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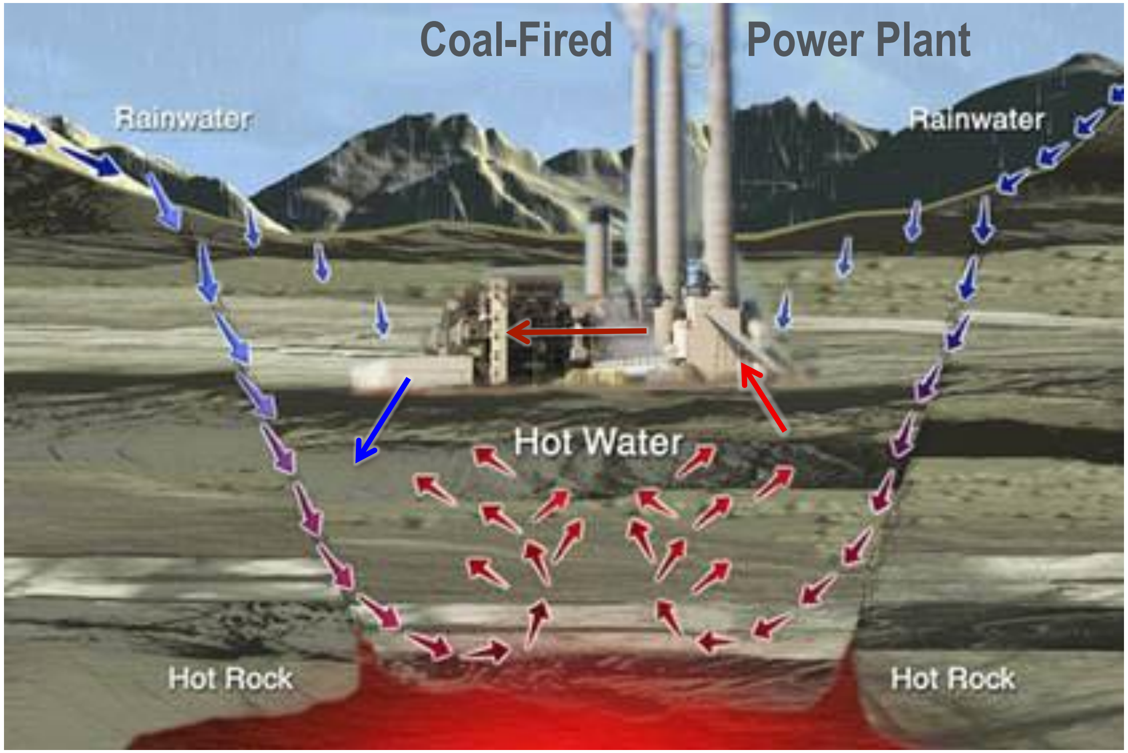

Geothermal Power Generation and CO_2 Capture Co-Production

Project Officer: Tim Reinhardt, Holly Thomas

Total Project Funding: $200,000

May 12, 2015

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Pacific Northwest National Laboratory

Relevance/Impact of Research

- The program aims to aid the Low Temperature and Systems Analysis programs by demonstrating the techno-economic viability of a hybrid coal-geothermal plant.
- This program identifies viability of marginalizing geothermal capital into larger infrastructure, where geothermal can provide heat duty to power energy-intensive units of operation at smaller capital costs.
  - Hybridization may enable reaching GTO’s target 6c/kW by combining geothermal infrastructure to capital expenditures of existing plants.
  - Hybrid plants are large enough that only a handful of plants make significant progress towards GTO’s target of 3 GWe installed capacity.
- This program is novel in that it investigates integration of direct-use, low temperature geothermal resources to coal plants with and without carbon capture and sequestration (CCS), aiding both DOE missions.
  - Aids GTO by identifying areas for large scale deployment at candidate plants and providing higher power generation than stand alone ORCs.
  - Aids CCS by efficiently powering CO_2 capture infrastructure, enhancing coal plant efficiency.

