Estimation and Analysis of Life Cycle Costs of Baseline EGS

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Systems Analysis, Resource Assessment, Data System Development, and Population Projects

This project will estimate EGS life cycle costs and analyze key cost drivers

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Project Objectives

1. Independent estimates of the current cost structure of EGS
2. Estimate costs impacts of new technologies and market issues
3. Insight into the state of EGS technology through patent analytics
4. Evaluation of novel process configurations, e.g., CO_2-EGS-IGCC
5. Outreach in industry, academia, and community to disseminate findings

Tackles DOE GTO Barriers

- Limited policy analyses
- Lack of datasets / models
- Unclear economic benefits
- Lack of integrated analyses
- Unknown infrastructure impacts

Supports DOE GTO Goals

- Assess likelihood of achieving EGS goals
- Estimate EGS technology readiness
- Evaluate cost impacts of new tools and technologies from DOE GTO R&D

Rigorous expert elicitation, modeling, and patent analytics are our core methods …

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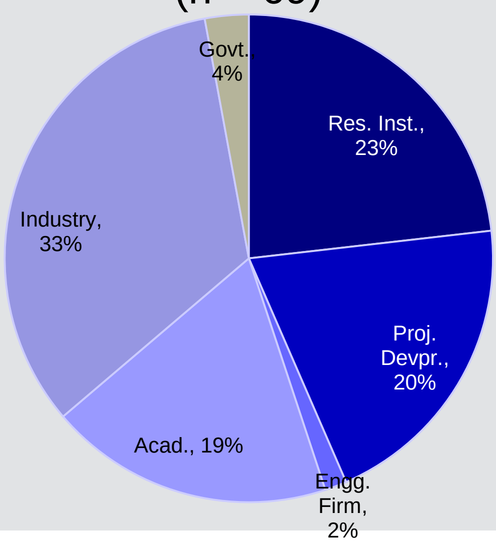
Expert Elicitation

- Designed using DOE best practices and training
- Builds on other DOE work
- Structured expert briefs
- Conducted continually, widely, formally, and informally

Expert Affiliations

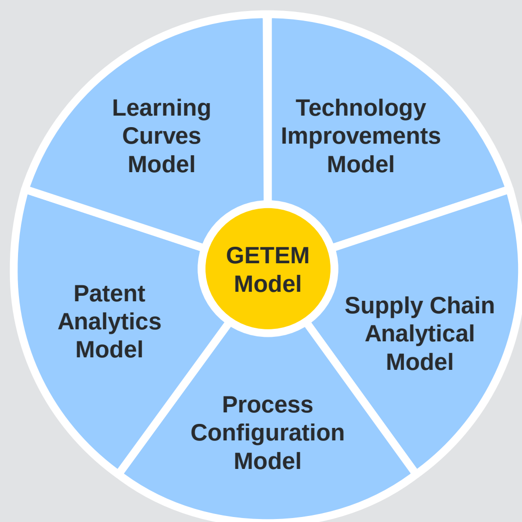
(n = 69)



Cost Modeling

- Leverages DOE's GETEM
- Integrates with other cost and process models
- Uses commercial software, e.g., Excel, @Risk, Aspen

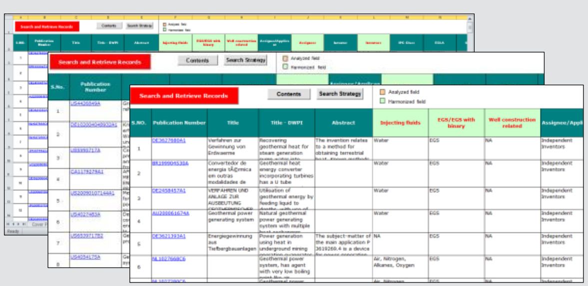
Model Integration



Patent Analytics

- Built a database of ~6,000 patents globally
- Developing insights on technology using various patent maps and analytics
- Correlating output to learning curves work

Patent Database



… Supplemented by tools and databases to help us meet our milestones

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Snapshot of Our Expert Brief

Assumptions

Key Inputs	Units	Reference Case	Literature Range
Depth	ft	16,000	1,800 – 6,000
Resource temp.	° C	200	180 – 350
Flow rate	kg/s	30	30 – 90
Thermal drawdown	%	0.3	0.3 – 3
Plant capacity	MW	50	5 – 30

- Estimates will be averaged, anonymized, and kept confidential
- Not necessary to estimate all inputs
- Reference case and literature range provided for context

Table for Experts to Fill

Key Inputs	Units	Ref. Case	Lit. Range	Low	Median	High
Flow rate	kg/s	30	30 – 90			
Thermal drawdown / yr	% / yr	0.3	0.3 – 3			
Exploration cost	$ Million/well	$7.8	$2 – $10			
Production injection ratio	Number	2	2 – 3			
Well cost	$ Million/well	$13.1	$13 - $20			
Surface equipment cost	$/well	$178, 000	$100 – $400 k			
Stimulation cost	$ Million/well	$2	$0.5-$3.0			
Rate of penetration	ft/hr	9.1 / 4.5	<10 – 50			
Water loss / total injected	%	5 %	2% – 5%			
O&M cost @ 5MW	$ Million	$1	$1 – $2			
Exploration / confirmation duration	Years	2	2-2.5			
Exploration wells drilled	Number	2	2-8			
Number of dry wells	Number	2	2			
Exploration success rate	%	50				

Snapshot of Our Metrics Database

EXCERPT

Cost Drivers	Components	Low Range	High Range
Drilling	Depth, meters	1,000	5,000
	Exploration wells	1	6
	Confirmation wells	1	8
	Injection wells	1	16
	Production wells	1	25
	Rate of Penetration, ft/hr	<10	50
Reservoir Stimulation	Flow rate, kg/s	12	30
	Thermal drawdown, percent	0.3%	3%
Power Plant	Surface equipment cost	$200,000	$400,000
	Plant capacity, MW	0.05	30
	O&M cost	$1,000,000	$2,000,000
	Transmission distance, meters	500	1000

Our Project's Milestones

Task	Milestone	Planned date	Actual date
1	Identification of most expensive components	1/1/2011	1/1/2011
	Impact of each component on LCOE	2/28/2011	2/28/2011
	Comparison of LCOE with other energy technologies	3/31/2011	3/31/2011
	Identification of component-wise cost reduction targets	5/31/2011	5/31/2011
2	Assessment of market economics for new entrants	5/31/2011	5/31/2011
	Identification of supply chain impacts on costs	8/31/2011	8/31/2011
3	Description of the technology through patent analytics	2/28/2011	2/28/2011
	Forecasts of technology evolution and learning curves	12/31/2011	12/31/2011
	Impact of learning curves on cost	5/31/2012	06/30/2013
	Identification of technology gaps and corresponding R&D needs	12/30/2012	09/30/2013
4	Assessment of IGCC-EGS configurations	11/30/2011	11/30/2011
	Identification of IGCC-EGS benefits	11/30/2012	09/30/2013
5	Distill and communicate findings to stakeholders	6/30/2012	09/30/2013
	Collaborate with partners for student education	Ongoing	On-going
	Identify R&D and policy implications	12/30/2012	09/30/2013
	Schedule and organize outreach activities	Ongoing	On-going

Task 4 is exploring feasibility of combining IGCC and CO_2-EGS

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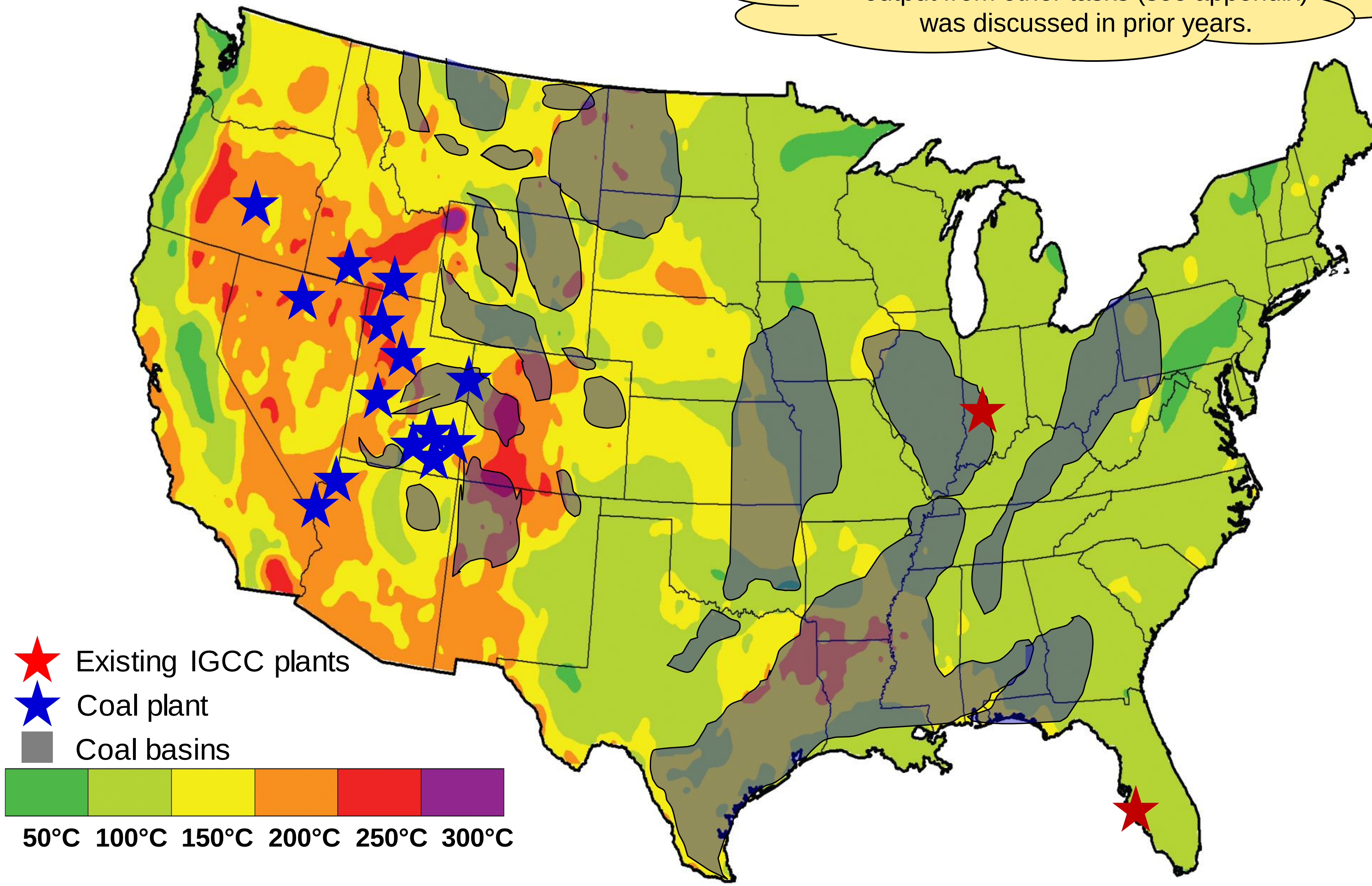
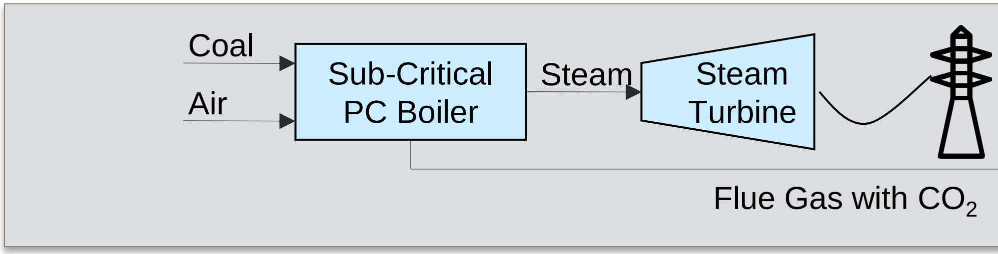
Task 4 is focus for this peer review as output from other tasks (see appendix) was discussed in prior years.

