Economic Analysis
Engineered Geothermal Systems

Michal C. Moore
Brian J. Anderson

Objectives

- Review research and data integration
- Discuss model results
- Discuss risk and sensitivity
- Discuss economic and competitive analysis

Basic Economics of Hydrogeothermal

- Discovery and seismic
- Drilling initial test wells
- Field design and learning curve
- In-well stimulation
- Installation of manifold and surface conversion facilities
- Learning curve
- Restimulation and redrilling
- Competitive price

GETEM and MITEGS

- Geothermal Electric Technology Evaluation Model (GETEM)
  - Princeton Energy Resources International developed for the U.S. DOE Geothermal Technology Program
  - About 80 user defined input variables
    - Temperature, depth, stimulation cost, flowrate, temperature drawdown rate, drilling contingency, exploration success, etc.
  - Detailed line-item costs
  - Based on Fixed Charge Rate
- MITEGS
  - Based on work by Tester and Herzog, 1990, 1991, 1997
  - Modified and updated to 2004 $ and to use cost analyses developed by the panel – Anderson, 2006
  - Similar user inputs to GETEM - built on correlations or user supplied costs
  - Uses BICYCLE II (Hardie, 1981 – LA-8909) including bond and equity rates, tax rates, etc.

Incorporating Field Analysis

- Subsurface mapping
- Drilling and field learning
- Matching well output potential to surface conversion
- Grid operations and interconnect

Geothermal Resources
A Regime of Gradation

Shallow depths
< 100m

Change in Resource Characteristics

Hydrogeothermal Resources
< 4 km (arbitrary)

Depth

EGS - Hot Dry Rock
> 200 ^{o} C
> 4 km

EGS Assessment Project Goals

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

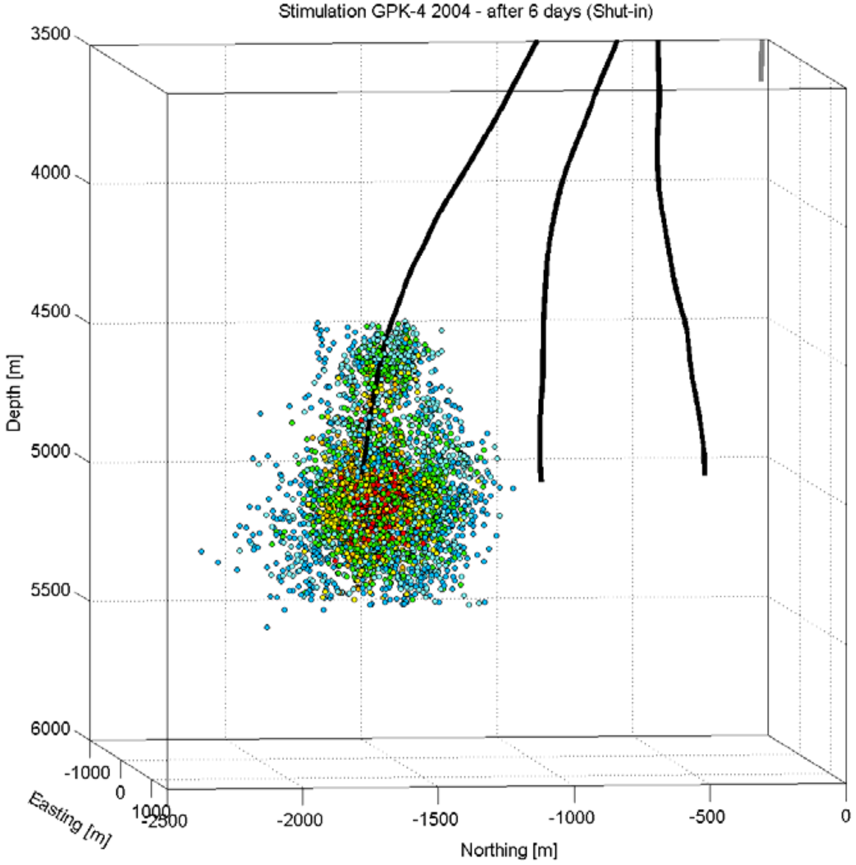
Major impact was defined as enabling 100,000 MWe of an economically viable EGS resource on line or as a true reserve by 2050

Approach to Research

- Estimate the EGS resource within Geothermal continuum
- Determine and estimate the potential costs of technology applications - drilling, reservoir and conversion
- Investigate the environmental attributes and constraints
- Model costs and project potential returns

Evaluating stimulation methods that will create consistent well-connected reservoirs

