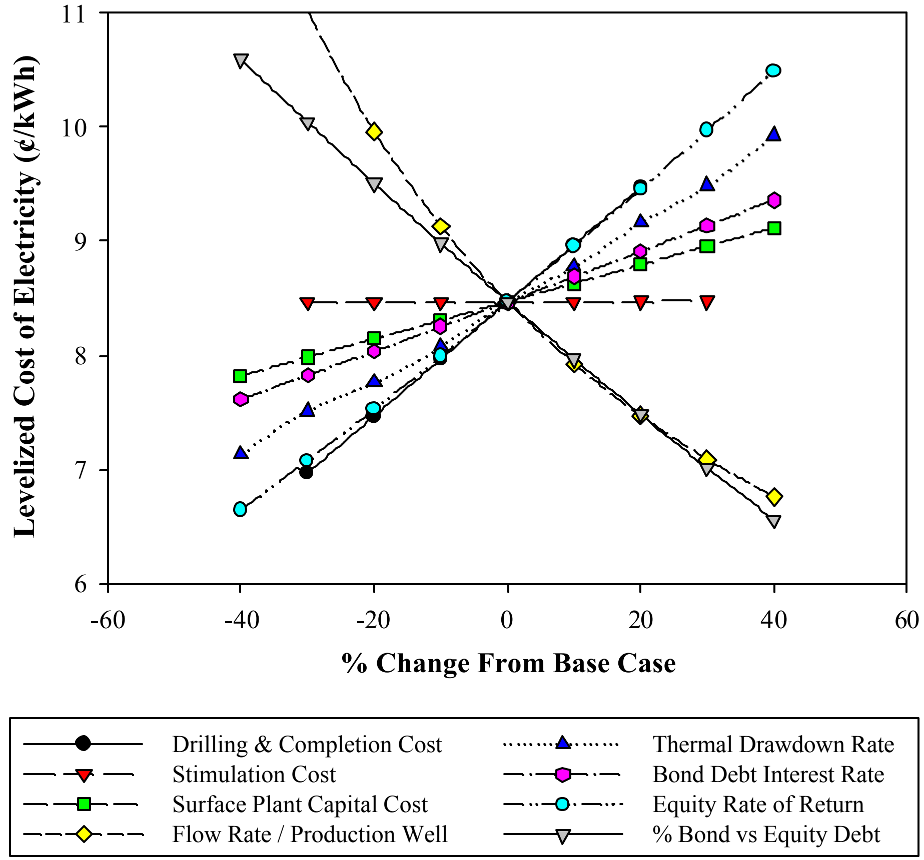
Sensitivity analysis – assessment of factors influencing costs