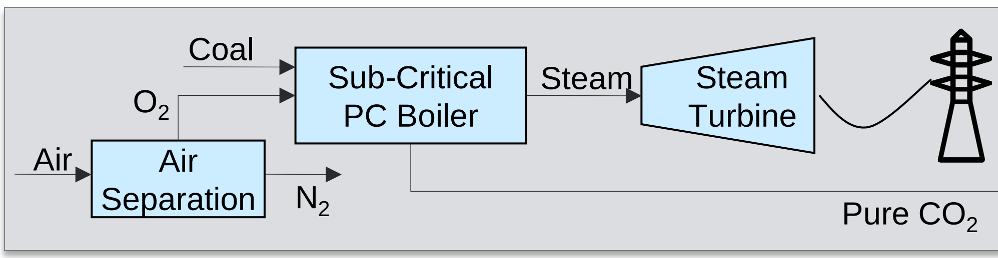


We began by assessing three configurations for IGCC/CO_2-EGS

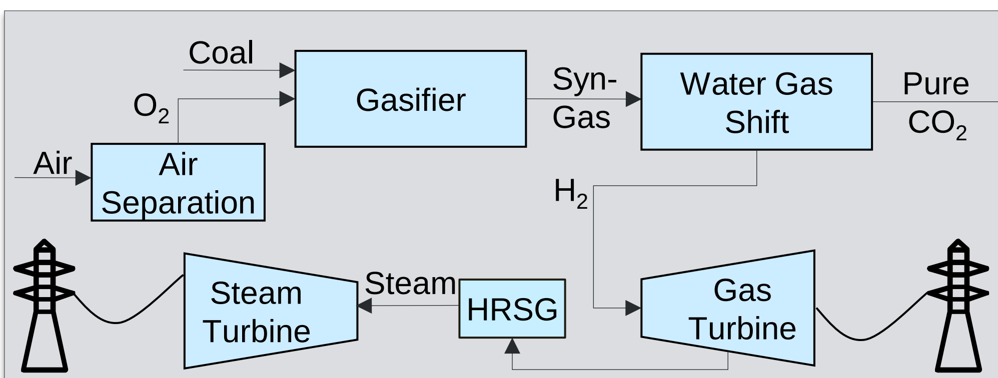
1a Sub-Critical Pulverized Coal Plant



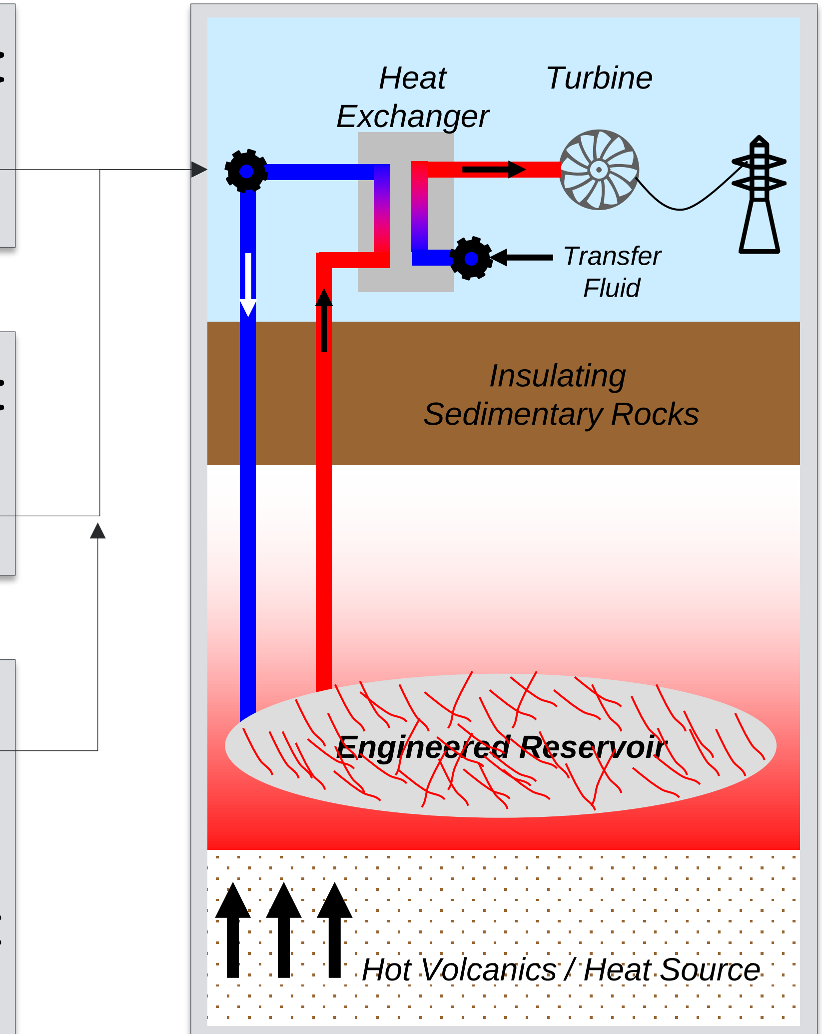
1b Oxycombustion with Sub-Critical Pulverized Coal Plant



