Baseline System Costs for 50.0 MW Enhanced Geothermal System

-- A Function of: Working Fluid, Technology, and Location, Location, Location --

15 June 2011

SMU

Presented By: Paul Dunn (PI), COO

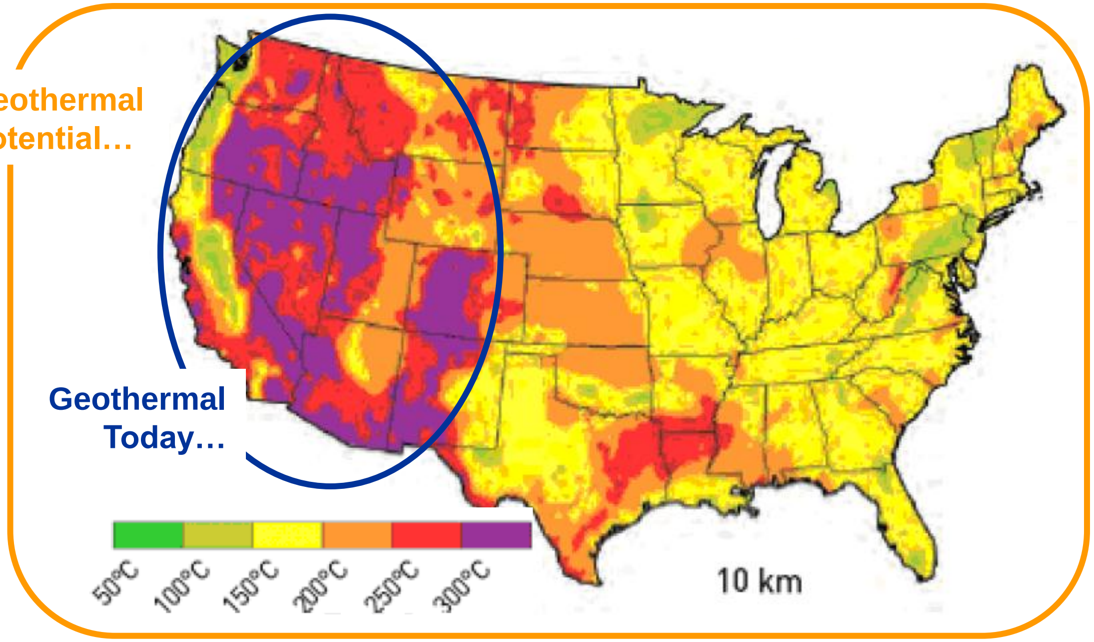
Gas Equipment Engineering Corp.

Impact Technologies LLC

Fort Point Associates

50 MW EGS Design Based Cost Analysis (DOE Grant DE-EE0002742)

- Goal: Answer key questions regarding the economic viability of EGS
  - Find out to what extent we really can achieve the vision of EGS anywhere
  - Starting with a 50 MW plant in Chicopee, MA!!
- Four part Statement of Project Objectives (SOPO):
  - SOPO 1: 50 MW Water EGS Cost Model
  - SOPO 2: CO2 EGS Cost Model
  - SOPO 3: Impact of Technology (CO2 & drilling)
  - SOPO 4: Impact of Location



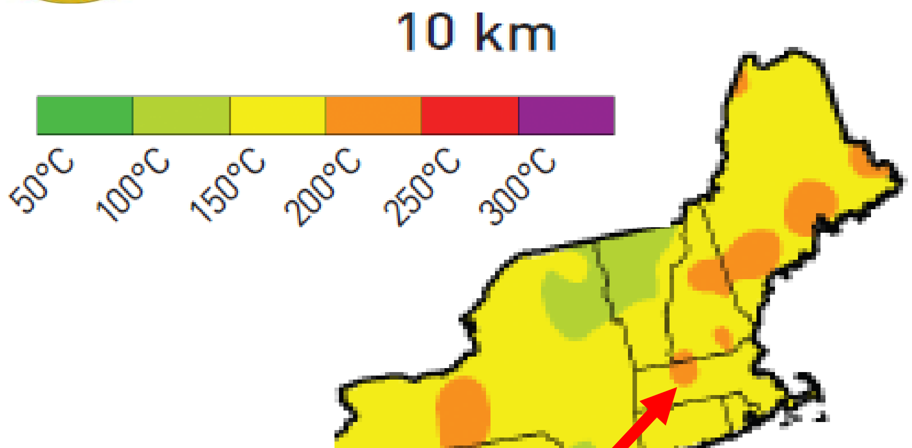
- Ten part cost Work Breakdown Structure (WBS):

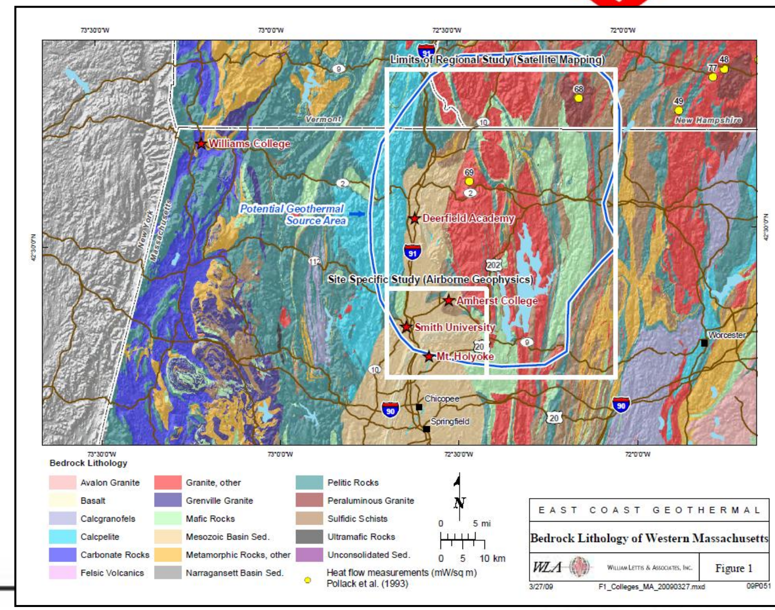
1. ID / Qualify / Quantify
2. Develop Reservoir
3. Generate / Manage Fluids
4. Make Power
5. Local Hook Up / Distribution
6. Grid Hook Up / Distribution
7. Top Side Facilities / Equipment
8. Land Acquisition / Royalty
9. Permits / Approvals
10. Management and Operation

What Does This Mean?