Relevance/Impact of Research

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Geothermal power plant upfront capital costs are a barrier to deployment

- To achieve 6 c/kW cost targets for GTO, this program identifies hybridization as a means to significantly cut capital expenditures because:
  - Units are already tied to the electrical grid and prepped
  - Unit costs may be cheaper or already paid
  - Geothermal powering of units of operation may enable higher net power for the CCS plant, enabling a quicker return on investment
  - Potentially higher efficiency by coupling geothermal steam to the plant's LP turbine than ORC
  - Geothermal capital expenditure is minimal to a coal plant

Power loss translates into high operational costs, which are the major barrier to CCS deployment

- – Carbon capture systems require large heat duties solely to regenerate solvent
- – Heat duty is provided by steam from the power plant's steam cycle, resulting in a ~20% loss in net power
- – Geothermal energy could be used to provide the reboiler heat duty or additional power, reducing parasitic load, and allowing for higher net power production
- – Potential for faster return on investment

Accomplishments, Results and Progress

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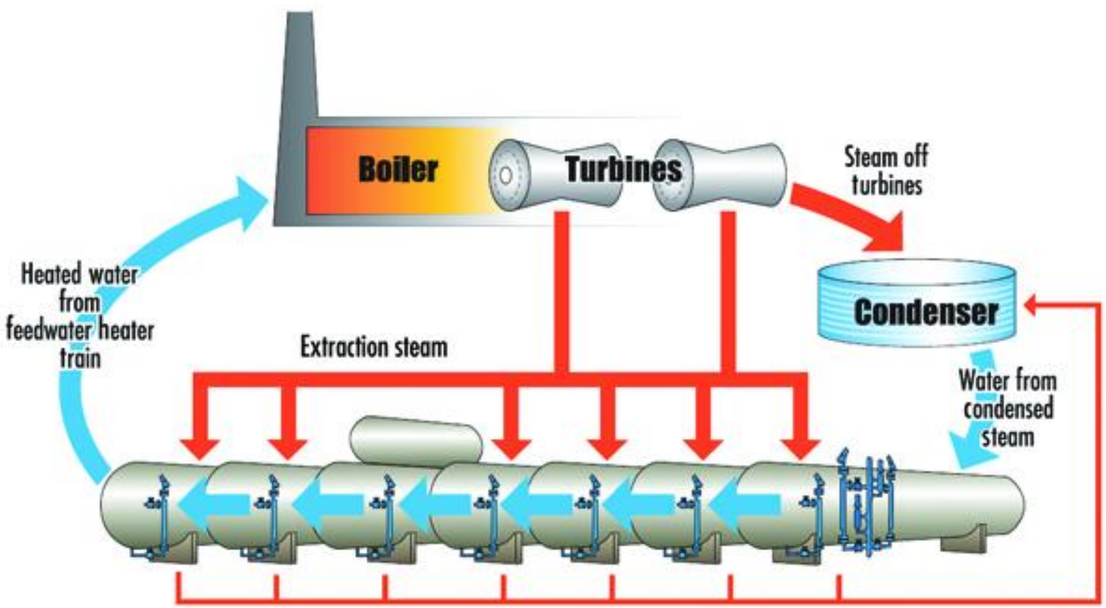
- Accomplishments/Progress to date.
  - (FY14 TEA) Hybridization COE of coal-fired power plants 5.93 cents/kWh (from 6.02) without CCS, and 10.72 cents/kWh (from 11.01) for coal plants with CCS
  - Potential for installed capacity of 19 MWe per plant with 10 candidate sites bringing potential for 190 MWe total capacity.
  - Manuscript in preparation.
- Project work was halted until funding arrived. 25k was received in October, and 40k in February, 75k in March. The program is now running as scheduled and is on track to meet target milestones and deliverables.

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Completion of initial techno-economic analysis	Confirmed hybridization can meet cost and deployment metrics	10/10/2014
Complete detailed geothermal resource report	Started, 2/15/2015	Scheduled 6/30/2015
Revised process simulation with site conditions	Scheduled 6/30/2015	Scheduled 6/30/2015
Completion of site-specific techno-economic analysis	N/A	Scheduled 9/29/2015

Scientific/Technical Approach
Direct Use Application: CCS Units

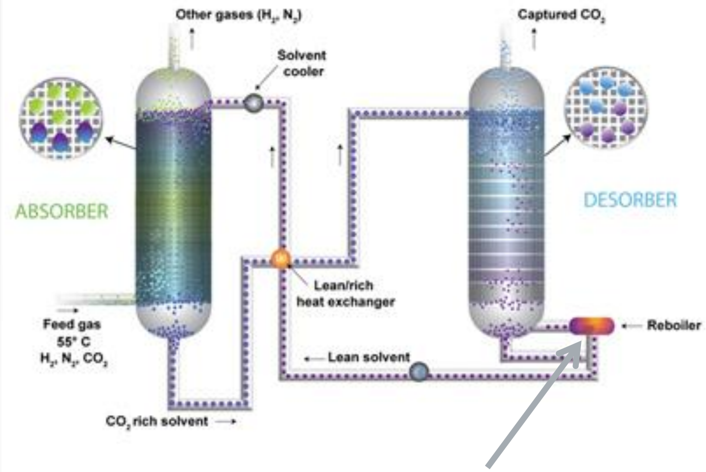
Steam-cycle boiler feedwater heaters:
Up to 10% draw on plant efficiency