1c Integrated Gasification Combined Cycle (IGCC) Plant

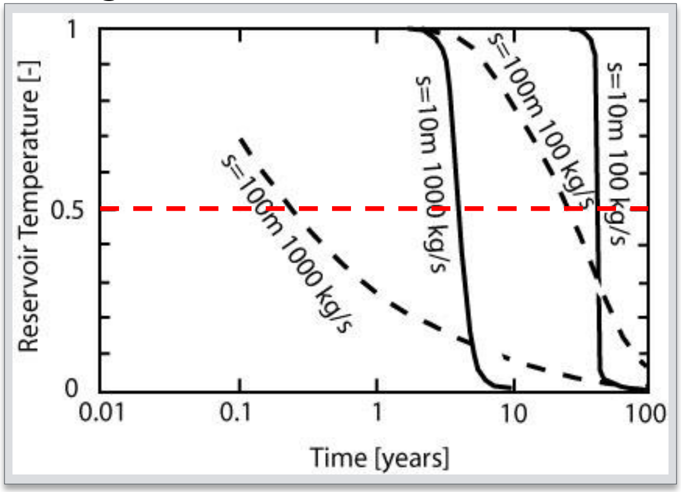


2 Enhanced Geothermal System

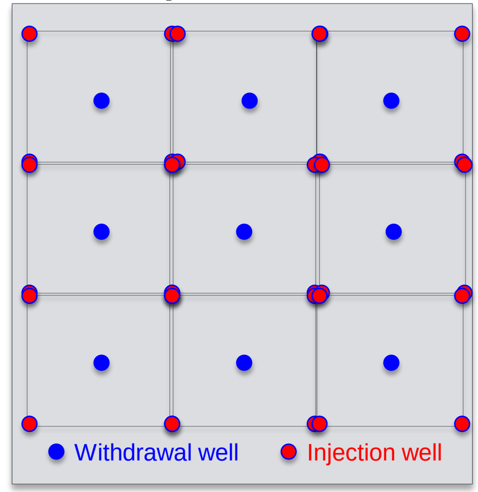


Technical metrics were estimated for key IGCC/CO_2-EGS configurations and …

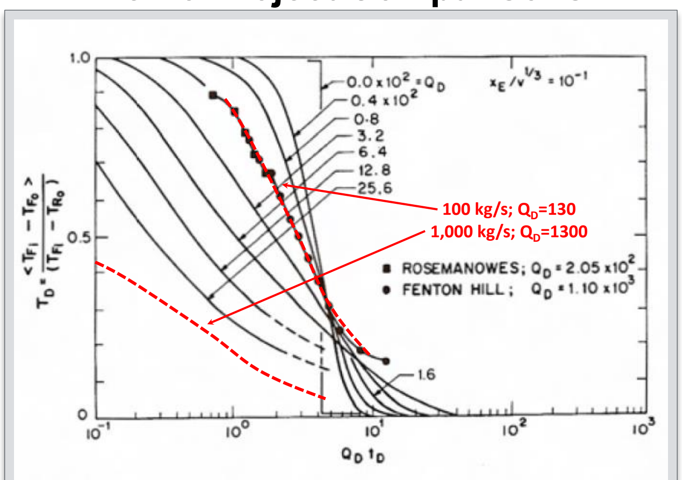
Using the Parallel Fracture Model, …



… A 5-Spot Pattern, and…



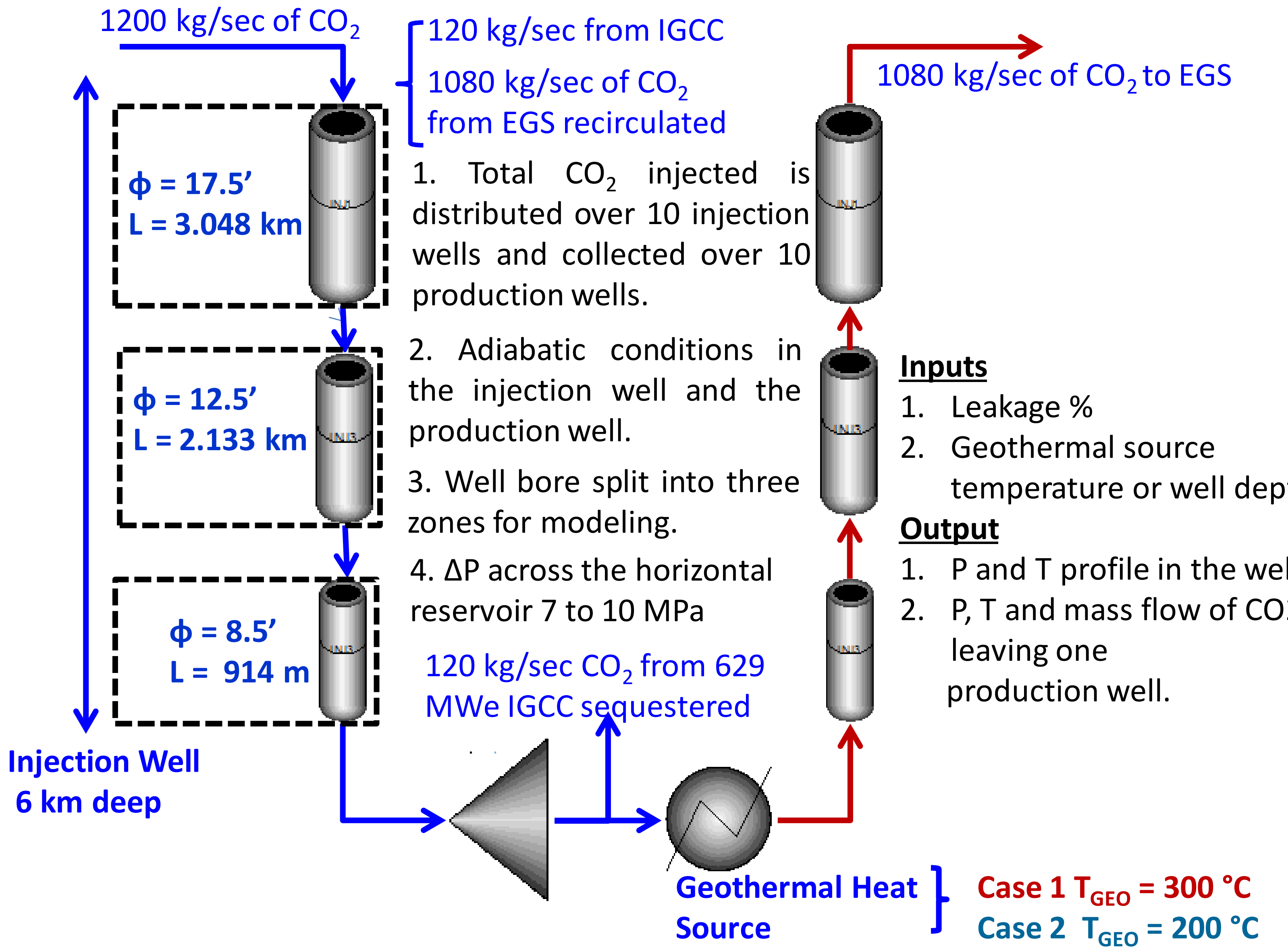
… Demo Project Comparisons …



… Drawdown Times at Different Flow Rates and Spacings

Flow Rate, kg/s	Fracture Spacing, m	Time to 50% Drawdown, y
1,000	100	0.2
	10	3
100	100	20
	10	50

… Set up a process simulation model to …



1. Total CO_2 injected is distributed over 10 injection wells and collected over 10 production wells.
2. Adiabatic conditions in the injection well and the production well.
3. Well bore split into three zones for modeling.
4. ΔP across the horizontal reservoir 7 to 10 MPa

Inputs

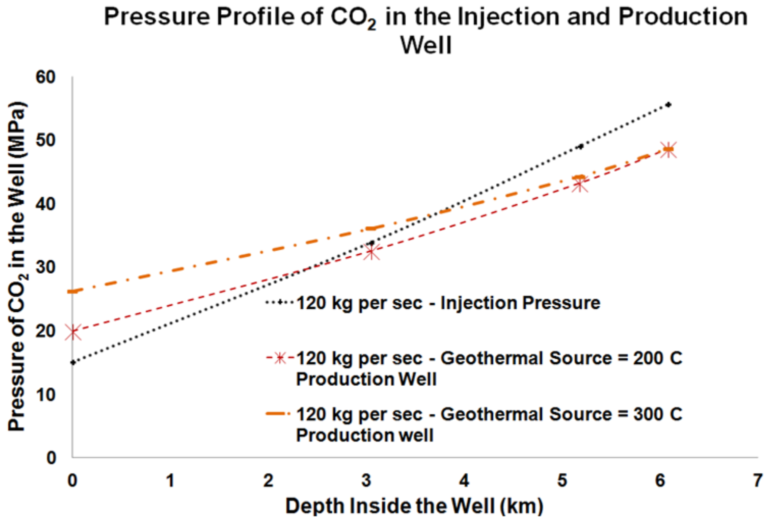
1. Leakage %
2. Geothermal source temperature or well depth

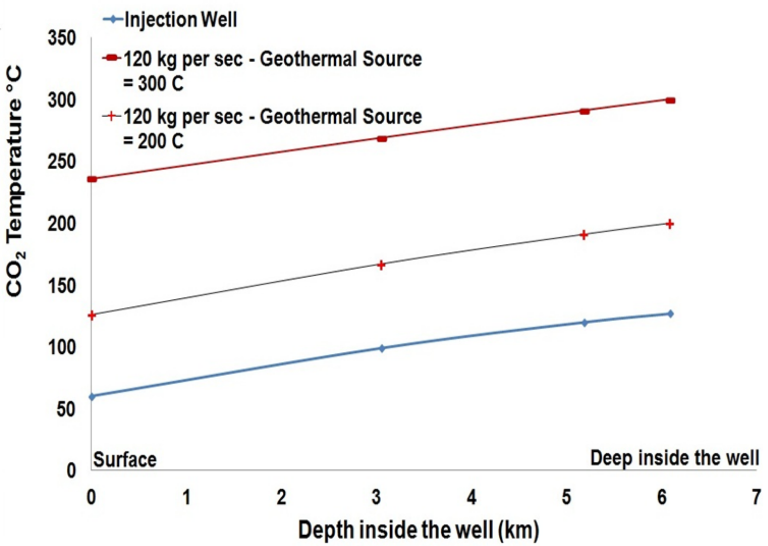
Output

1. P and T profile in the wells
2. P, T and mass flow of CO2 leaving one production well.

… Estimate pressure and temperature profiles of CO2 and …

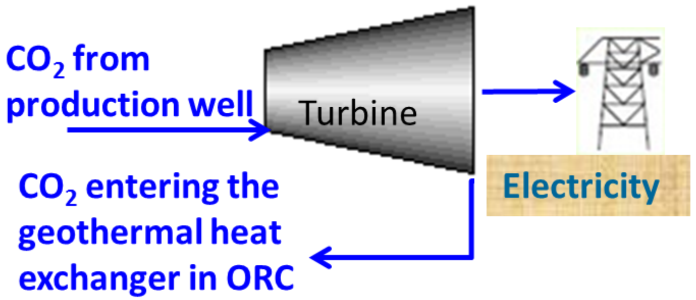
Pressure and Temperature Profile of CO_2





P & T of CO_2 leaving the production well after sequestration

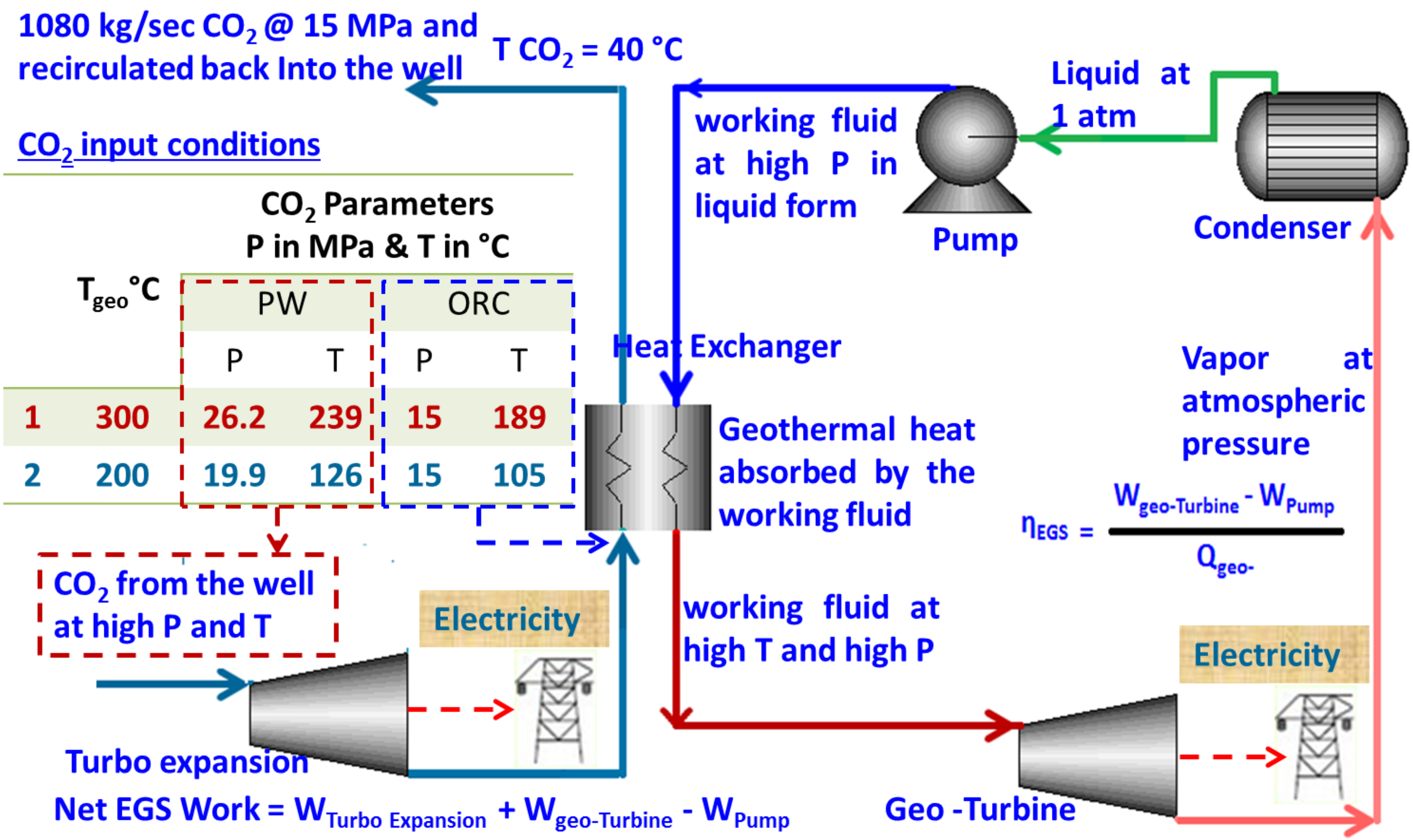
Mass flow of CO_2 = 1080 kg per sec			
Cases	T_{geo} °C	T_{CO2} °C	P_{CO2} MPa
1	300	239	26.2
2	200	126	19.9



P & T of CO_2 entering the heat exchanger of the ORC

Cases	T_{geo} °C	$W_{Turbine}$	T_{CO2} °C	P_{CO2} MPa
1	300	35 MW	189	15
2	200	11 MW	105	15