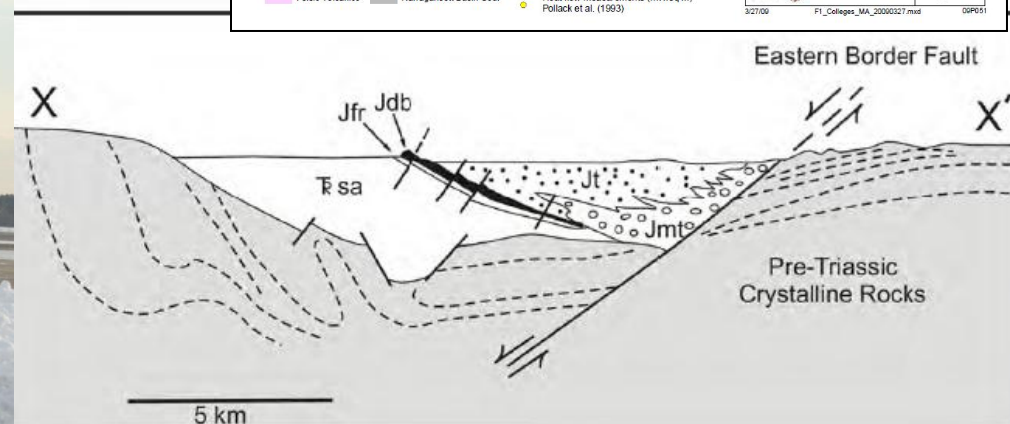
- **Last time we were at this conference, DOE announced this grant award (thank you)**
- **Today, we will tell you the preliminary results, for 50 MW EGS Cost in a <u>really</u> challenging environment (Western MA)**
  - **50 MW Net Water-EGS (70 MW Gross)**
  - **50 MW Water-EGS Diesel / CNG Hybrid (20 MW Water Pumps)**
  - **50 MW CO2 EGS – Today's Cost --- No Magic**
  - **50 MW CO2 EGS – Cost with reasonable application of CO2 Generation and Drilling Technology**
- **We will also tell you what other (reasonable) locations we will study**
  - **We expect a final report to be produced later this year**

Westover Air Force Base
Chicopee, MA





- **Westover:**
  - **~400 F @ 30,000 ft**
  - **~300 F @ 21,000 ft**



EGS Working Fluid: High Pressure Water or Carbon Dioxide?

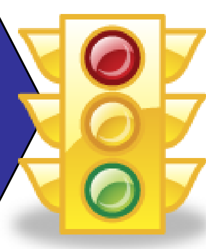
High Pressure Water

- Well understood
- Reacts with bedrock
  - Direct use of steam problematic
- Mobility low and pressure drop high at depth
  - Viscosity / Density not favorable
- Very high pumping power
  - Could be ~40% of gross power
- High specific heat
- Temperature loss up-hole can be low (heat transfer driven)
- Cheap (working fluid price)
  - At least locally

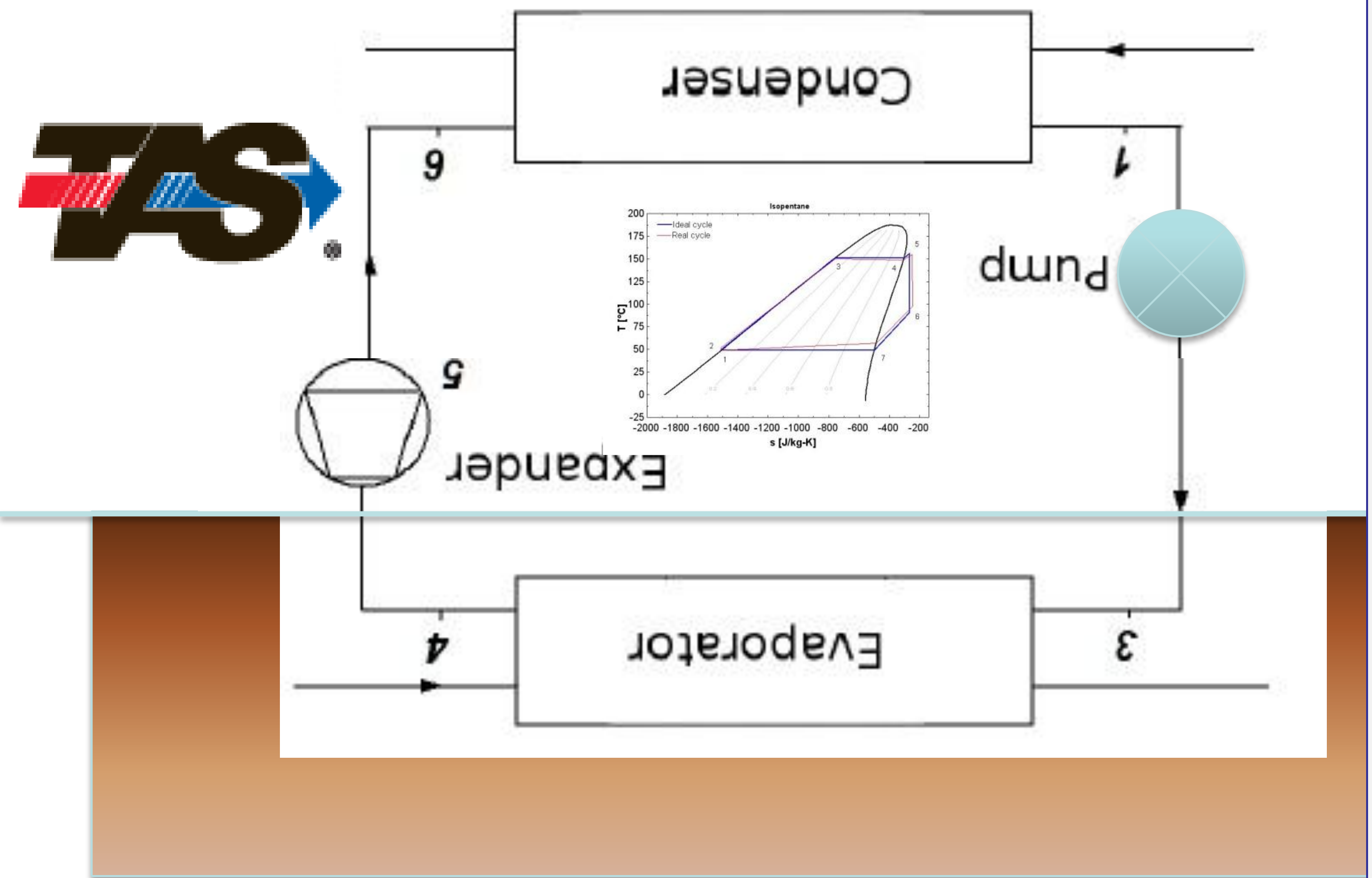
Super Critical Carbon Dioxide

- Not as well understood
- Reacts with bedrock, but for the most part favorably
  - After development, direct use of working fluid in machinery may be possible
- Mobility higher and pressure drop lower than water at depth
  - Viscosity / Density favorable
- "Negative" pumping power
  - Strong thermal siphon
- Lower specific heat than water
  - But more than compensated by flow rate
- Temperature loss up-hole more complex
  - Think isentropic expansion
- "Lost" CO_2 in the process is sequestered in deep rock (carbonates)
  - And that by itself is good
- Very high purchase price
  - And carbon credits are currently trading at low values

In CO_2 vs. Water EGS, the yellows and greens are interesting, but the big issues are the huge cycle efficiency advantage for CO_2 (confirmed by analysis), and the barrier, with a big "B", created by the purchase price of CO_2



EGS by CO_2 Direct Expansion… Turning ORC Upside Down!