The critical challenge: 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

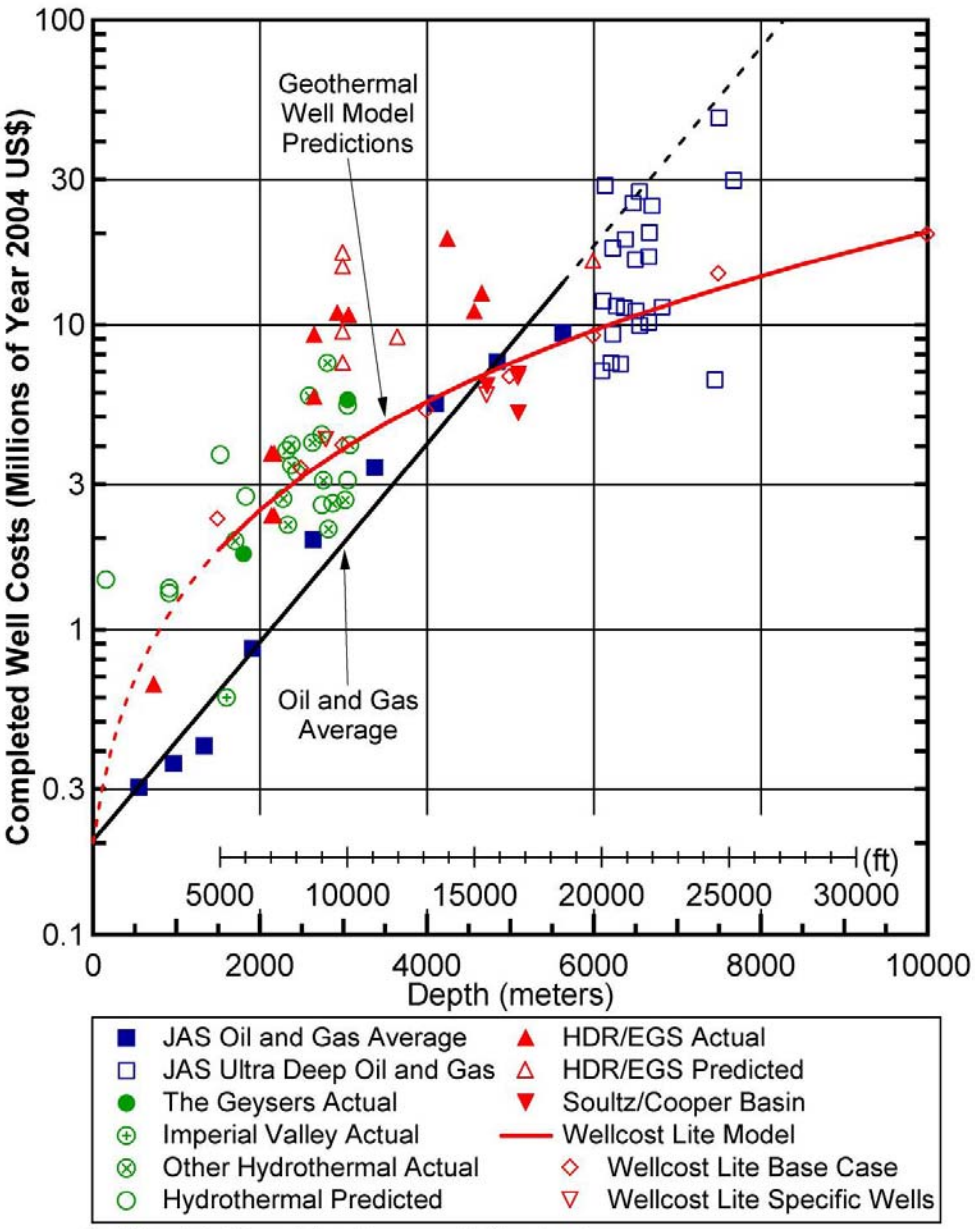
"snap shot" of microseismic events during hydraulic fracturing at Soultz Source: Roy Baria

EGS Drilling and Costs in Model

- critical cost component, particularly for low-grade EGS requiring deep wells
- no drilling 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
- multilateral completions and advanced casing designs considered
- actual drilling costs for geothermal and oil and gas wells were normalized to 2004 $ 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