…Develop an optimal configuration to be refined based on ongoing cost modeling

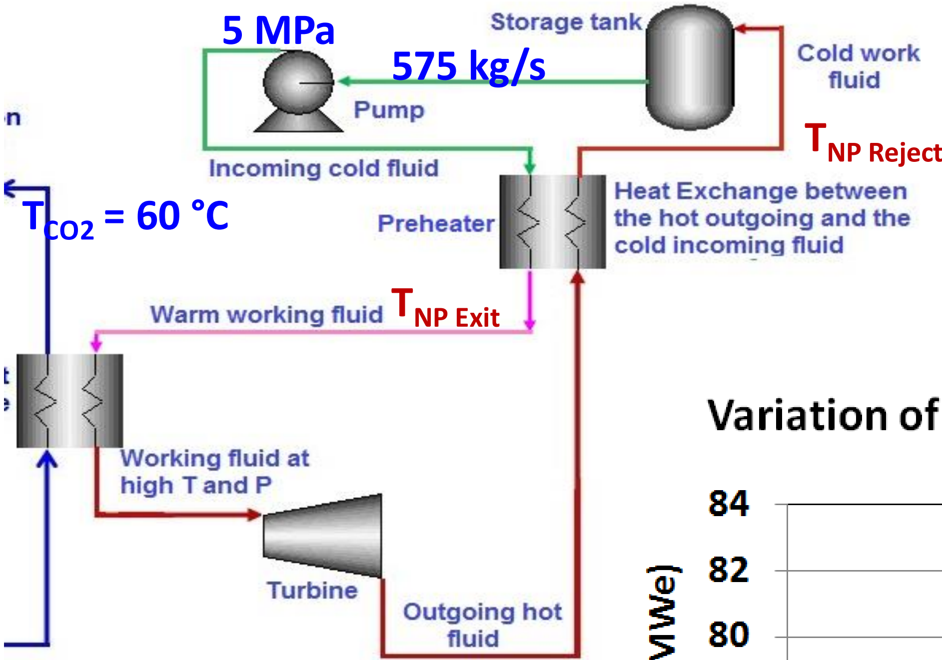


CO_2 Parameters
P in MPa & T in °C

	T_{geo} °C	PW		ORC	
		P	T	P	T
1	300	26.2	239	15	189
2	200	19.9	126	15	105

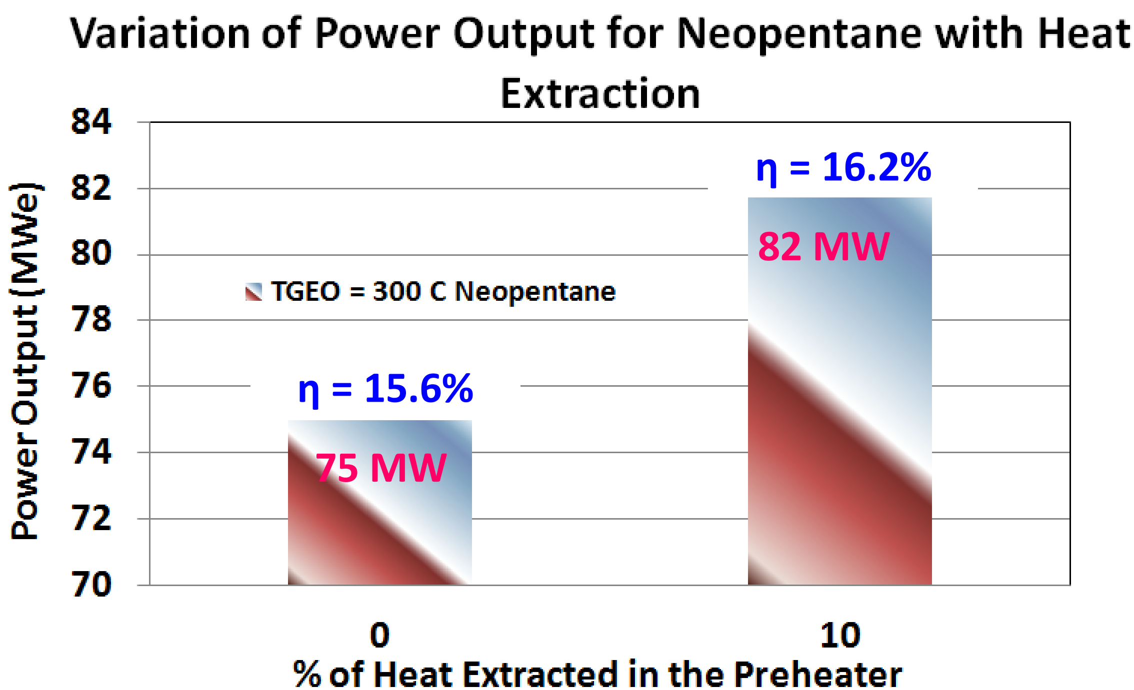
1. No temperature crossover in the preheater and geothermal heat exchanger.
2. Working fluid should completely be in vapor phase at the turbine inlet.
3. No condensation during expansion in the turbine or at the turbine outlet.

In addition, we have explored different optimization ideas, e.g., a second ORC …



T_{CO2} = 189 °C

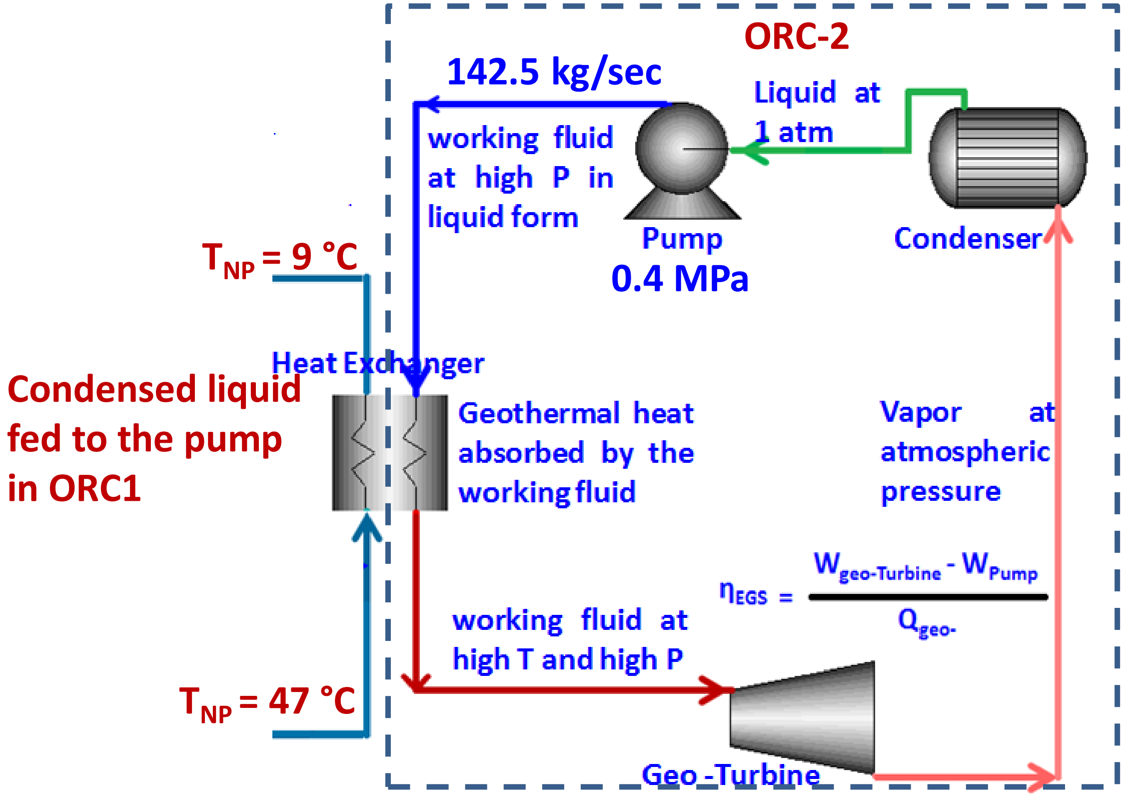
% Preheating	$T_{NP\ EXIT}$ °C	$T_{NP\ Reject}$ °C
0	15	46
10	31	47



T_{Reject} for Neopentane = 47 °C
$T_{condensation}$ for Neopentane = 9 °C

There is an opportunity for second ORC

… Including assessing its impact on power output and …



	WF	Heat Source	Preheater	Power MWe	η%
ORC1	Neopentane	CO_2	Yes – 10%	81.7	16.1
ORC2	Ammonia	Neopentane	No	17.6	8.1
			Total Power	99.3	
ORC1	Ammonia	CO_2	No	87	21.5

… Evaluation of different working fluids along with …

- Power generated from EGS without preheater for each T_{Geo}

Working Fluid	Input conditions for ORC to meet modeling constraints			
	T_{Geo} =300 °C		T_{Geo} =200 °C	
	P (MPa)	Mass flow (kg/sec)	P (MPa)	Mass flow (kg/sec)
Ammonia	0.5 - 5	145	0.2 – 0.8	75
Neopentane	0.2 - 12	575	0.4 - 1	260
n-Butane	0.5 - 10	500	0.4 - 1.5	220
Isopentane	0.5 - 3	575	0.2 - 0.6	250
Isobutane	0.5 - 20	540	0.4 - 2	230

- Maximize the power output by modifying the configuration of ORC for neopentane as a working fluid
- Economic and environmental footprint analysis

… Quantifying their impact on power output

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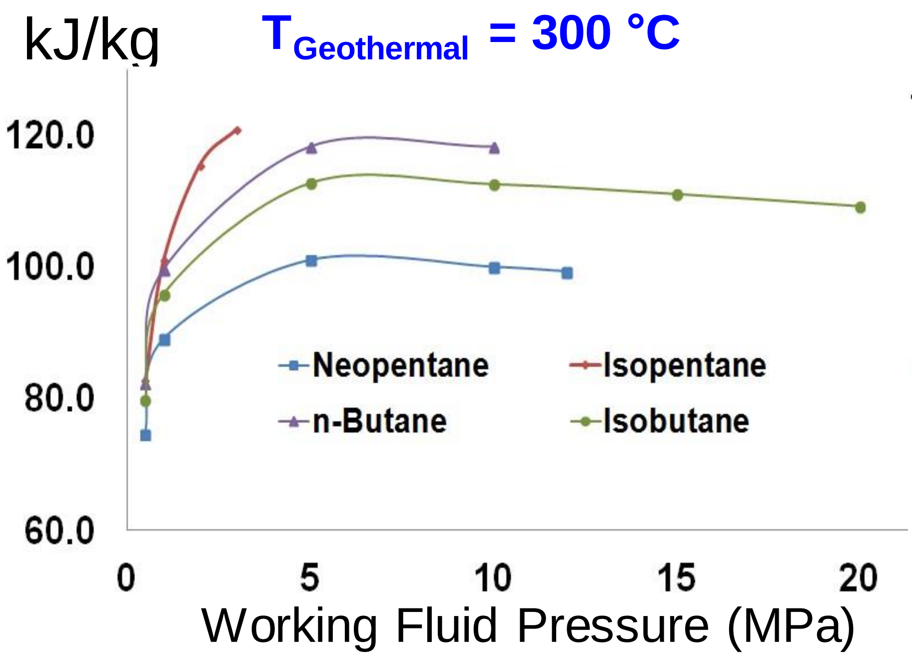