- Pump not required
- Down hole compression provides pre-heat
- Up hole expansion results in loss of temperature, but not enthalpy
- Lots of pressure available to make power directly topside

"Earth Cycle Efficiency" -- Technical Observations -- Surprises

Summary for 50 MW Net Power	Depth (kft)	Massflow (lbm/sec)	Heat Extracted from Earth MMBTU/hr	Earth Cycle Efficiency %	
Water Baseline	20	4000.3	2702.6	6.3%	
CO2 ORC	30	9238.7	2706.5	6.2%	1
CO2 Topside Turbine (no ORC)	20	5815.4	1119.9	15.2%	
	30	2698.4	799.2	21.3%	2
CO2 ORC with Topside Turbine	30	3499.9	1167.2	14.6%	
CO2 Bottom Turbo Expander (no ORC)	20	5670.5	1092.0	15.6%	3
	30	2596.8	769.1	22.2%	

1. **Traditional CO_2 ORC appears to be a loser (compared to water, in MA)**
   - **No pumps, but much deeper holes, plus cost of CO_2!! ☹**
2. **CO_2 Turbo expander (direct turbine generator) looks very good ☺**
   - **Higher cycle efficiency and <u>lowest</u> machinery / auxiliary costs**
3. **"Clever" CO_2 cycles probably not so bright**
   - **Not really better, or hugely complex / risky (turbines 5 miles below surface)**

A Subset of the Variants Considered (All Western MA)

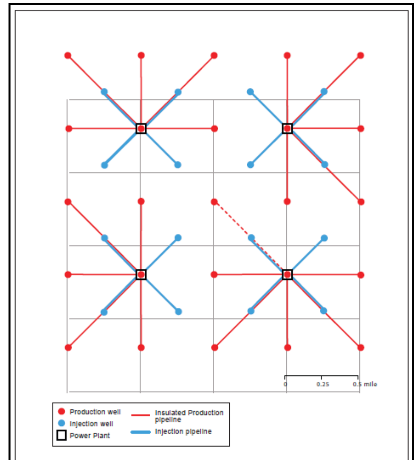
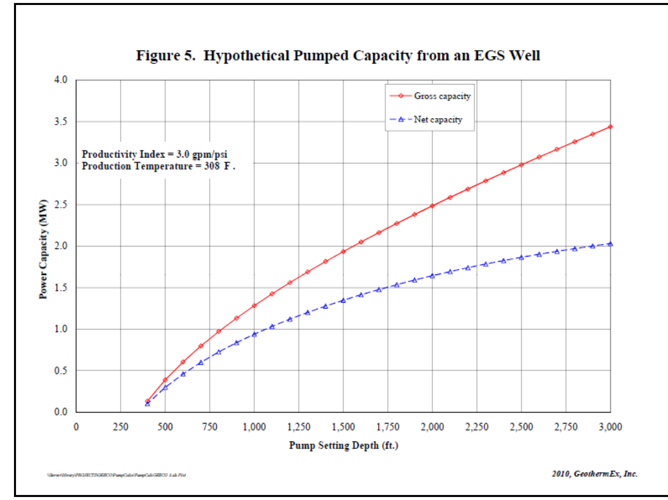


Figure 7: Proposed surface facilities for the GEECO project



Case	Gross Power (MW)	Depth	Heat Removal Rate (MMBTU/HR)	# & Dia Injectors	# & Dia Producers (DC)	Massflow (lbm/sec)
H_2O	70	21kft	2703	16 -- 10”	25 -- 8”	4000
H_2O (Hybrid)	50	21kft	1931	12 – 10”	20 – 8”	2857
CO_2 ($)	50	30kft	799	6 – 10”	12 – 8” (SS)	2698
CO_2 (Gen)	50	21kft	1120	8 – 10”	15 – 10” (Cladded)	5800

SOPO 1.0 Summary Result Sheet: Baseline H_2O EGS

- **Even with unrealistically cheap money (4%), the conventional EGS does not look good in Western, MA**
  - No huge surprise
- **The hybrid diesel pump version (next page) is better than all electric pumps**
  - Lower capital cost
  - Better ROI

Parameters:	Water EGS		Comment	
Gross Power	70	MW	Geothermal Gross Power, Not Plant	
Net Power	50	MW		
Water Pump Power	20	MW	(from WBS 3)	
Cost of Electricity (retail)	$167	$/MW-hr	(US DOE EIS 2008 MA)	
Cost of Electricity (wholesale)	$81	$/MW-hr	(ISO NE 2008 Hub Price)	
MA Renewable Market Class 1 RPS	$13	$/MW-hr		
Capital Cost	$1,162,460,446	(roll up)	(from capital sheet)	
Cost of Capital	4.0%	(high)	(variable)	
Annual Capital Cost	$67,225,203	(30 year)	(calculation)	
O&M Cost	1.0%	(of capital $)	(guess)	
Availability	99.5%	(uptime)	(guess)	
Cost Item	$			
Annual Capital Cost	$67,225,203		Escalation Rate (%/year)	
O&M Cost	$11,624,604		2.0%	
O&M Cost Engines	$240,960			
Purchased Costs (Fuel / Electricity)	$827,206		1.811361584	(30 year)
Total Annual Cost	$79,917,973			
	Revenue (1st Year)		Revenue (30th Year)	
		Percent	Impact of Escalation in Electric Costs	
Offset of Retail Electricity	$36,390,135	50.0%	$65,915,693	
Wholesale Electricity	$17,650,305	50.0%	$31,971,084	
MA Renewable Market Class 1 RPS	$5,665,530		$5,665,530	
Renewable Investment Tax Credit	$8,716,200		(Zero After 10 Years)	
Total Revenue	$68,422,170		$103,552,307	
Profit / Loss	($11,495,803)		$23,634,334	

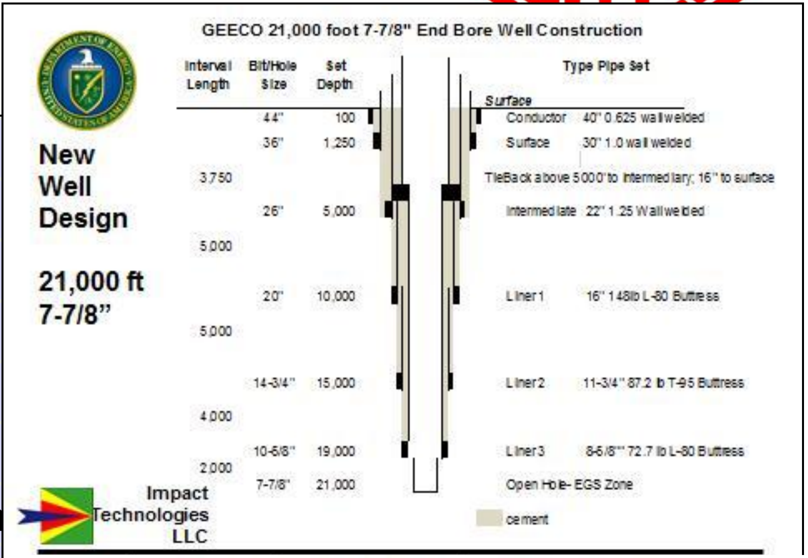
SOPO 1.0: H2O EGS with Diesel (CNG) Water Pumps