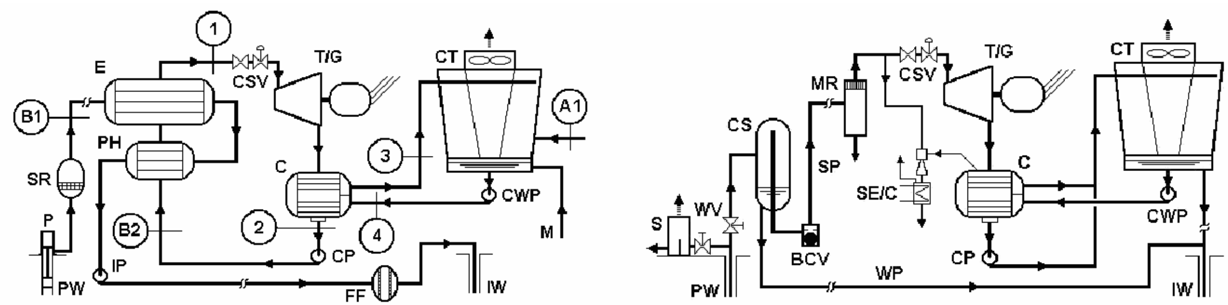
EGS well costs vary less strongly with depth than oil and gas wells.

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

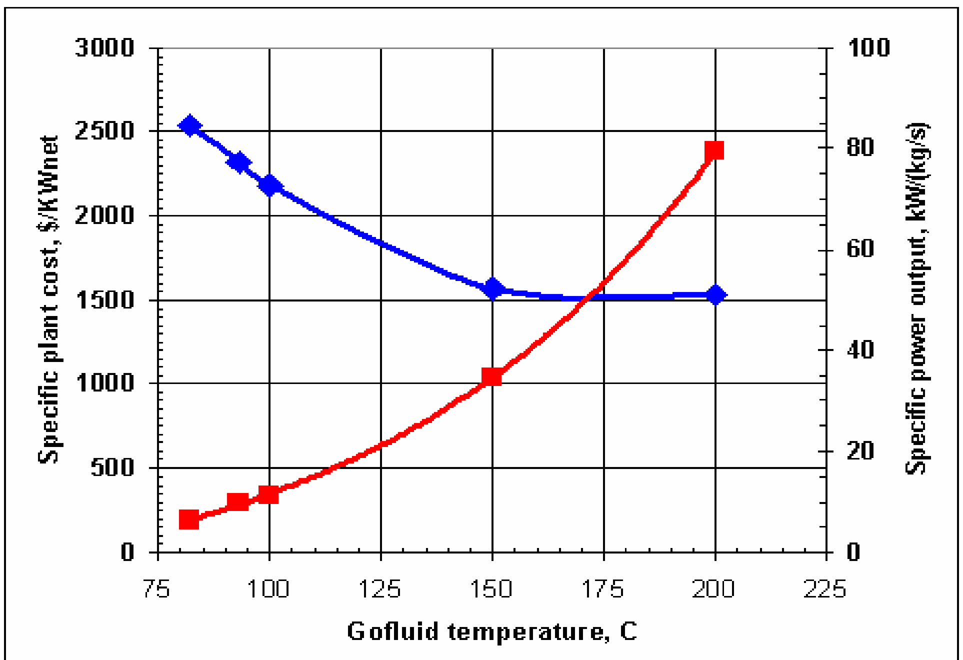


1. JAS = *Joint Association Survey on Drilling Costs.*
2. Well costs updated to US$ (yr. 2004) using index made from 3-year moving average for each depth interval listed in JAS (1976-2004) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Ultra deep 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 were 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

Base case parameters for EGS economic modeling

Major Impact with higher uncertainty and risk --

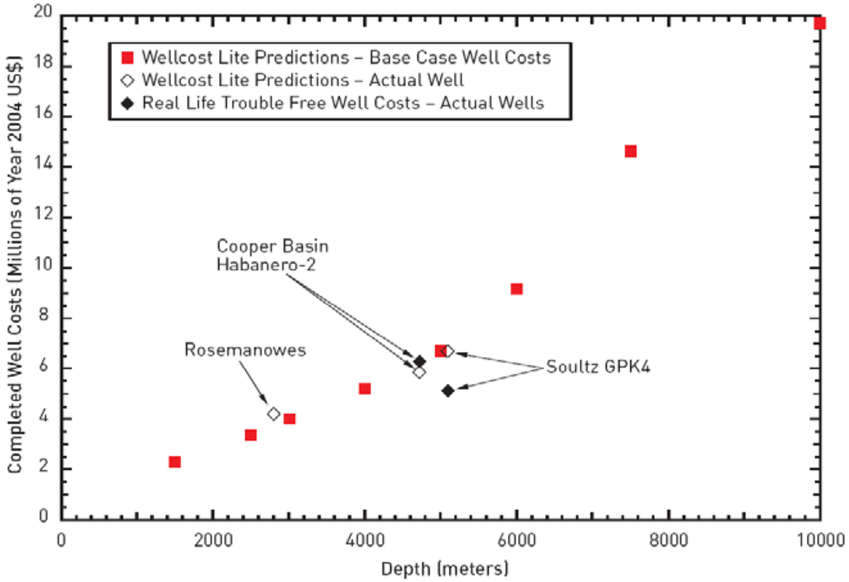
- Flow rate per production well (20 to 80 kg/s)
- Thermal drawdown rate / redrilling-rework periods (3% per year / 5-10 years)
- Resource grade – defined by temperature or gradient = f(depth, location)
- Financial parameters
  - Debt/Equity Ratio (variable depends on EGS resource grade)
  - Debt rate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