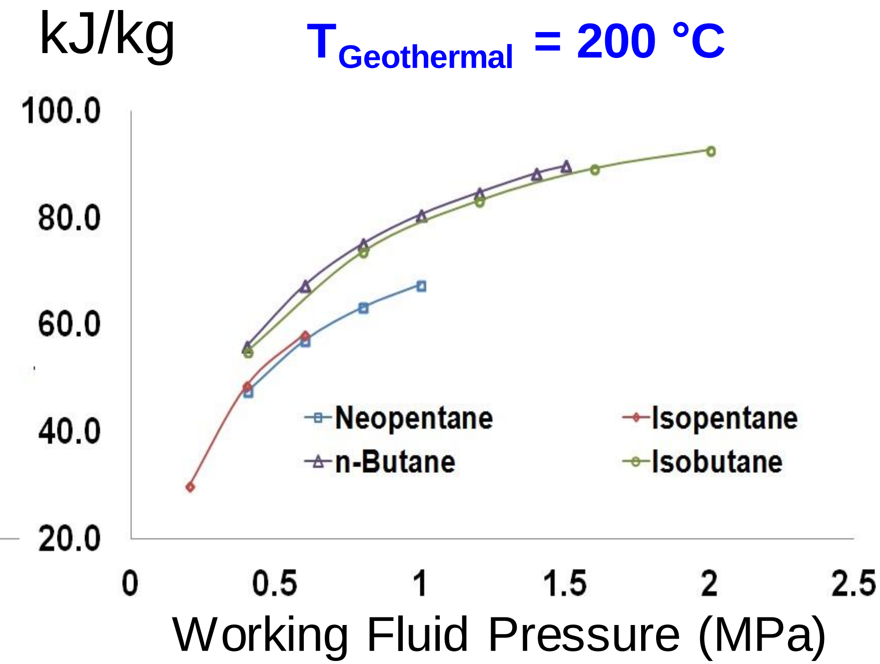

	Neopentane		Isopentane		Butane		Isobutane	
	$T_{Geothermal}$ °C		$T_{Geothermal}$ °C		$T_{Geothermal}$ °C		$T_{Geothermal}$ °C	
	300	200	300	200	300	200	300	200
Total Maximum Power Output (MW)	75	26	75	23	78	29	78	30
EGS_{300} / EGS_{200}	2.9		3.3		2.7		2.6	

Future directions

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Future Work

Tasks 1 - 3

- Complete documentation of results
- Use findings for outreach efforts

Task 4

- Refine economic / environmental analysis
- Complete documentation of results
- Use findings for outreach efforts

Task 5

- Continue student education / research work
- Continue publishing papers

Output

- Published ~10 papers to date (select below) and another 2 are under preparation
- Towards affordable geothermal power: Economic impacts of innovation and new technology, V. Shembekar and U. Turaga, 35th Annual Meeting of the GRC, 2011
- Pairing of an Integrated Gasification Combined Cycle power plant (IGCC) with CO2-EGS as a strategy for deployment in arid regions, U. Turaga et al., 35th Annual Meeting of the GRC, 2011
- Assessing innovation in geothermal energy technologies: A review of the patent landscape, U. Turaga et al., 35th Annual Meeting of the GRC, 2011
- Combined scCO2-EGS IGCC to reduce carbon emissions from power generation in the desert southwestern United States (New Mexico), D. Chandra et al., 35th Annual Meeting of the GRC, 2011
- Combined scCO2-EGS IGCC to reduce carbon emissions from power generation in the desert southwestern United States (New Mexico), D. Chandra et al., Energy & Fuels, 2012
- Toward affordable low-carbon power: Economic and environmental analyses of integrating CO2-EGS with IGCC, U. Turaga et al., 36th Annual Meeting of the GRC, 2012
- Supply chain challenges in commercial deployment of EGS, U. Turaga et al., 36th Annual Meeting of the GRC, 2012
- Assessing innovation in geothermal energy using patent quality indicators, U. Turaga et al., 36th Annual Meeting of the GRC, 2012
- Assessing Innovation in Renewable Energy Technologies Through Patent Analytics, U. Turaga et al., TechConnect World 2012
- Using CO2 from an IGCC plant as a heat transfer fluid for the extraction of geothermal energy for power generation from EGS, Ram Mohan et al., Stanford Geothermal Workshop, 2013
- Utilization of Carbon Dioxide from Coal based Power Plants as a Geothermal Fluid for the Electricity Generation in Enhanced Geothermal Systems (EGS), RamMohan et al., submitted to a peer-reviewed journal

Summary

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- Our project is progressing toward its five goals: (1) an independent appraisal of EGS costs, (2) evaluating economics of new technologies and market issues, (3) benchmarking technology through patent analytics, (4) assessing novel configurations, e.g., EGS-IGCC, and (5) promoting outreach
- Expert elicitation on EGS has validated and gathered estimates and uncertainties for major cost categories and used them to model LCOE for near- (mean ~20 c/kWh) and deep-field (mean ~40 c/kWh) cases
- These efforts have also shown that new technologies have the potential to reduce costs of several EGS categories by up to 50% and that of LCOE by ~40%
- Our work on patent analytics has landscaped the state of geothermal and EGS technologies and has identified their technical and economic value as well as their rate of development and deployment offering a number of policy insights
- Combining IGCC with EGS can be promising and so far we have assessed its technical feasibility and environmental benefits; ongoing work is focused on understanding costs and, environmental benefits, and optimal operating envelopes
- For outreach, we have published ~10 papers with 2 more in preparation, sponsored 4 student projects, taught geothermal modules at schools and universities, and collaborated with NGDS, universities, geothermal companies, and local energy groups
- Future work will focus on completing Tasks 4 and 5 and documentation of all project output

Project is on track with new schedule, which was revised due to kick-off delays

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Timeline			
Planned start date	Planned end date	Actual start date	Current end date
January 1, 2010	December 30, 2012	June 3, 2010	September 30, 2013

Budget*					
Federal share	Cost share	Planned expenses to date	Actual expenses to date	Value of work completed to date	Funding needed to complete work
$1,335,727	$336,823	$1,302,685	$1,018,574	$1,283,776	$653,976

Coordination with GTO

- Tapped experts at national labs, e.g., ANL, INL, Sandia
- Collaborating with groups at Penn State, West Virginia, and Utah

Sharing data with NGDS

- Discussed process with NGDS
- Completed survey
- Plan to submit output

Supporting outreach

- Collaborating with EGS / geothermal companies
- Pursued international projects
- Spoke at local energy groups
- Taught module and advised student research, e.g., NREL "Rio Grande" at Penn State

*All timeline and budget data are as of December 31, 2012; budget data output from model provided by DOE GTO

Supplemental slides with select results reported at 2010-2012 peer-reviews

Expert elicitation in Task 1 identified EGS cost segments, required reductions and…

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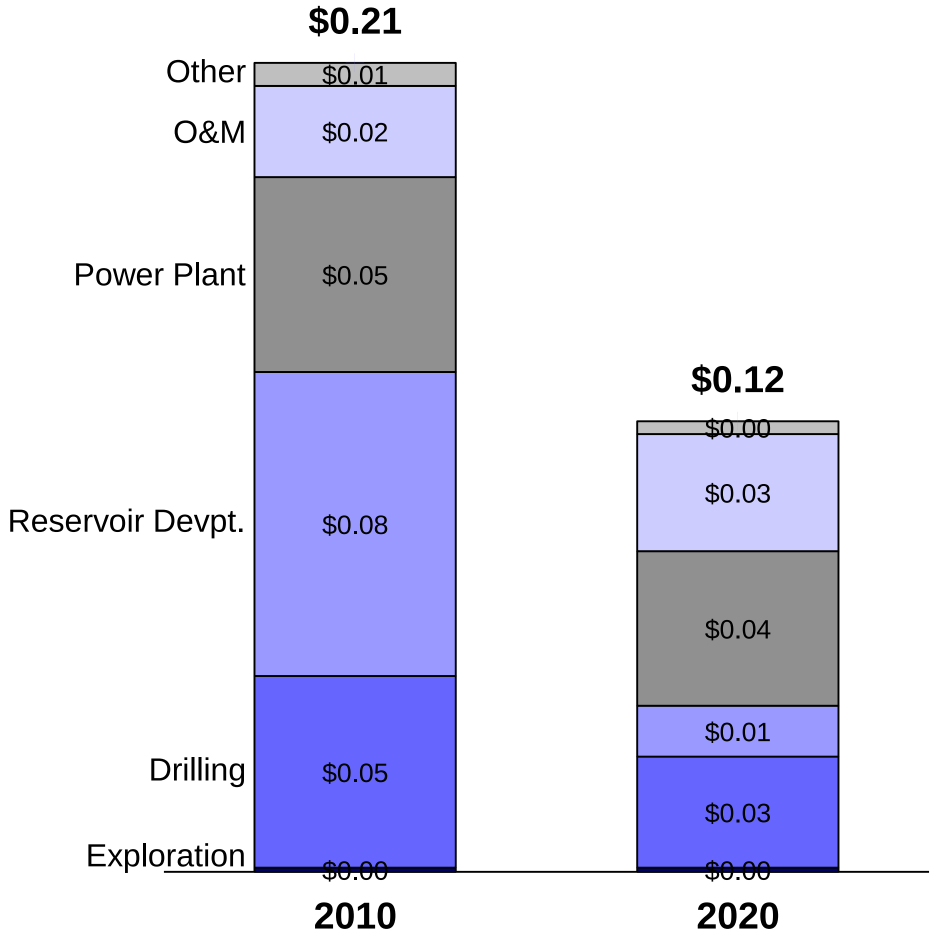
Major EGS Cost Categories and Relative Cost Contributions

Drilling including rig rates and operating costs	**40-70%**
Reservoir development including "fracing", stimulation and fluid production	**15-30%**
Power plant including heat exchangers and turbines	**20-35%**
Risk management including surveillance, seismic issues, stakeholder relations, etc.	**2-5%**
Transmission including infrastructure, grid integration	**1-5%**