2003 US $

High grade EGS resource- Clear Lake conditions



Low grade EGS resource – Conway conditons



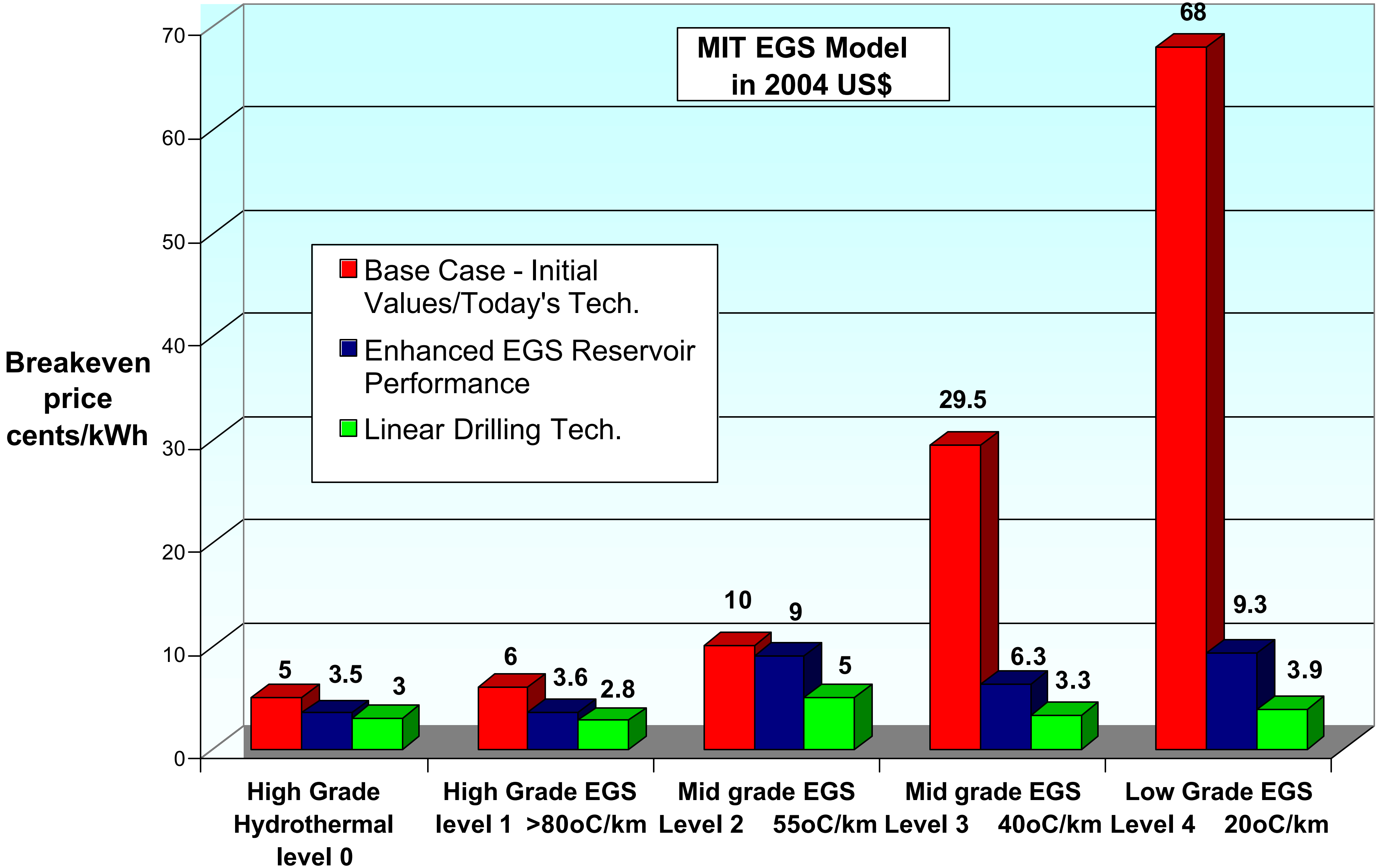
80 kg/s flow rate per production well in a quartet configuration (1 injector : 3 producers)

Levelized Cost of Electricity (LEC) estimated for 6 targeted sites for EGS development