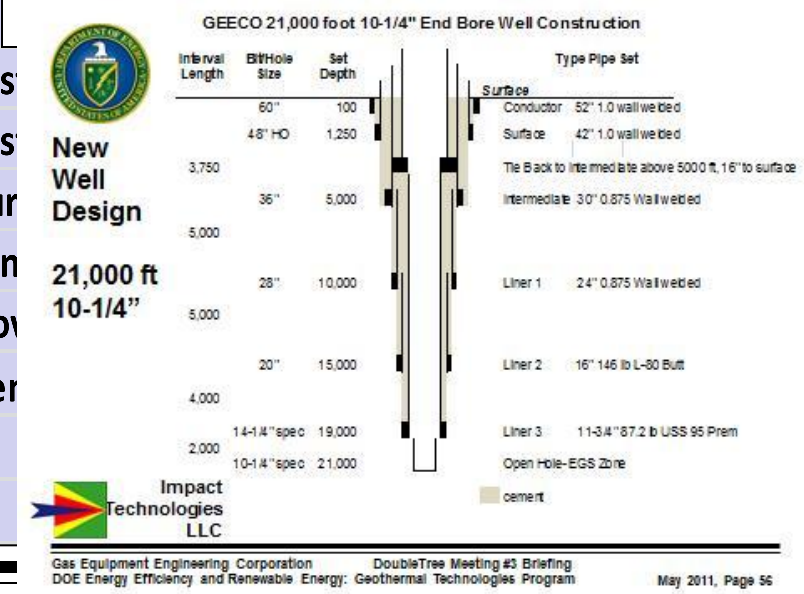
- **Diesel water pumps enable the maximum use of renewable credits and lowers the size of the reservoir**
  - **But, it still loses money, even at 4%**

Parameters:	Water EGS		Comment	
Gross Power	50	MW	Geothermal Gross Power, Not Plant Total	
Net Power	50	MW		
Water Pump Power	20	MW	(from WBS 3)	
Cost of Electricity (retail)	$167	$/MW-hr	(US DOE EIS 2008 MA)	
Cost of Electricity (wholesale)	$81	$/MW-hr	(ISO NE 2008 Hub Price)	
MA Renewable Market Class 1 RPS	$13	$/MW-hr		
Capital Cost	$962,071,235	(roll up)	(from capital sheet)	
Cost of Capital	4.0%	(high)	(variable)	
Annual Capital Cost	$55,636,675	(30 year)	(calculation)	
O&M Cost	1.0%	(of capital $)	(guess)	
Availability	99.5%	(uptime)	(guess)	
Cost Item	$			
Annual Capital Cost	$55,636,675		Escalation Rate (%/year)	
O&M Cost	$9,620,712		2.0%	
O&M Cost Engines	$2,273,504			
Purchased Costs (Fuel / Electricity)	$7,435,621		1.811361584	(30 year)
Total Annual Cost	$74,966,512			
	Revenue (1st Year)		Revenue (30th Year)	
		Percent	Impact of Escalation in Electric Costs	
Offset of Retail Electricity	$36,390,135	50.0%	$65,915,693	
Wholesale Electricity	$17,650,305	50.0%	$31,971,084	
MA Renewable Market Class 1 RPS	$5,665,530		$5,665,530	
Renewable Investment Tax Credit	$8,716,200		(Zero After 10 Years)	
Total Revenue	$68,422,170		$103,552,307	
Profit / Loss	($6,544,342)		$28,585,795	

SOPO 1.0 (H2O Baseline)
Capital Cost Tab

WBS	Capital Cost		WBS Element
	70 MW Gross	50 MW Gross (GT)	
	50 MW Net	20 MW Hybrid Pump	
	Electric Drive	Diesel Drive	
1.0	$3,710,000	$3,710,000	Resource ID / A
2.0	$890,540,446	$699,109,235	Reservoir Deve
3.0	$11,070,000	$38,512,000	Fluid Managem
4.0	$187,400,000	$151,000,000	Power generati
5.0	$3,500,000	$3,500,000	Integration / Dis
6.0	$18,000,000	$18,000,000	Integration / Dis
7.0	$10,430,000	$10,430,000	Topside Structur
8.0	$15,430,000	$15,430,000	Land Acquisition
9.0	$4,130,000	$4,130,000	Permits / Approv
10.0	$18,250,000	$18,250,000	Project Manager
Total	$1,162,460,446	$962,071,235	





WBS2 (Drilling for Water EGS) ---
1st Level Down in WBS Structure

WBS	70 MW Gross		number	unit cost ($)	unit
2.0	$890,540,446	Reservoir Development	Learning Curve		
			Mult Fac	# @ 91	# @ 82
2.1	$1,000,000	Reservoir Planning	0.837	3	13
2.2	$1,000,000	Reservoir Model Development (integrate test bore results)	0.831	3	22
2.3	$361,681,079	Injection Well Drilling	16	$27,011,283	/well
2.4	$460,659,367	Production Well Drilling	25	$22,179,074	/well
2.5	$32,000,000	Hydraulic stimulation	16	$2,000,000	/well

WBS	50 MW Gross				
2.0	$699,109,235	Reservoir Development	Learning Curve		
			Mult Fac	# @ 91	# @ 82
2.1	$1,000,000	Reservoir Planning	0.843	3	9
2.2	$1,000,000	Reservoir Model Development (integrate test bore results)	0.834	3	17
2.3	$273,084,071	Injection Well Drilling	12	$27,011,283	/well
2.4	$369,725,164	Production Well Drilling	20	$22,179,074	/well
2.5	$24,000,000	Hydraulic stimulation	12	$2,000,000	/well
2.6	(included)	Intangible Drilling Costs (Mud / Temporary Equipment / Removal)			
2.7	(included)	Special Sand / Fluid Injection (Hold Fractures Open)			
2.8	(included)	Special Sealing Fluid Injection (probably more for CO2 system)			
2.9	$12,000,000	Production pumps	20	$600,000	/well
2.10	$6,000,000	Specialized logging	8	$750,000	/well
2.11	$6,000,000	Coring and leak-off testing	8	$750,000	/well
2.12	$3,200,000	Post-completion testing	32	$100,000	/well
2.13	$3,000,000	System circulation testing prior to plant start-up	4	$750,000	/module
2.14	$100,000	Water Well Drilling	4	$25,000	/well

SOPO 2.0: Impact of CO_2

- CO_2 EGS, without any technology tricks, will require stacks of money
  - Mostly driven by TRL9 decision on corrosion control
  - Nothing proven (and inexpensive) is out there now…

Parameters:	CO2 EGS		Comment
Geothermal Power (Net)	50	MW	Geothermal Net Power
Total Net Power	50	MW	Yearly Total (Not Including Filling)
CO2 System Net Power (extra to be sold)	0	MW	(from WBS 3)
Cost of Electricity (retail)	$167	$/MW-hr	(US DOE EIS 2008 MA)
Cost of Electricity (wholesale)	$81	$/MW-hr	(ISO NE 2008 Hub Price)
MA Renewable Market Class 1 RPS	$13	$/MW-hr	
Capital Cost	$1,454,099,373	(roll up)	(from capital sheet)
Cost of Capital	4.0%	(high)	(variable)
Annual Capital Cost	$84,090,711	(30 year)	(calculation)
O&M Cost	1.0%	(of capital $)	(guess)
Availability	99.5%	(uptime)	(guess)
Cost Item	$		
Annual Capital Cost	$84,090,711		Escalation Rate (%/year)
O&M Cost	$14,540,994		2.0%
O&M Cost Engines	$240,960		
Purchased Costs (Fuel / CO2)	$8,127,206		1.811361584 (30 year)
Total Annual Cost	$106,999,871		
	Revenue (1st Full Year)		Revenue (30th Year)
		Percent	Impact of Escalation in Electric Costs
Offset of Retail Electricity	$36,390,135	50.0%	$65,915,693
Wholesale Electricity	$17,650,305	50.0%	$31,971,084
MA Renewable Market Class 1 RPS	$5,665,530		$5,665,530
Renewable Investment Tax Credit	$8,716,200		(Zero After 10 Years)
Total Revenue	$68,422,170		$103,552,307
Profit / Loss	($38,577,701)		($3,447,564)