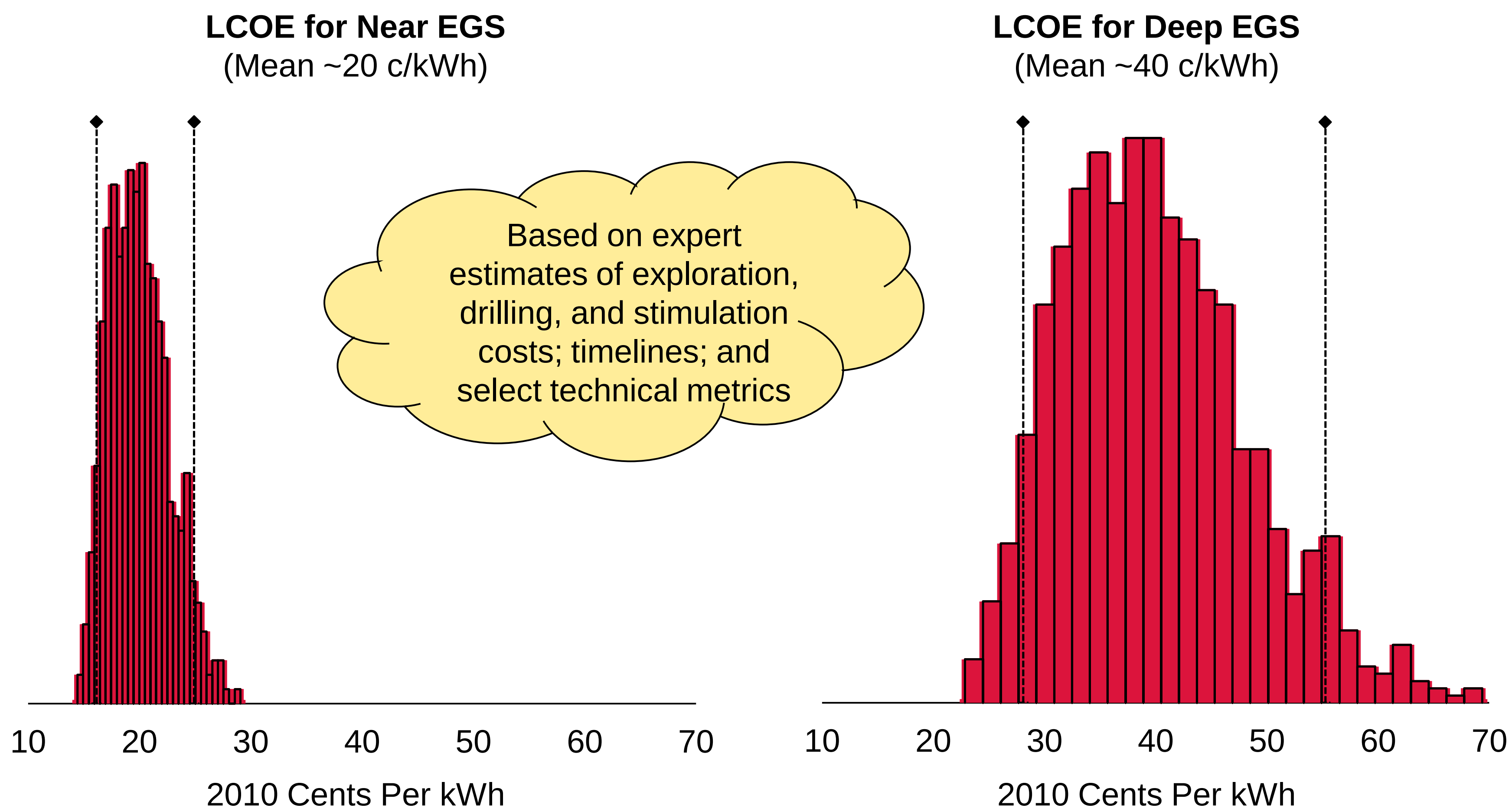
Cost-reduction Targets Required to Achieve Near-Field EGS Goal by 2020

(Levelized Cost of Electricity, 2010 $/kWh)



Note: Rounding leads to differences in LCOE estimates on slides 6 and 7

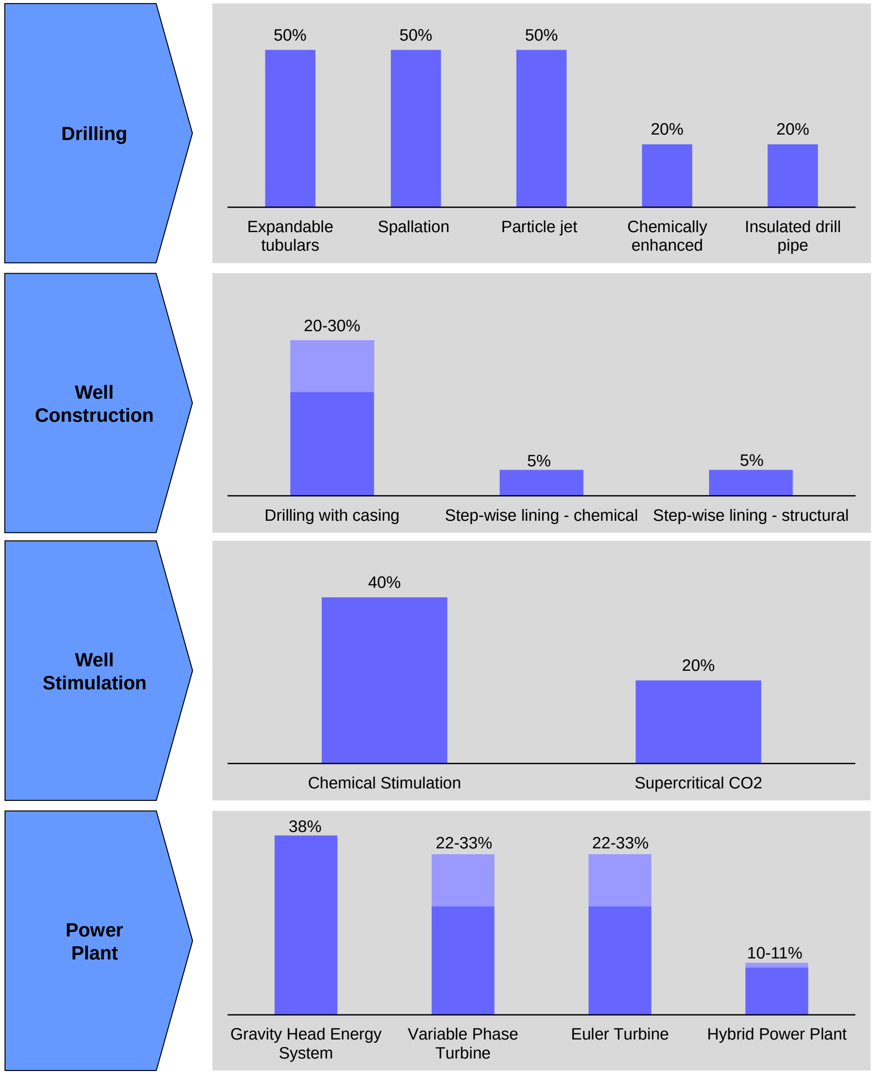
…Quantified and analyzed uncertainties to obtain estimates of LCOE



Results based on GETEM and assume 200 °C resource; 30 kg/s flow rate; depth of 1,000 and 5,000 m for near- and deep-EGS, respectively; and 0.3% and 3% thermal drawdown for near- and deep-EGS, respectively

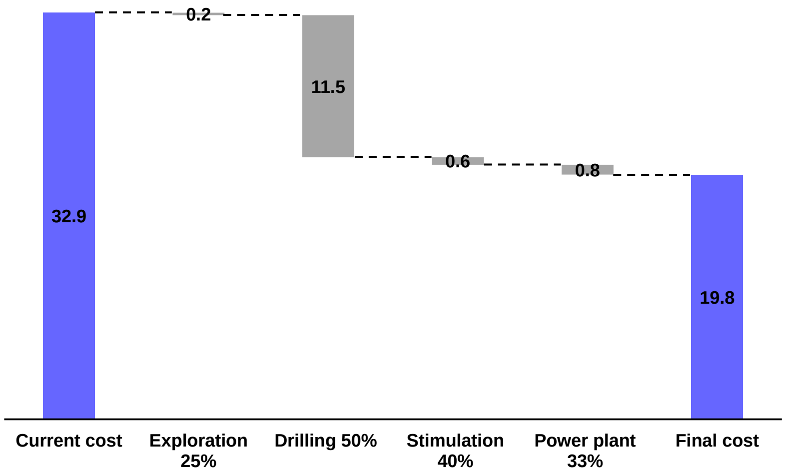
In Task 2, we evaluated impact of new technologies on EGS costs and LCOE …

Impact of New Technologies on Cost of EGS Components and …



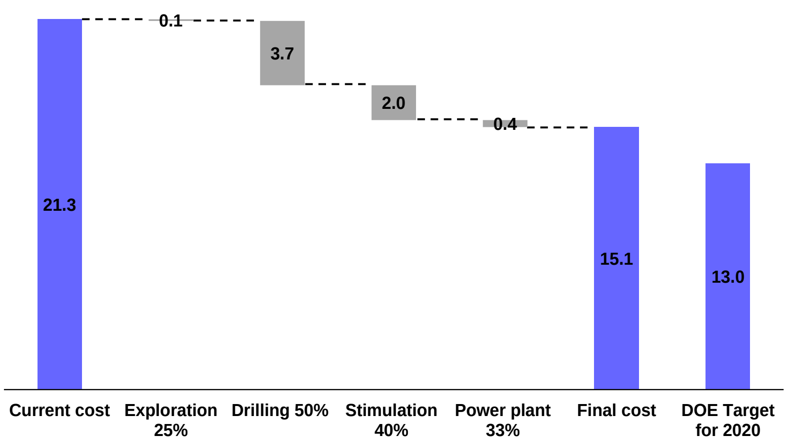
… Resulting Impacts on LCOE for Deep EGS and …

(Levelized Cost of Electricity, 2010 c/kWh)