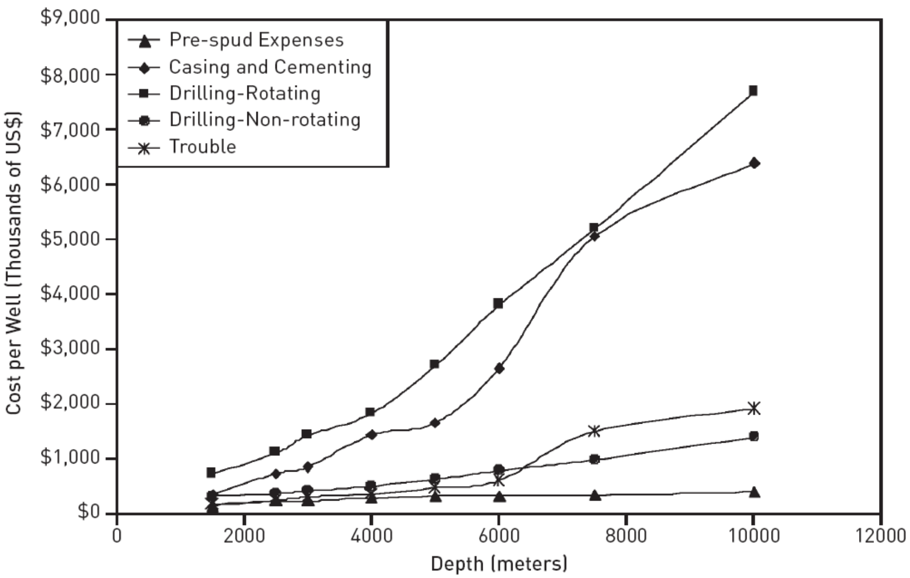
Lesser impact but still important --

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

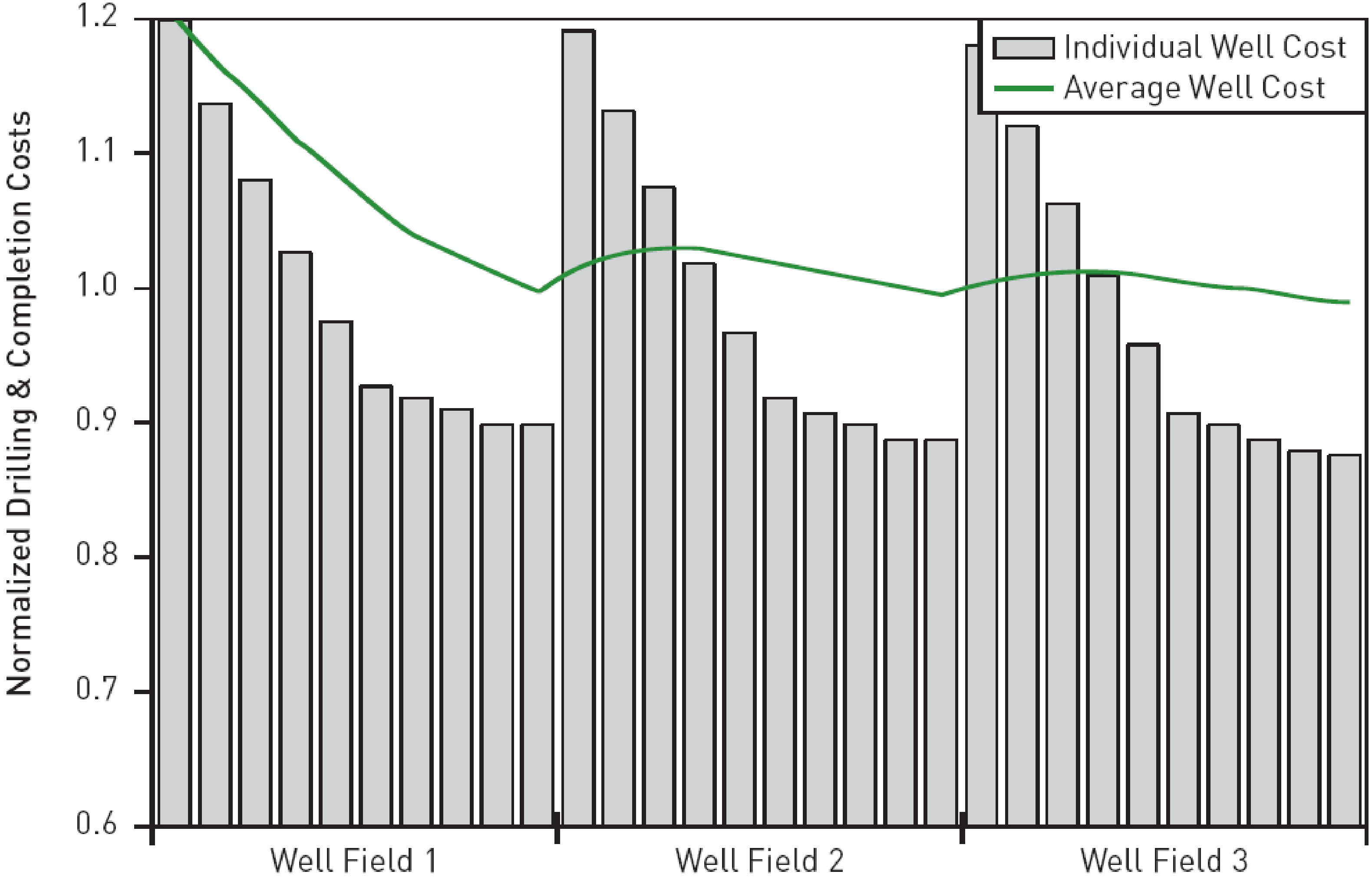
Drilling and Well Costs Are Significant

Shallow			Mid Range			Deep		
Depth, m (ft)	No. of Casing Strings	Cost, million $	Depth, m (ft)	No. of Casing Strings	Cost, million $	Depth, m (ft)	No. of Casing Strings	Cost, million $
1,500 (4,900)	4	2.3	4,000 (13,100)	4	5.2	6,000 (19,700)	5	9.7
2,500 (8,200)	4	3.4	5,000 (16,400)	4	7.0	6,000 (19,700)	6	12.3
3,000 (9,800)	4	4.0	5,000 (16,400)	5	8.3	7,500 (24,600)	6	14.4
						10,000 (32,800)	6	20.0