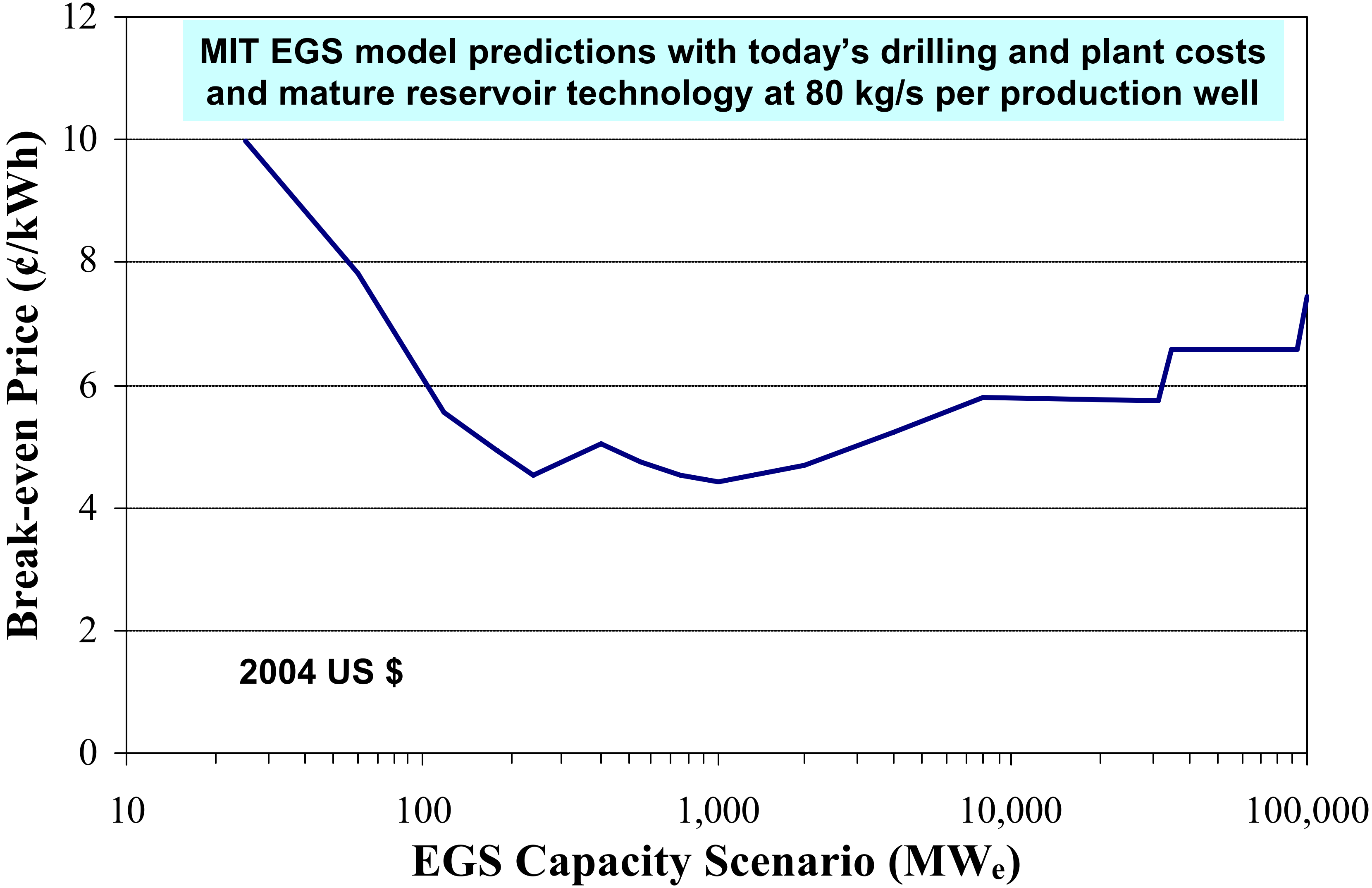
Site Name	?T/?z (°C/km)	Depth to Granite (km)	Complet-ion Depth (km)	Fracture Costs ($K)		LEC Using Initial Values for Base Case (¢/kWh)		Optimized LEC Using Commercially Mature Values (¢/kWh)		
				@ 93 l/s	@ 180 l/s	MIT EGS	GETEM	MIT EGS	GETEM	Depth (km)
East Texas Basin	40	5	5	145	171	29.5	21.7	6.2	5.8	7.1
Nampa	43	4.5	5	260	356	24.5	19.5	5.9	5.5	6.6
Three Sisters Area	50	3.5	5	348	450	17.5	15.7	5.2	4.9	5.1
Poplar Dome a	55	4	2.2	152	179	74.7	104.9	5.9	4.1	4.0
Poplar Dome b	6.7	4	6.5	152	179	26.9	22.3	5.9	4.1	4.0
Clear Lake	67	3	5	450	491	10.3	12.7	3.6	4.1	5.1
Conway Granite	26	0	7	502	580	68.0	34.0	9.2	8.3	10*

*10 km limit put on drilling depth − MITEGS LCE reaches 7.3 ¢/kWh at 12.7 km and 350 °C geofluid temperature.