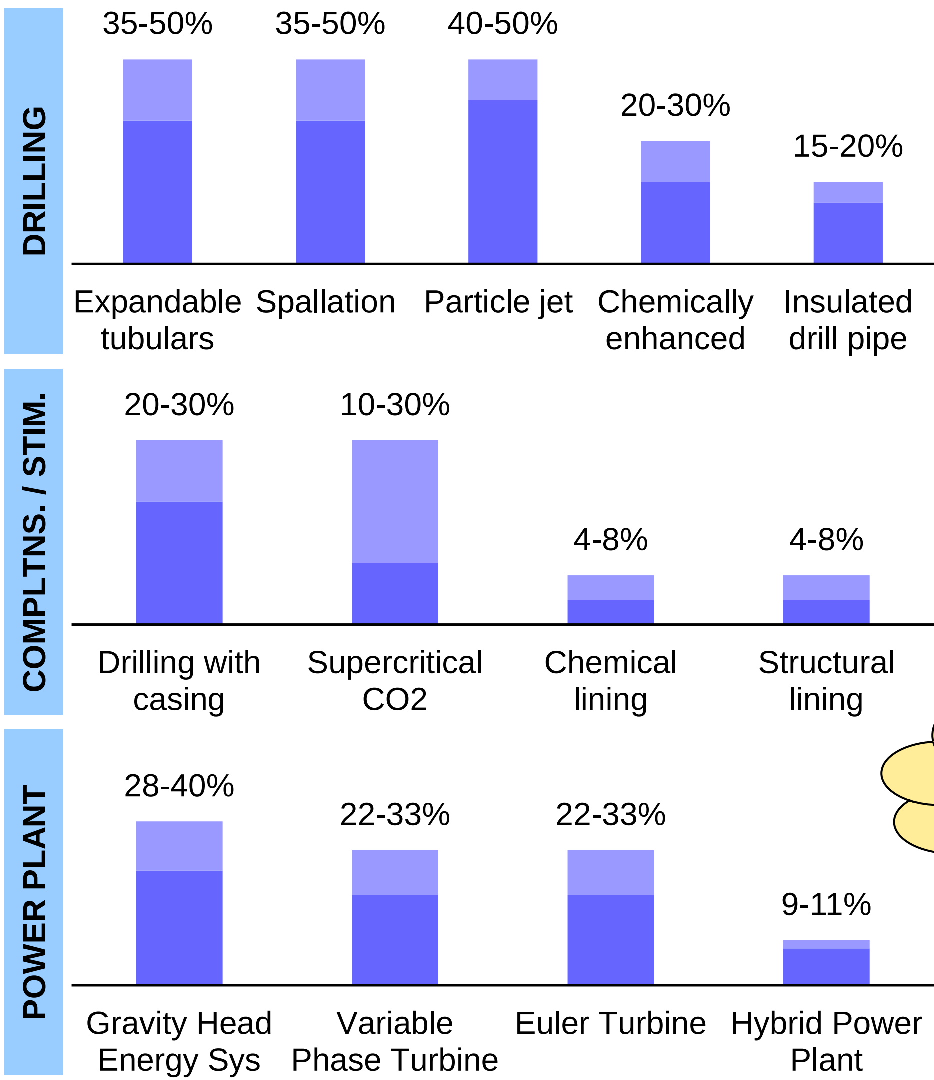
… Near-field EGS Cases

(Levelized Cost of Electricity, 2010 c/kWh)



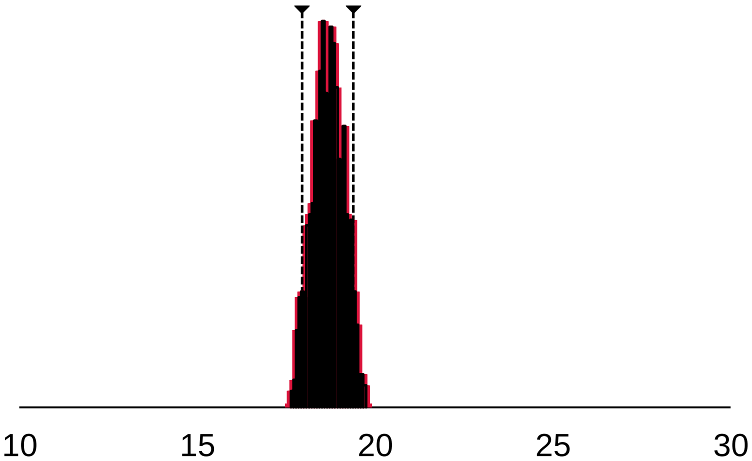
… Refined them continually and estimated risked estimates of LCOE impacts and …

New Technology Can Reduce Costs and …



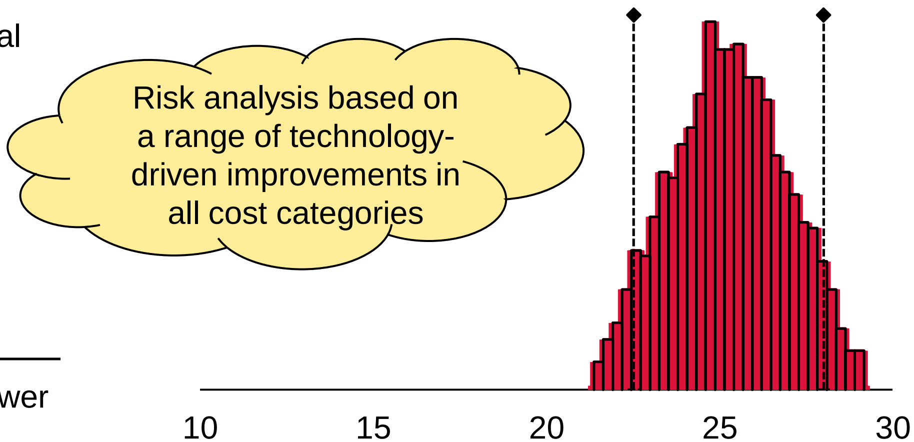
… Impact LCOE for Near EGS and …

(2010 Cents Per kWh, Mean ~19 c/kWh)



… More so for Deep EGS

(2010 Cents Per kWh, Mean ~25 c/kWh)



… Analyzed market issues such as impact of growing EGS capacity on supply chains

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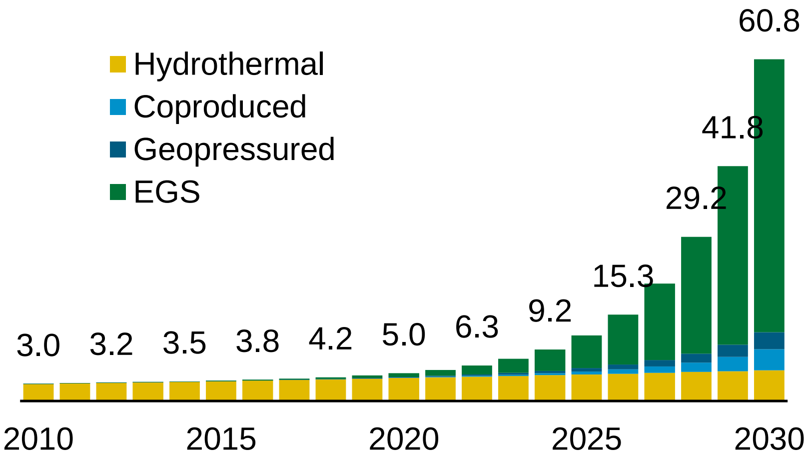
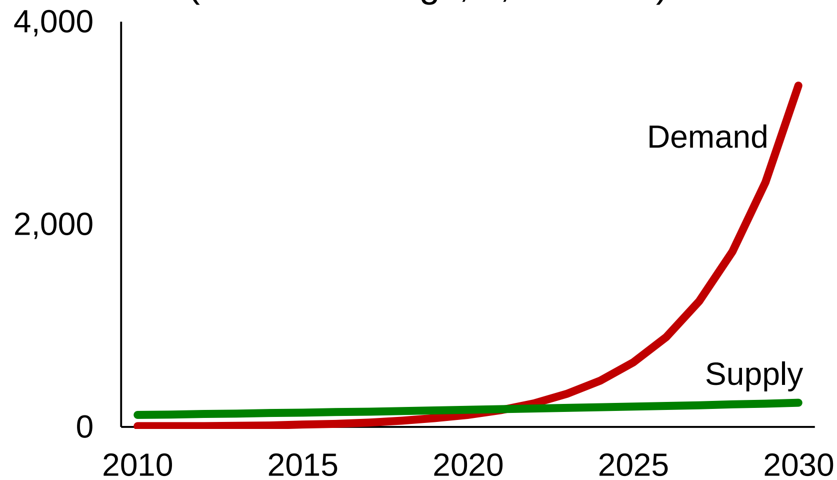
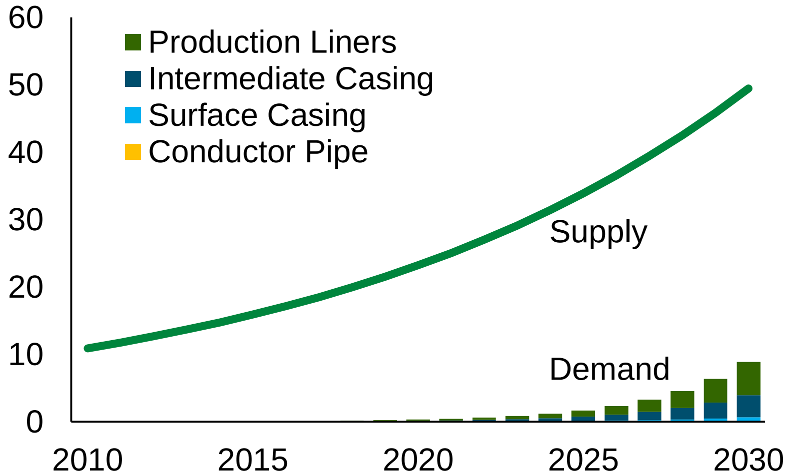
If 10% of U.S. power by 2030 is geothermal…
(Geothermal Capacity, GW)



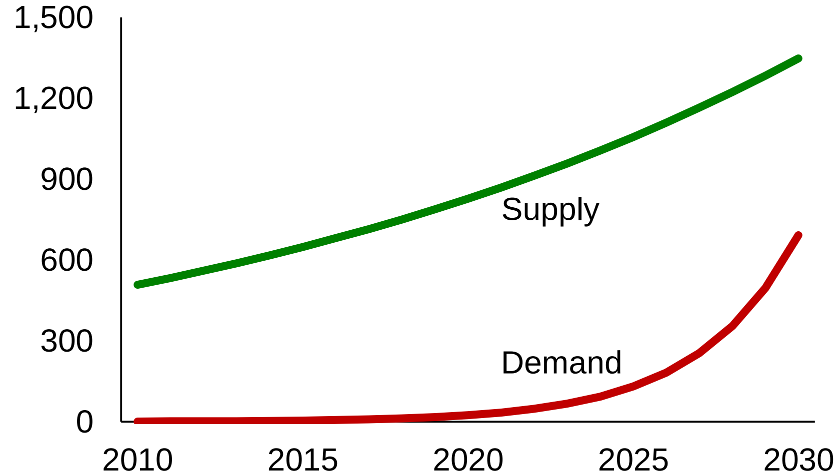
… EGS rig supply will fall short of demand …
(Number of Rigs, 2,000+ HP)



… Tubular and casing supply will be sufficient …
(Million Tons Per Year)

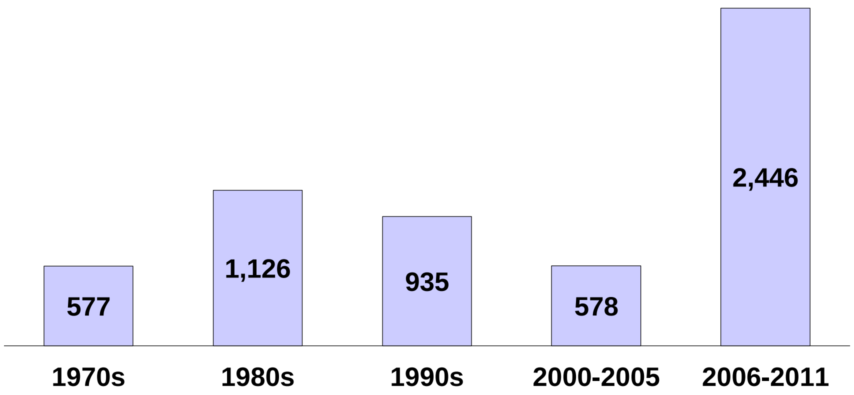


… As will exploration capacity
(Number of Seismic Crews)