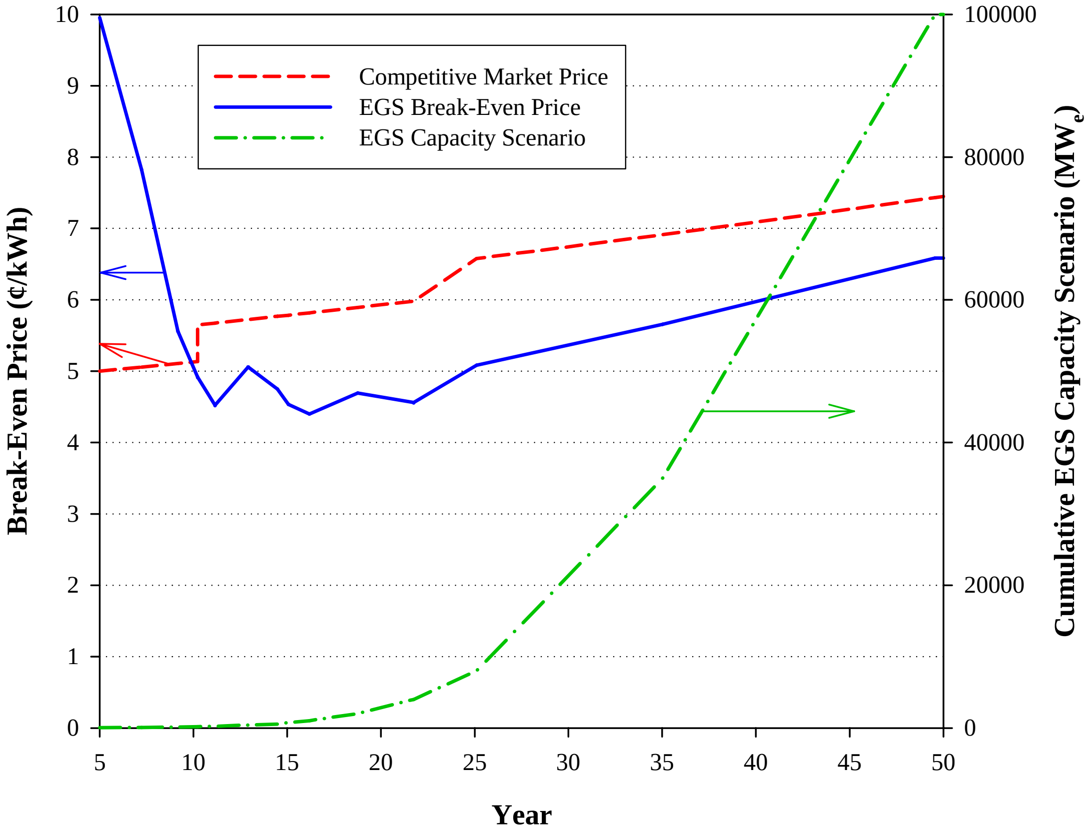


Learning Curves and Technology Diffusion



Ikoku, 1978; Brett and Millheim, 1986 ; Kravis et al., 2004; McDonald