SOPO 2.0: CO2 EGS Capital Cost Tab

- The CO2 EGS reservoir is substantially smaller (30kft design), but the reservoir development cost is substantially higher!!
  - Stainless liners

WBS	Capital Cost 50 MW Net	WBS Element
1.0	$3,710,000	Resource ID / Analysis
2.0	$1,132,274,373	Reservoir Development
3.0	$183,770,000	Fluid Management & CO2 (filling)
4.0	$70,000,000	Power generation
5.0	$3,500,000	Integration / Distribution (local)
6.0	$18,000,000	Integration / Distribution (grid)
7.0	$12,630,000	Topside Structures
8.0	$7,015,000	Land Acquisition / Land Use
9.0	$4,930,000	Permits / Approvals
10.0	$18,270,000	Project Management
Total	$1,454,099,373	

SOPO 2.0 WBS3: Price of CO_2 (and topside fluid management)

- **Though not the driver as shown, the CO_2 is pricey, but the biggest deal here is risk**
  - **If porosity estimate is off by factor of 3 you are out another >$0.5B**

WBS	Cost	Item	Basis / Comment	
3.0	**$183,770,000**	**CO2**	MT Required	
3.1	**$175,200,000**	Filling CO2	**0.73**	
3.2		Price / Ton (In Massive Quantity)	**240**	
3.3				
3.4	**$2,000,000**	Electric Blower to Start Thermal Siphon?		
		1000 hp multi-stage compressor, electric drive (Solar Turbines)		
3.5	**$3,580,000**	Diesel Genset for Backup Power	ROM	
		Details (for backup genset as well)		
	Cost of 1 OP Dual	Fuel Engine & Generator plus Auxiliaries & Controls	1790000	
		Power Level	1506	kWe = 100% rated load
		Specific Fuel Consumption	6400	BTU/hp-hr @ 100% load
		Fuel Price ($/mmBTU)	4	Current cost of natural gas
			2	Backup Genset
		Hours of operation per year	8000	Assumes 97% availability
3.6	**$400,000**	Filtration	ROM	
3.7	**$90,000**	Freeze Protection	ROM	
3.8	**$2,500,000**	CO2 Compression (Local Dewar, LP Transfer Pump, HP Liquid Pump)		
3.9	**$8,127,206**	Fuel & CO2 Top Off		
	$827,206	**NG Fuel Costs (Not Summed Above)**	TPD Required	
	$7,300,000	**Per Year CO2 Top Off Costs (Not Summed Above)**	66.7	
		Price / Ton (Not In Massive Quantity)	300	
	$240,960	**Engines Maintenance Costs (Not Summed Above)**	0.01	
		Based on $.01/kW-hr. OP engine: $.01 x (1506x3) x 8000.	32/40: $.01 x (5975x4) x 8000	

SOPO 3.0 (CO_2, Plus CO_2 Generation and Drilling Technology) Summary Result

- **<u>CO_2 EGS rocks!!</u>**
  - Revenue Up
  - Cost Down
- **Semi-Closed Cycle diesel top off system generates extra power / revenue**
- **Semi-Closed Cycle turbine filling system generates power at retail offset (during development phase of project)**

Geothermal Power (Net)	50	MW	Geothermal Net Power
Total Net Power	63	MW	Yearly Total (Not Including Filling)
CO2 System Net Power (extra to be sold)	13	MW	(from WBS 3)
Cost of Electricity (retail)	$167	$/MW-hr	(US DOE EIS 2008 MA)
Cost of Electricity (wholesale)	$81	$/MW-hr	(ISO NE 2008 Hub Price)
MA Renewable Market Class 1 RPS	$13	$/MW-hr	
Capital Cost	$950,537,614	(roll up)	(from capital sheet)
Retail / Wholesale Split Filling System (default 100% retail)		100.0%	Retail %
One Time Power Generated (filling system)	443858	MW-hr	(from WBS 3)
Capital Cost Adjustment, One Time Power	$74,124,324	Filling Sys.	(Retail Portion)
Capital Cost Adjustment, One Time Power	$0	Filling Sys.	(Wholesale Portion)
Adjusted Capital Cost (Minus Filling Income)	$876,413,290		
Cost of Capital	4.0%	(high)	(variable)
Annual Capital Cost	$50,683,067	(30 year)	(calculation)
O&M Cost	1.0%	(of capital $)	(guess)
Availability	99.5%	(uptime)	(guess)
<u>Cost Item</u>	<u>$</u>		
Annual Capital Cost	$50,683,067		Escalation Rate (%/year)
O&M Cost	$9,505,376		2.0%
O&M Cost Engines	$1,076,512		
Purchased Costs (Fuel / CO2)	$3,511,009		1.811361584 (30 year)
Total Annual Cost	$64,775,965		
	<u>Revenue (1st Full Year)</u>		<u>Revenue (30th Year)</u>
		Percent	Impact of Escalation in Electric Costs
Offset of Retail Electricity	$45,517,719	50.0%	$82,449,047
Wholesale Electricity	$22,077,456	50.0%	$39,990,257
MA Renewable Market Class 1 RPS	$7,086,591		$7,086,591
Renewable Investment Tax Credit	$10,902,448		(Zero After 10 Years)
Total Revenue	$85,584,214		$129,525,895
Profit / Loss	$20,808,249		$64,749,930

SOPO 3.0: CO2 + Technology Capital Cost Tab

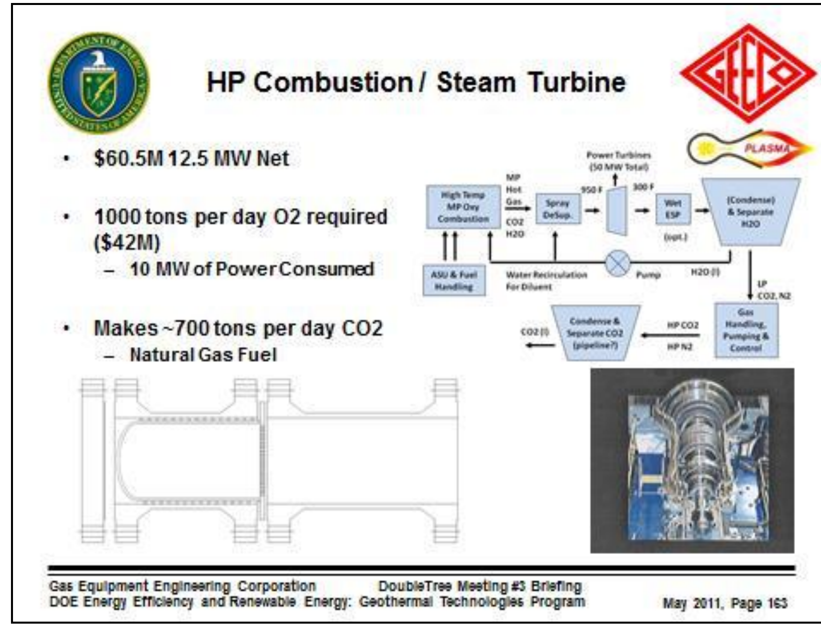
- WBS2 Costs are lower mostly as a result of clad liners vs. stainless – and lower price of CO2 enabled shallower depth design (21kft)
- WBS3 Costs are offset by $74M of one time (filling revenue) & 125% of yearly revenue (top-off)
- Net result:
  - 60ish% of the costs
  - 125ish% of the revenue