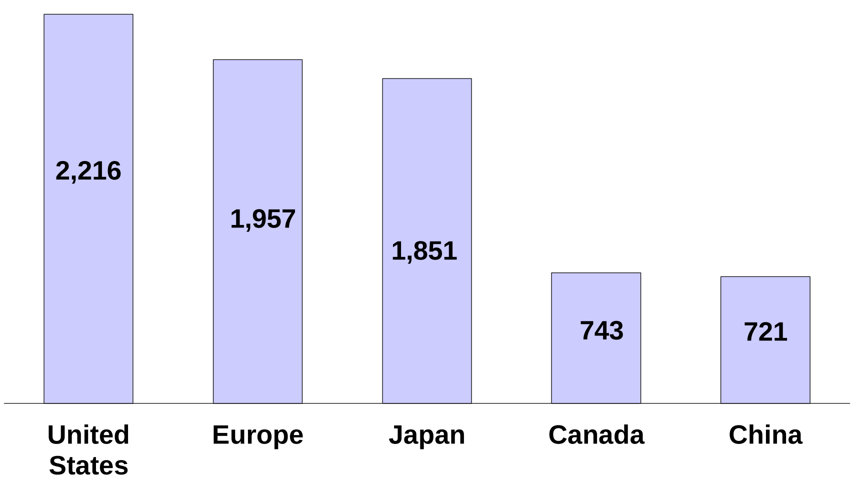


Patent analytics helped us map EGS technology status in Task 3 and …

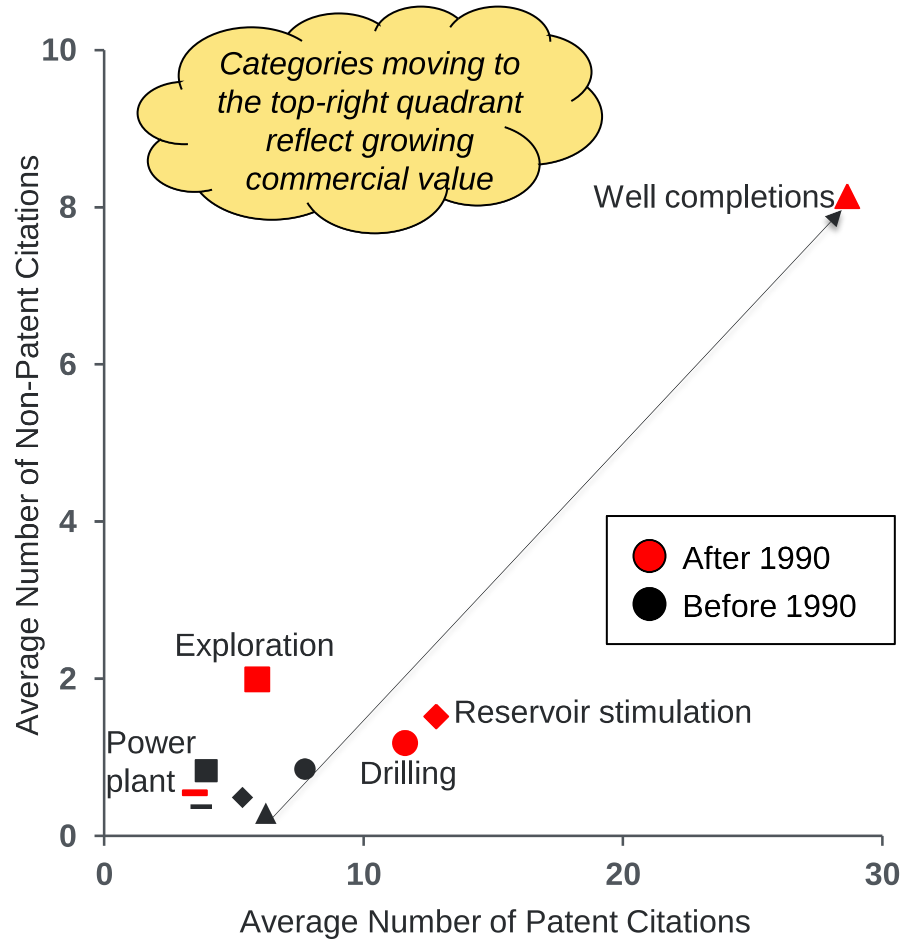
Geothermal patenting has increased dramatically…



… With U.S. and Europe dominating activity and …



… Leading to significant technology improvements, e.g., in Well Completions



… Quantified EGS technology evolution to identify innovation gaps and needs

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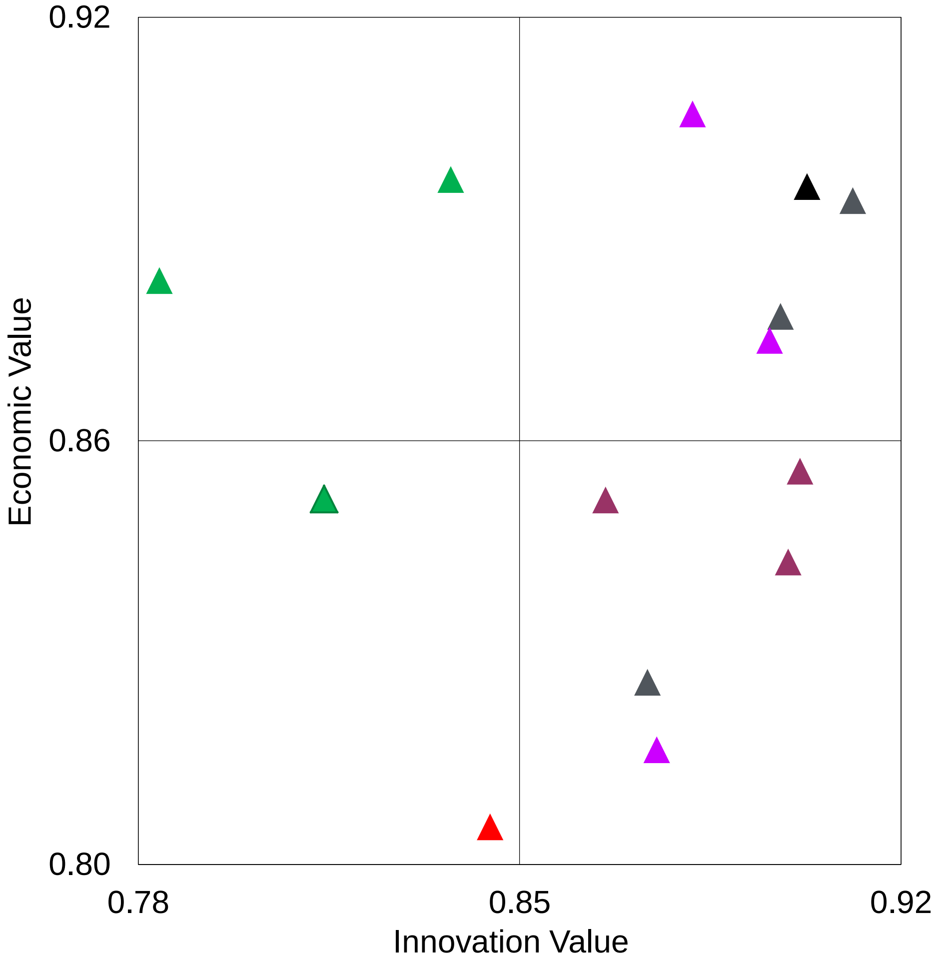
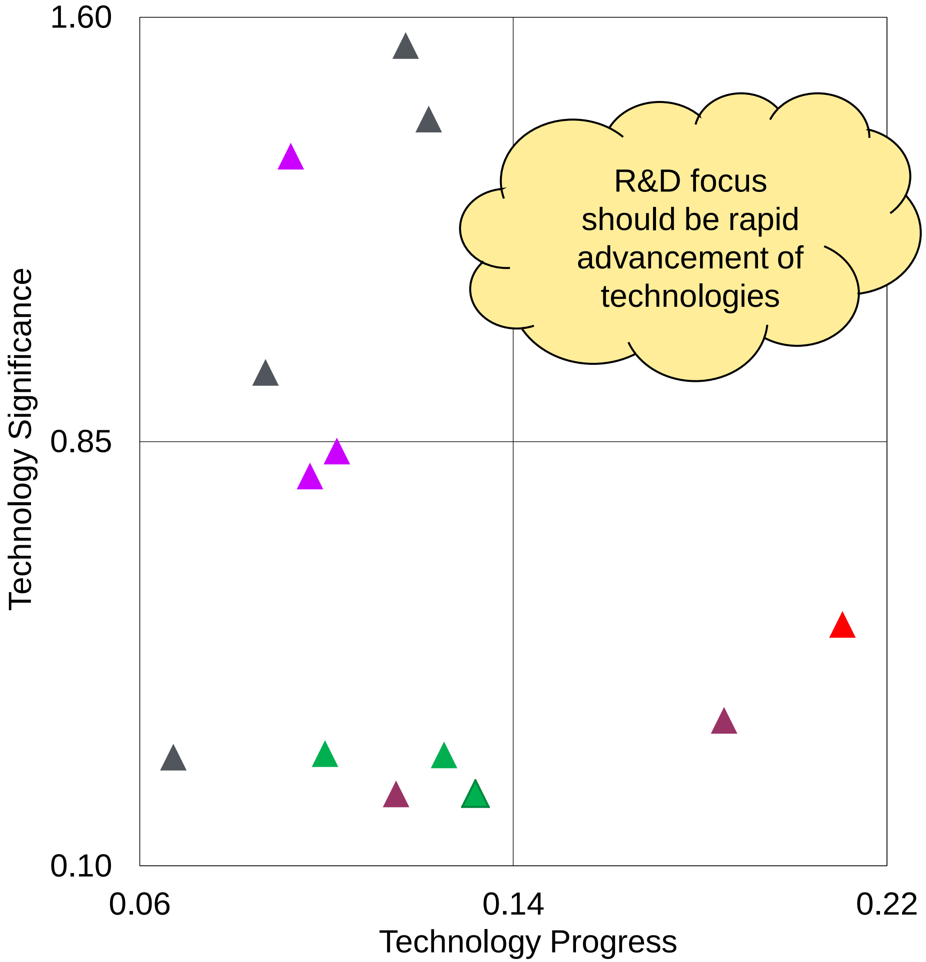
Geothermal and EGS patent portfolios have both economic and innovation value …



… But significant technologies are not advancing rapidly



▲ Exploration ▲ Drilling ▲ Completions ▲ Stimulations ▲ Power plant