and Schrattenholzer, 2001

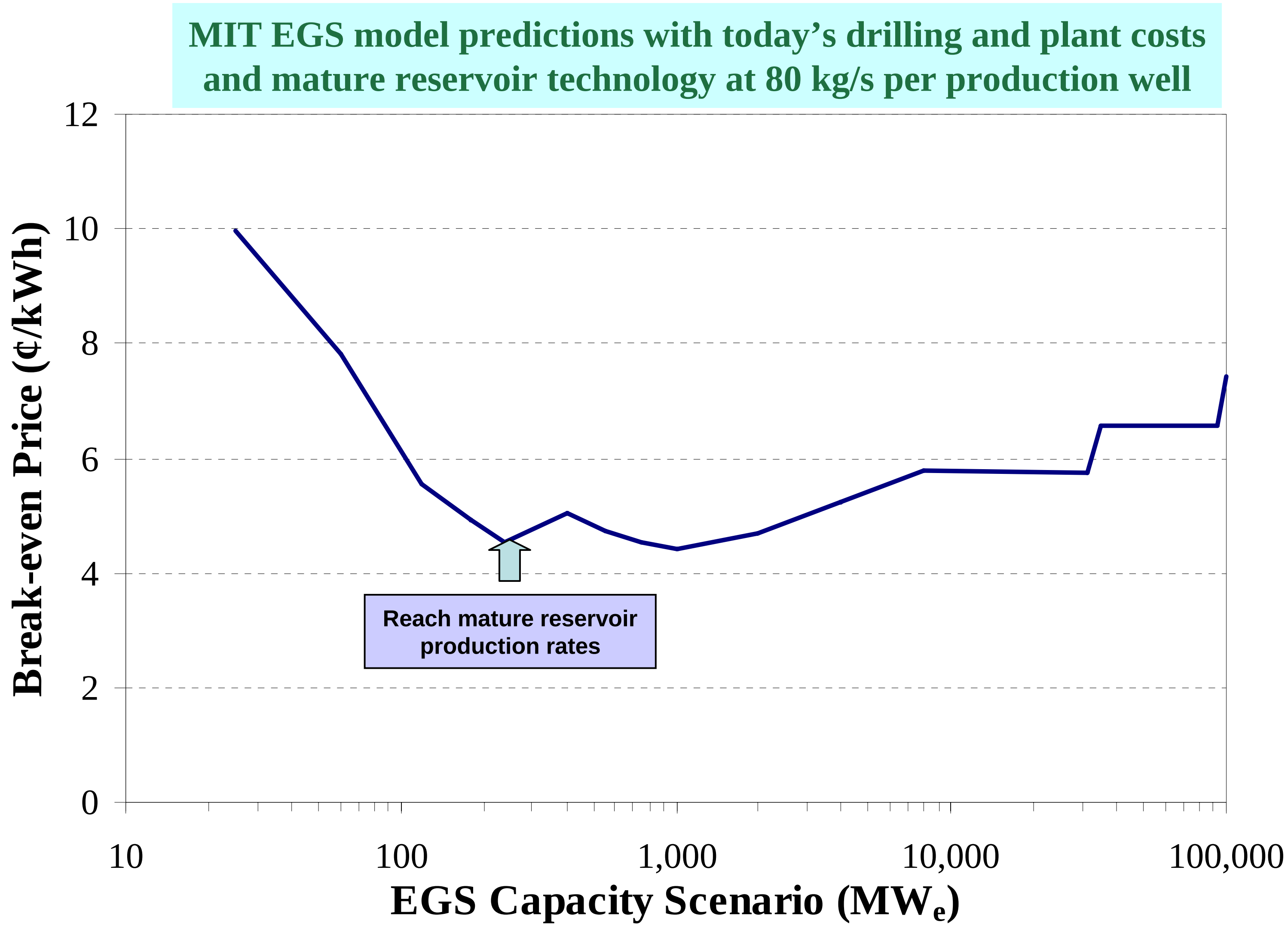
Predicted levelized break-even price (LEC) and growth in supply using MIT EGS model