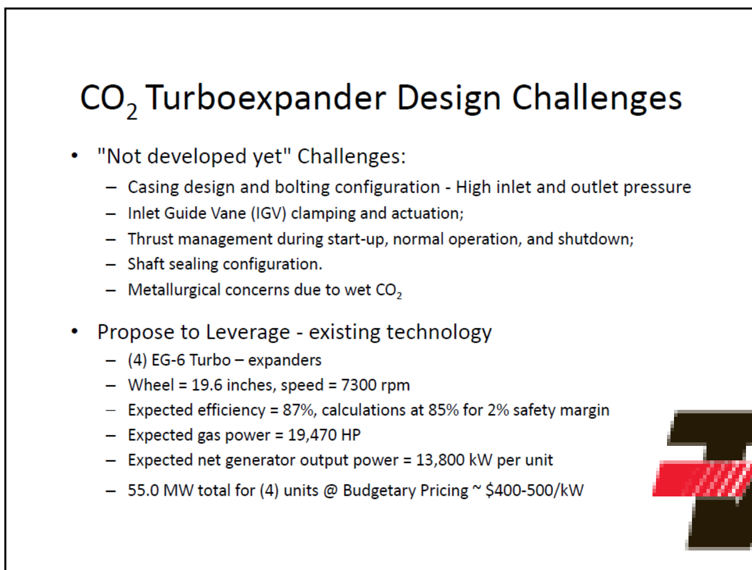
WBS	Capital Cost 50 MW Net	WBS Element
1.0	$3,710,000	Resource ID / Analysis
2.0	$686,053,958	Reservoir Development
3.0	$124,898,656	Fluid Management & CO2 (filling)
4.0	$70,000,000	Power generation
5.0	$3,500,000	Integration / Distribution (local)
6.0	$18,000,000	Integration / Distribution (grid)
7.0	$12,630,000	Topside Structures
8.0	$8,545,000	Land Acquisition / Land Use
9.0	$4,930,000	Permits / Approvals
10.0	$18,270,000	Project Management
Total	$950,537,614	

Turbines, Turbines, Turbines

- Plasma reservoir filling system uses Dresser Rand Model 1
  - Semi-closed combustion turbine with captured $CO2$

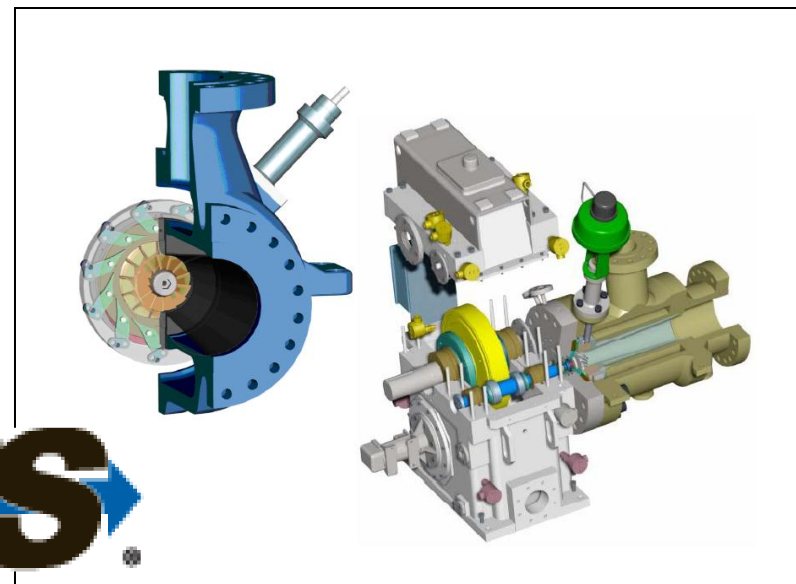
- Main power turbines by TAS



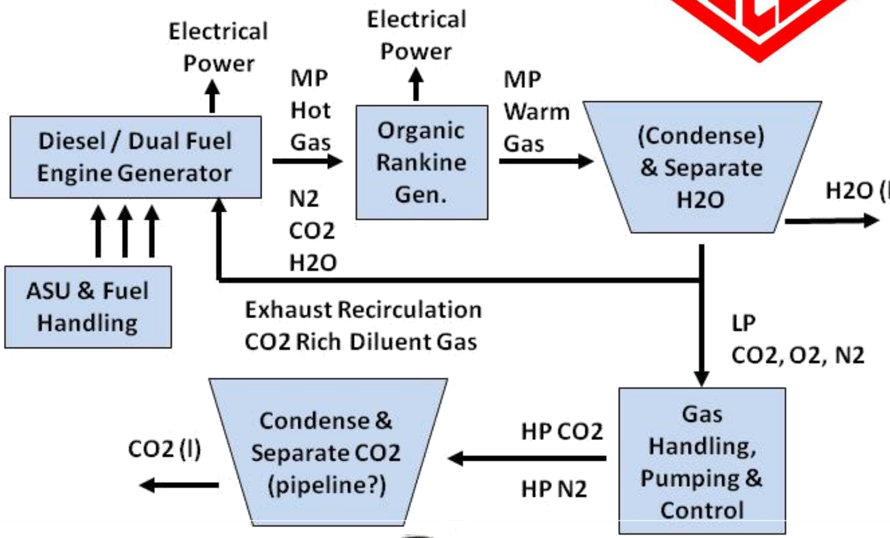


CO_2 Turboexpander Design Challenges

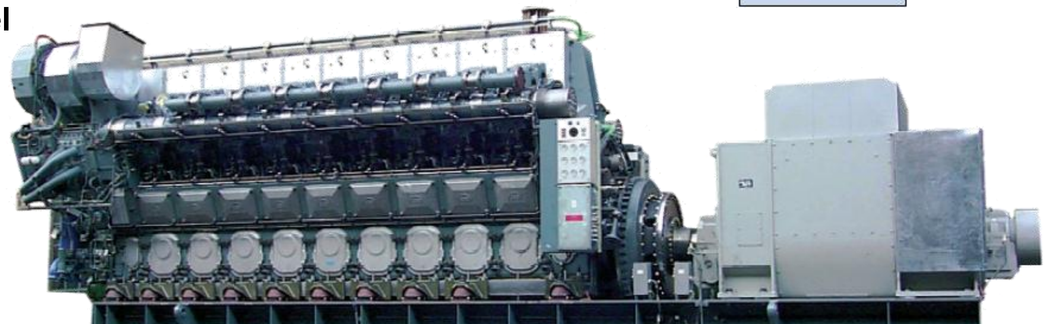
- "Not developed yet" Challenges:
  - Casing design and bolting configuration - High inlet and outlet pressure
  - Inlet Guide Vane (IGV) clamping and actuation;
  - Thrust management during start-up, normal operation, and shutdown;
  - Shaft sealing configuration.
  - Metallurgical concerns due to wet CO_2
- Propose to Leverage - existing technology
  - (4) EG-6 Turbo – expanders
  - Wheel = 19.6 inches, speed = 7300 rpm
  - Expected efficiency = 87%, calculations at 85% for 2% safety margin
  - Expected gas power = 19,470 HP
  - Expected net generator output power = 13,800 kW per unit
  - 55.0 MW total for (4) units @ Budgetary Pricing ~ $400-500/kW