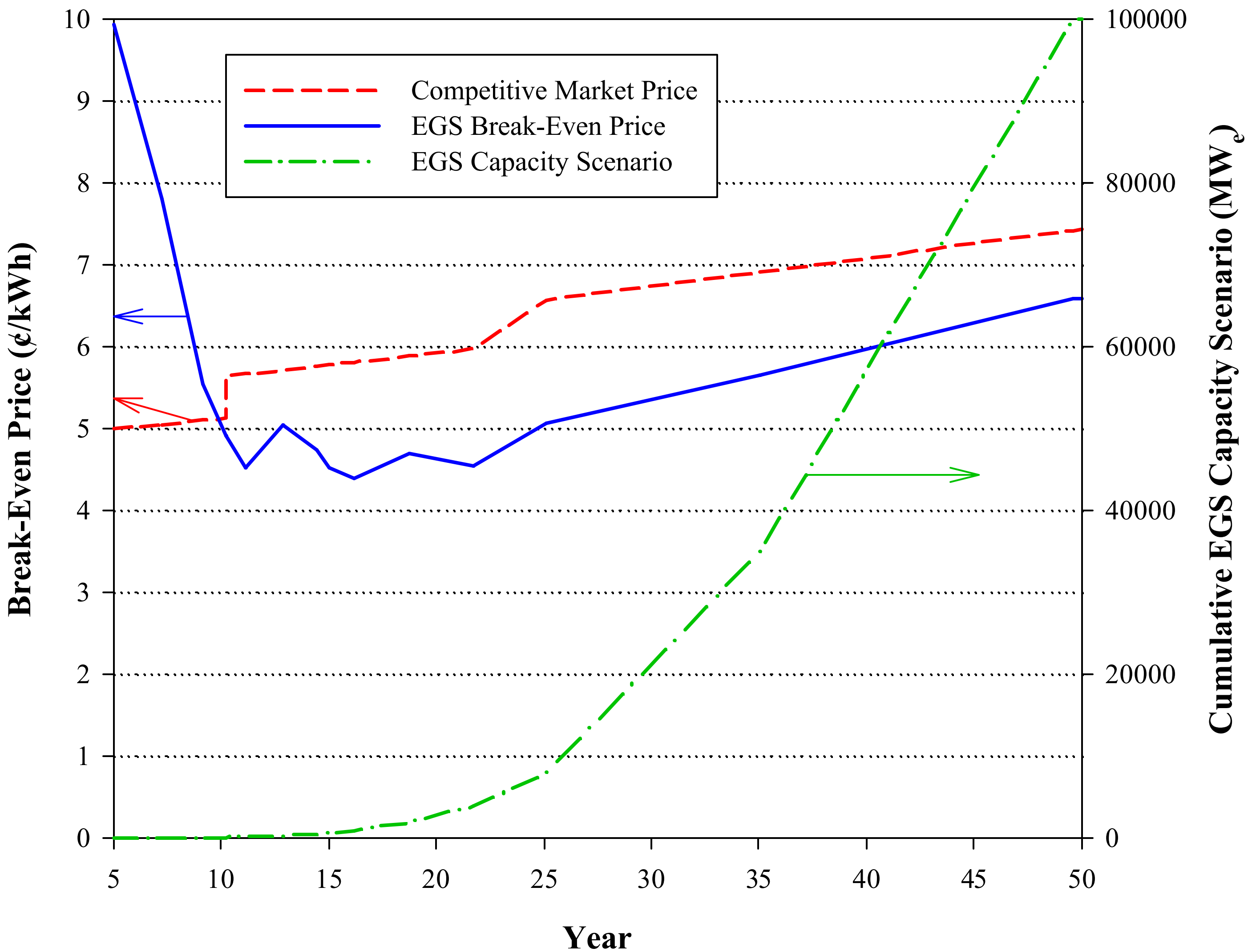
Predicted electricity costs for US geothermal resources



Supply Curve for the US EGS resource



Levelized break-even price using MIT EGS for the 100,000 MWe



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).

Summary -- Why should the US 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. EGS can sustain production of 100,000 MWe of base load electric power
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 are inherent modular making them easily deployable in all regions of the US.
4. **Technically feasible** -- Much progress has been accomplished in 30+ years of testing worldwide – the major elements of the technology to capture and extract EGS are already 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. **R&D costs low** -- A modest investment of $300-400 million over15 years would demonstrate EGS technology at a commercial scale at several US field sites to reduce risks for private investment and enable the development of 100.000 MWe.

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

- ❑ **Support national scale EGS resource assessment**
- ❑ **Support 3-5 field demonstrations in the next 15 years to refine technologies for demonstrating commercial-scale EGS**
- ❑ **In the short term utilize high grade EGS targets at the margins of hydrothermal reservoirs in the 3 to 6 km regime**
- ❑ **In the longer term, move towards using lower gradient EGS requiring deeper heat mining methods >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 $300 to 400 million in RD&D over 15 years to enable 100,000 MWe capacity for the US

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

Acknowledgements

U.S. DEPARTMENT OF ENERGY

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

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- ❑ National Renewable Energy Laboratory
- ❑ Sandia National Laboratories

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Thank you

The Blue Lagoon in Iceland