- 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

Supply Curve for the US EGS resource

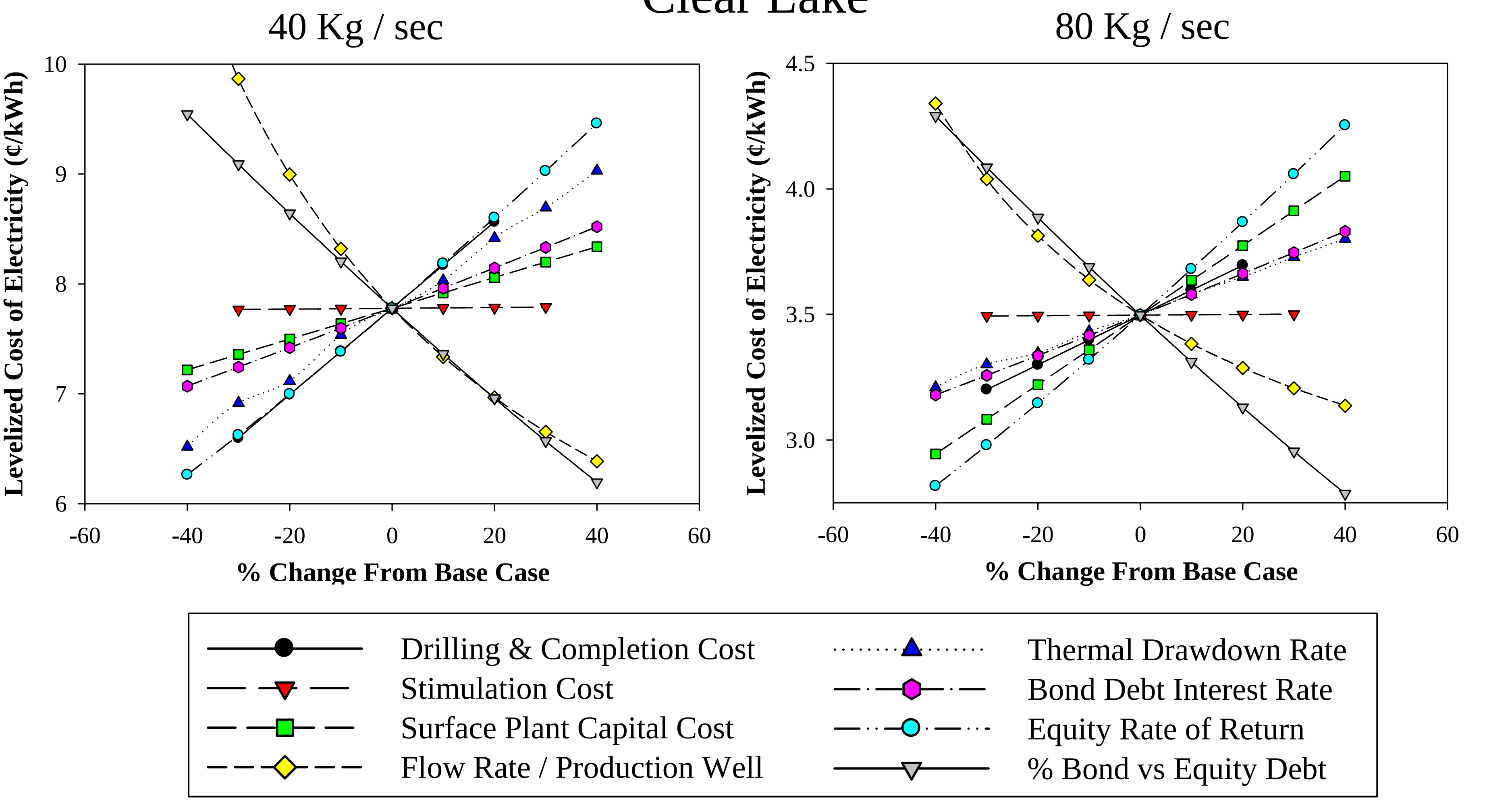


Sensitivity Analysis

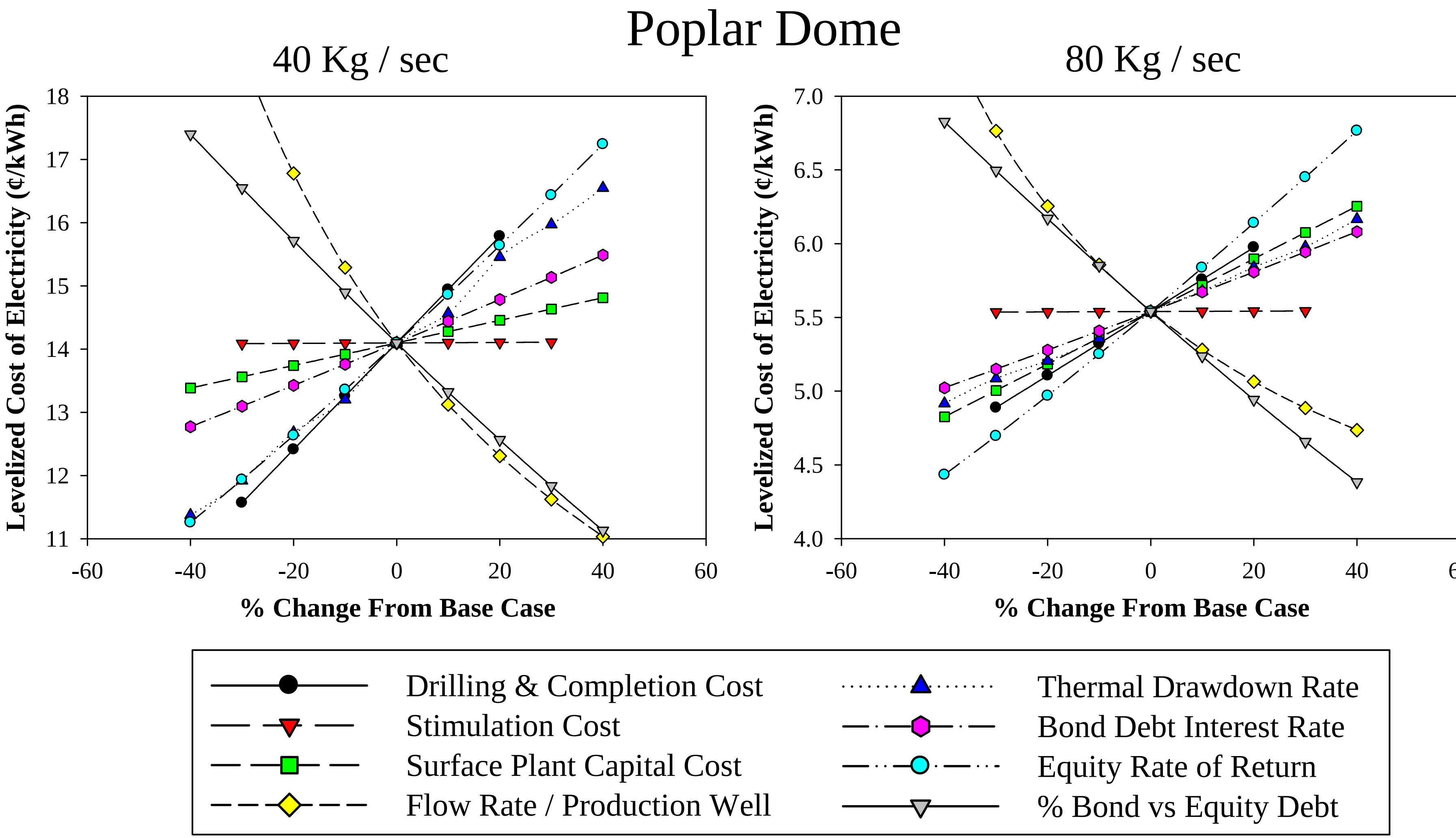
- A couple of examples
  - Clear Lake
  - Poplar Dome
- Changes in flow rates are critical
- Base heat conditions are critical

Sensitivity Analysis

Clear Lake



Sensitivity Analysis



The Issue of Risk

- What is it
- How does the market overcome it

Technology Diffusion and Adoption

- Level of R and D
- Subsidies for early adopters
- Technology adaptation
- Cost of capital
- Delivered, competitive cost of energy

Key Outcomes of Economic Analysis

- **EGS is a natural but not inevitable extension of hydrothermal technologies**
- **Well configuration and stimulation techniques affect reservoir productivity and lifespan**
- **Highest correlation for costs is effectiveness of stimulation to achieve acceptable reservoir productivity**
- **High sensitivity to early R&D investment**
- **Invested costs are reasonable compared to other alternative energy programs and can yield competitive baseload contribution in under 15 years**
- **Pursuing EGS aggressively does not diminish but extends the role of hydrothermal**