CO2 Top Off System: Semi-Closed Cycle Medium Speed Dual Fuel Diesel



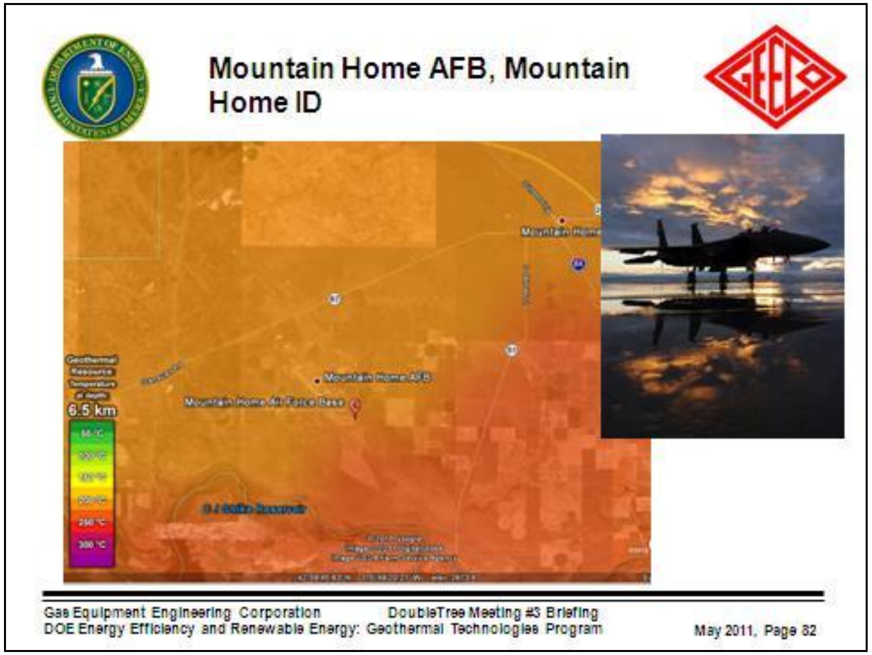
- **$29.4M for 12.5 MW Net**
- **~140 tons per day CO2 at 2200 psig**
- **System make up:**
  - **Two 16 cylinder FME 32/40 Generator Sets (5975 kW), modified for closed cycle**
  - **~Two 100 TPD VPSA ASU's (926 kW each)**
  - **Two Ariel CO2 Compressors (69 TPD, 400 hp)**
  - **Two TAS 800 kW ORC (to cool diesel exhaust from 750 F)**
- **<u>~40% cycle efficiency on CNG</u>**

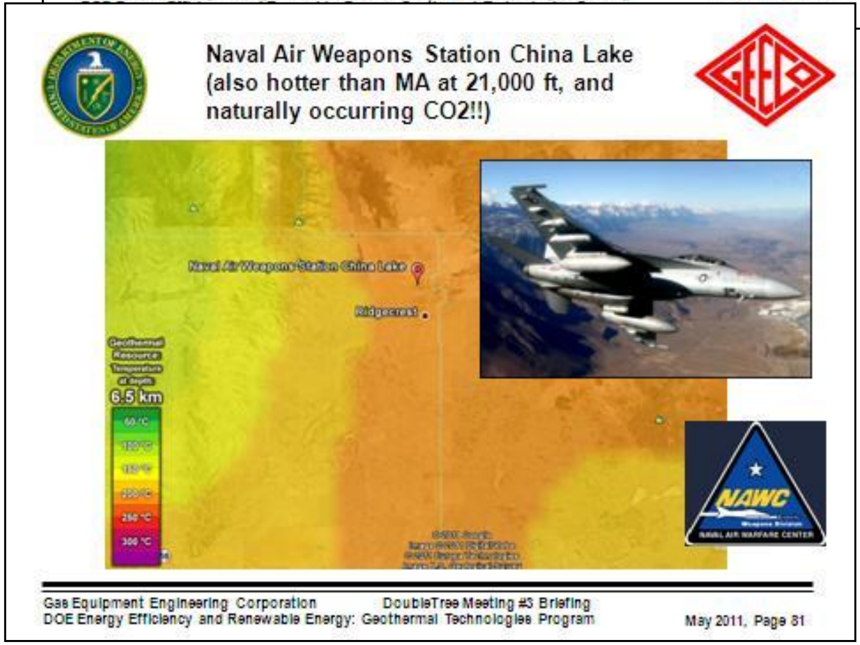


Cost of CO2 to the project is <u>negative</u>, after amortization, maintenance, and everything else!!!

SOPO 4.0 Locations (with Technology)

- **Ft. Bliss will be a Water EGS**
  - **It might be a good site for CO_2 sequestration, but not EGS!!**
- **Others will be CO_2**
- **Net result is a range of locations, EGS designs, and costs**





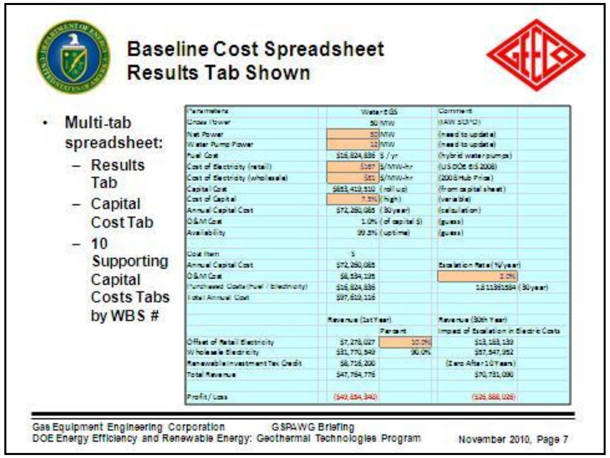
Summary

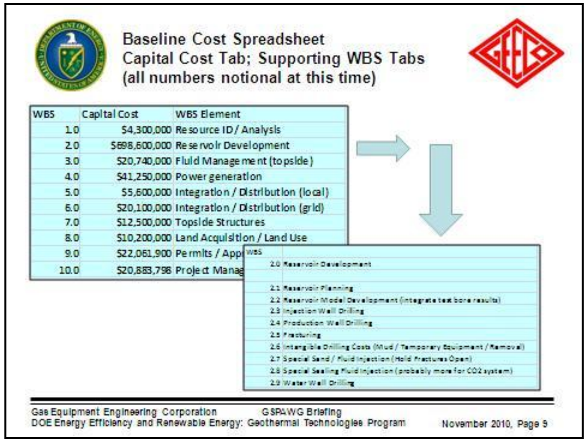
- Detailed WBS based EGS cost models have been developed as a result of a DOE Grant

- The baseline (50 MW Water EGS) in Massachusetts is untenably high cost (well over $1B capital – 70+% of which is associated with reservoir development) and is not profitable, even with high electric rates, unless money is close to free!