1. Reduce the steam to the CCS stripper reboiler
2. Reduce steam extractions to the low pressure boiler feedwater heaters



CCS solvent reboiler:

- Regenerates the CO_2 capture solvent
- Requires 1520 btu/lb of CO_2
- 30 % parasitic load to plant



3. Supply part/all of the carbon capture reboiler duty

Scientific/Technical Approach
Preliminary Site Selection (FY14)

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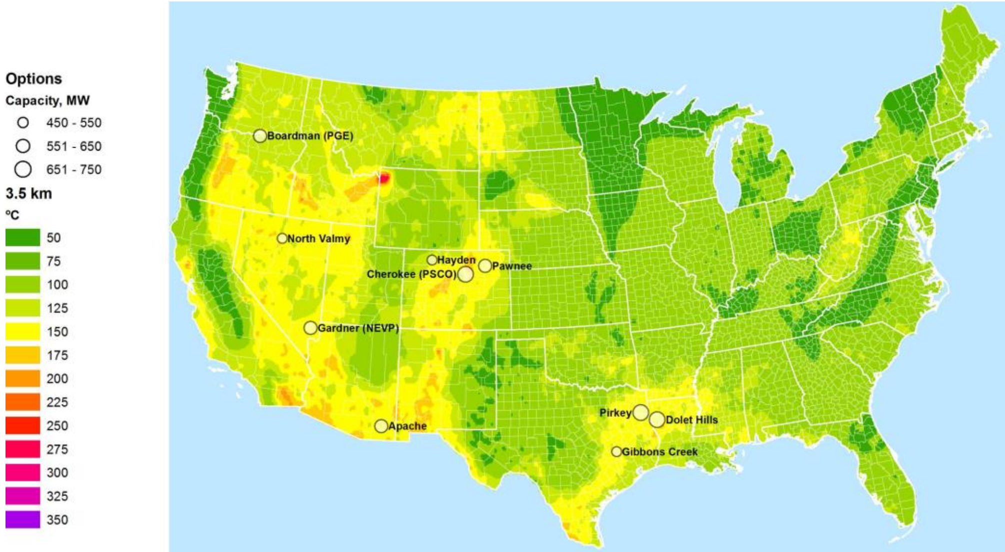


- 602 Coal-fired power plants have 125-150 ˚C resource <3.5 km (364 GWe capacity)
- 10 candidate sites with most promise
  - 190 MWe potential geothermal capacity
- 4 Final sites chosen with HIGH, MODERATE, MARGINAL resource viability for study

Plant	Capacity (MW)	Location (City, ST)	Vintage (First, Last)	Approx Temp @ 3.5 km (°C)
Apache	627	Cochise, AZ	1963, 2002	150
Boardman	601	Boardman, OR	1980, 1980	125-150
Cherokee	730	Denver, CO	1957, 1988	125-175
Dolet Hills	720	Mansfield, LA	1986, 1986	150
Gardner	637	Moapa, NV	1965, 1983	150
Gibbons Creek	470	Grimes, TX	1983, 1983	150-175
Hayden	465	Hayden, CO	1965, 1976	125
North Valmy	521	Valmy, NV	1981, 1985	150
Pawnee	552	Brush, CO	1981, 1981	150
Pirkey	721	Hallsville, TX	1985, 1985	150

Apache!Power!Station! !Arizona!Electric!Power!! Cooperative!

Geothermal!Resource! Quality:!MODERATE!

Boardman!Coal!Plant! Portland!General!Electric

Geothermal!Resource! Quality:!MARGINAL!

North!Valmy!Station!Sierra! Pacific!Resources!

Geothermal!Resource! Quality:!HIGH!

Hayden!Station!Xcel!Ener

Geothermal!Resource! Quality:!MARGINAL!

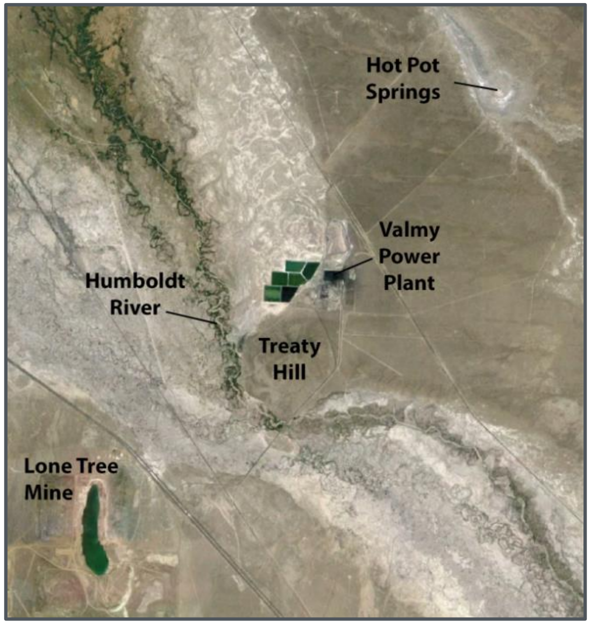
*Data on coal power stations c. 2011, from Platts; geothermal resource maps, Google Earth / World Energy Explorer

Scientific/Technical Approach
Final Candidate: North Valmy Site

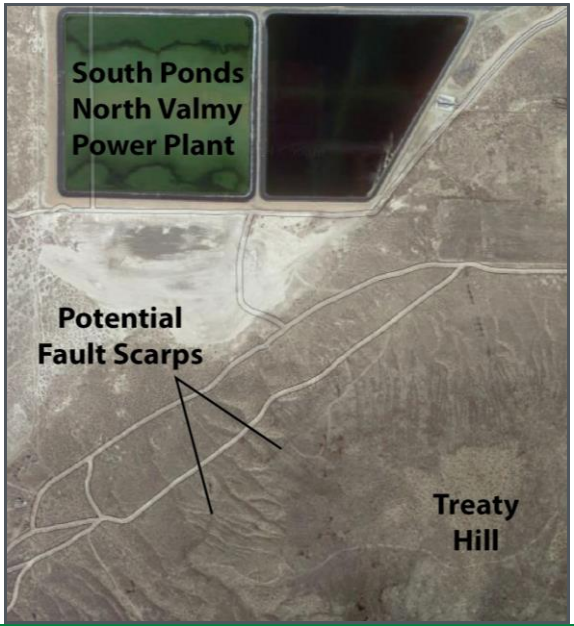
- North Valmy power plant is that it's located only 1.5 to 2 miles south-southwest of the "Hot Pot" thermal anomaly, which is an area currently leased for geothermal development by Oski Energy, LLC.
- If private development is already taking place just over the property line then there is likely a good resource.
- Site is currently shut down due to a lack of cost-share for Phase 2

*Lane, et al. 2012. PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, January 30 - February 1, 2012 SGP-TR-194.

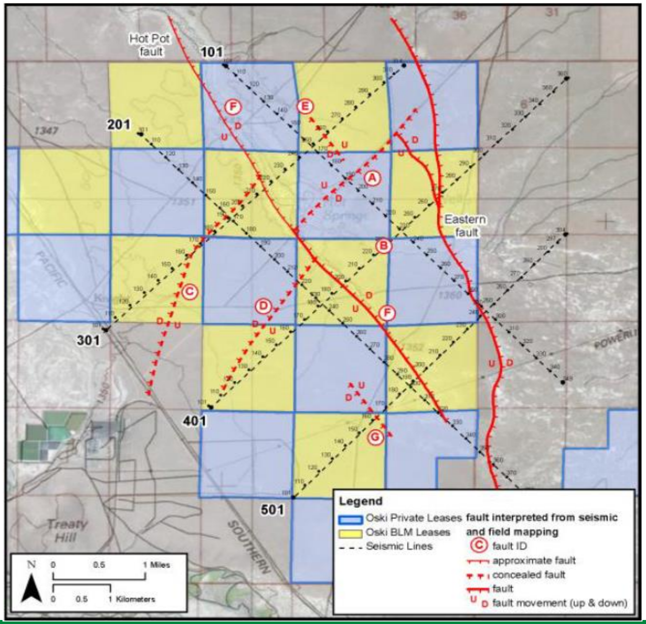
Location Map



Potential Quaternary fault scarp along the northwest flank of Treaty Hill.