- CO2 EGS (with direct turbine) operates at a much higher net cycle efficiency, resulting in a smaller reservoir (lower cost), but requires greater massflow (larger drill diameters, or closer spacing, fancy completions, and a corrosion program)
  - CO2 EGS is only practical in areas with locally available low cost CO2, or with CO2 generated on site (hybrid system) – until the CO2 rules change

- We are studying a wide range of other locations (CA, TX, ID) and electricity costs
  - We will complete and publish this year





Acknowledgement

- This briefing material has been assembled from a number of sources generated by the team
  - We have an amazing team…
- We would also like to thank the DOE Geothermal Technology Program, in particular Ms. Arlene Anderson, for her support

GeothermEx
A Schlumberger Company

FUGRO

FAIRBANKS MORSE ENGINE
an EnPro Industries company

PLASMA

TAS

CLF VENTURES, INC

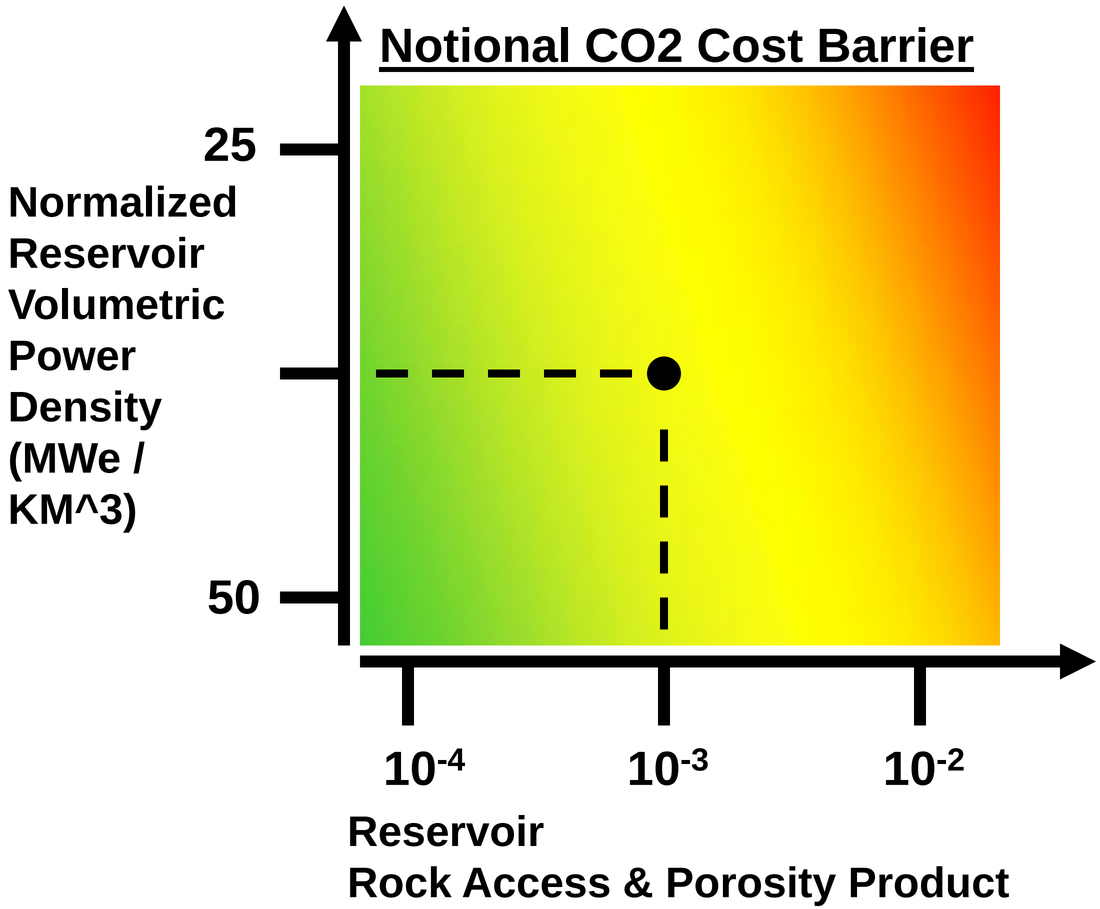
Impact Technologies LLC

Fort Point Associates

BACKUP

Reservoir Size Implications…

The Size of the Reservoir, and Parameters, Such as Porosity and Access, Significantly Drive Cost Example Shown Below for $240/ton Trucked In CO2 (Unaffordable!!)



- **The mass of CO2 required to charge a given reservoir is a function of the density (average at temperature and depth), volume, and porosity**
- **The "dot" is at ~$5.3M per MWe, e.g.**
  - **50 MW, 1.3 km^3**
  - **0.1% Access / Porosity Product, e.g.**
    - **5% is accessible**
    - **2% porosity**
  - **50 lbm/ft^3 density**
  - **~1.1 Mega Tons CO2**
  - **$264M @ $240/ton**

SOPO 1.0 Water
Bottom Depth 21,000 ft

- 70 MW Case (50 MW Net); 2703 MMBTU/hr heat removal rate
  - 25 Production Wells and 16 Injector Wells – 0.5 mile spacing
    - 160 lbm/sec production well; small bores OK; dual completion
    - 250 lbm/sec injection well; big bores required
  - 3.2 km^3 reservoir volume

- 50 MW Case (Diesel driven pumps)
  - Proportionally lower heat removal rate and well count (5/7th)
  - 20 Production Wells and 12 Injector Wells – 0.5 mile spacing
  - Same casing sizes, nominally the same per well flow rates

- Other than dual completion on production wells, this is conventional construction
  - Production pumps set in 16” diameter @ nominally 3,000 ft

SOPO 2.0 (CO_2: Purchased, Existing Technology (SS))

- 50 MW requires 799 MMBTU/hr heat removal rate (@ 30kft)
- 12 Production Wells and 6 Injector Wells – 0.45 mile spacing
  - System flow rate is down to 2700 lbm / sec (H_2O was 4000 lbm/sec)
    - 450 lbm/sec per injector well
    - 225 lbm/sec per production well
  - Big Bore Injector Wells to 30,000 ft – no exotic materials needed
    - Manageable pressure drop ~150 psig (nothing compared to siphon)
  - Small Bore Production Wells, Dual Completion, in STAINLESS!!
    - Manageable pressure drop ~700 psig (still ok compared to siphon)
- Reservoir Size 0.94 km^3 (vs. 3.2 km^3 for SOPO 1.0)
- At 44 lbm/ft^3 bottom (hot) density, this is 730,000 tons of CO_2
  - 5% of reservoir is accessible to CO_2 flow
  - 2% porosity in this area
  - $175M delivered (initially!!) – then that much again over time

SOPO 3.0 (CO_2: Clad Casing, Hybrid Generated CO_2)

- **50 MW requires 1120 MMBTU/hr heat removal rate (@ 20kft)**
- **12 Production Wells and 8 Injector Wells – 0.5 mile spacing**
  - **System flow rate is up to 5800 lbm / sec**
    - **650 lbm/sec per injector well**
    - **360 lbm/sec per production well**
  - **Big Bore Injector Wells to 21,000 ft – no exotic materials needed**
    - **Manageable pressure drop ~460 psig (OK compared to siphon)**
  - **Big Bore Production Wells, Dual Completion, Cladded**
    - **Manageable pressure drop ~350 psig (OK compared to siphon)**
- **Reservoir Size 1.3 km^3 (vs. 3.2 km^3 for SOPO 1.0)**
- **At 44 lbm/ft^3 bottom (hot) density, this is 1 Mega Ton of CO_2**
  - **5% of reservoir is accessible to CO_2 flow**
  - **2% porosity in this area**