Location of Oski Energy, LLC geothermal leases, the Hot Pot seismic program survey lines, and interpreted structures



Aspen Economic Analyzer Estimate of NETL's Case 9&10 coal-fired plants:

Case 9 (No CCS): Cost comparisons of the boiler feed water heating capital or ORC system running *iso*-butane working fluid

- 1 mile 18" piping, supply/return pumps, cooling tower, heat exchangers (tube & shell)

Case 10 (With CCS): Cost comparisons of the Case 10 boiler feed water heating capital

- Partial MEA Reboiler & BFW Heating with 5,400 gpm geothermal fluid
- Total MEA Reboiler & BFW Heating with 74,000 gpm geothermal fluid
- Advanced CCS Reboiler (~80%) & BFW Heating with 20,000 gpm geothermal fluid
  - 1 mile 18" piping, Supply/return pumps, Cooling tower (incremental), heat exchangers (tube and shell – stainless steel SS304 construction)

	NETL Case 9 No CCS BFW Heating	No CCS ORC	NETL Case 10 CCS 7% Reboiler Duty + BFW	NETL Case 10 CCS Max Reboiler	NETL Case 10 Advanced CCS Max Reboiler
150 ˚C Flow (gpm)	5,400	5,400	5,400	74,000	20,000
Net Power (MW)	19	9	21	101	121
Capital (USD)	$34,715,584.00	$47,196,637.00	$41,416,161.00	$108,649,325.00	$51,600,033.00

- SiteSite-specific cost parameters and resulting cost estimates for production and injection well requirements

- Drilling depths to reach a sufficient fluid temperature of 150° C with conservative gradient of 70° C/km to (90° C/km

- Drilling depths of approximately 5,000 feet (Case 1) and 6,600 feet (Case 2).

- Butler et al.[10] reported that at the similar Beowawe site, produces from the same heavily fractured reservoir of interest for this project,
  - 3,600 gpm (1.8 million lb/h), a per-well average of 1,200 gpm (600,000 lb/h)

- Assuming that this average rate could be replicated, process water needs
  - 5,400 gpm (2.7 million lb/h) could be met using 4 or 5 production wells

- Shevenell's,[11] review of efforts to estimate well drilling costs for geothermal projects in Nevada can be used to assume 5 required production wells, would require 3 injection wells.

- Site-specific, conservative approach is consistent with the 2:1 ratio at Beowawe.

- Cost estimates for projection and injection wells done based on work by Shevenell,[11] Klein et al,[12] Bradys[13] and Augustine et al.[14]

Accomplishments, Results and Progress

- Site-specific cost parameters and resulting cost estimates for production and injection well requirements at North Valmy
- Average per-well costs for production wells is between $1.2M and $1.6M each, cost variance resulting from increased depth to reach 150 ˚C water in Case 2 (70 ° C/km) relative to Case 1 (90 ° C/km)
- Injection wells appear to cost about 5% more than production wells at Beowawe 5% adder was included in injection well cost estimates

Total well costs

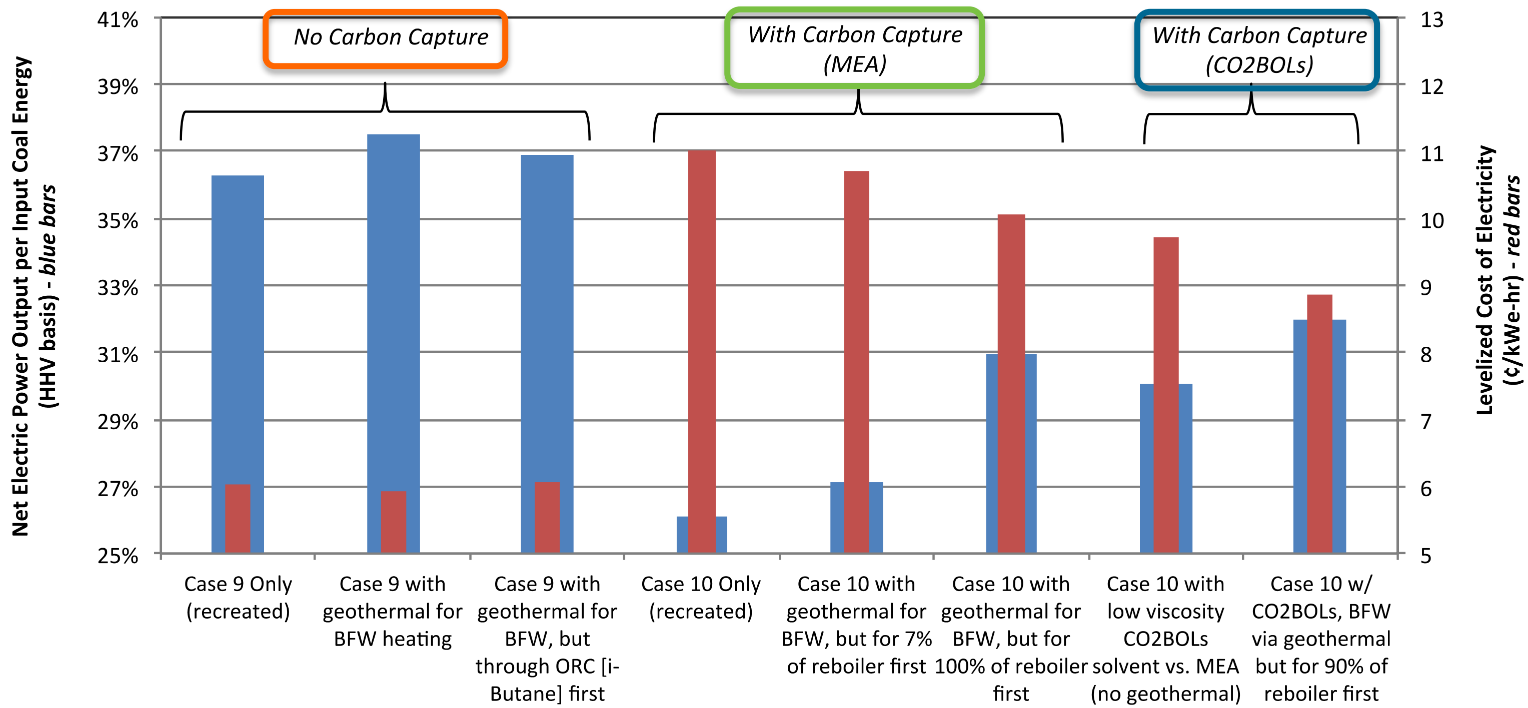
- Based on averages and statistical relationships
- Function of depth alone, assuming avg well diameters
- Depth to recover 150 ˚C water:

  Case 1 = 5,000 ft

  Case 2= 6,600 ft
- Assumes typical drilling conditions and standard well completions

	Case 1	Case 2
Avg Temp Gradient, °C/km	90	70
Desired Temp, °C	150	150
Projected Drill Depth, ft	4,922	6,562
Per-Well Flow Rate, lb/h	600,000	600,000
Required Flow Rate, lb/h	2,500,000	2,500,000
Required Wells, Production	5	5
Required Wells, Injection	3	3
Production Well Costs, each	$ 1,274,394	$ 1,618,930
Production Well Costs, total	**$ 6,371,969**	**$ 8,094,651**
Injection Well Costs, each	$ 1,338,114	$ 1,699,877
Injection Well Costs, total	**$ 4,014,341**	**$ 5,099,630**
TOTAL WELL COSTS	**$ 10,386,310**	**$ 13,194,281**

Accomplishments, Results and Progress LCOE Estimates and Summary of Costs



LCOE (cents/kwh)							
6.02	5.93	6.06	11.01	10.72	10.06	9.71	8.87

*LCOE values for modeled cases is based fuel, capital variable, fixed and TSM costs

Accomplishments, Results and Progress
LCOE Estimates for Each Model Case

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- 150° C geothermal water for boiler feed water preheating offers a higher net electric power, at a comparable LCOE, compared to a stand-alone Case 9 sub-critical power plant option.
- Stand-alone ORC is estimated to produce less overall net power (9 MWe) than for boiler feed water preheating (19 MWe)
- For CCS, infeasible water requirements are needed to offset entire MEA (CO_2 capture solvent) regeneration energy, though varying levels can be provided depending on resource viability.
- (5,400 gpm) water can offset ~7% of a MEA reboiler duty, resulting in ~1% of recovered net electric power lost to the overall CCS parasitic load, but at a similar (high) LCOE to CCS alone.
- Advanced solvents (e.g. CO_2BOLs) more feasible, with ~0.75cents per kWe-hr projected LCOE savings and ~2 points of net electric power increase versus CO_2BOLs alone.
- Model case result could significantly change with higher (or lower) geothermal water temperatures.

Future Directions

- Schedule on site visit to North Valmy (Nevada) for on site analysis and discussions with site operators encouraging development/deployment with both organizations
- Perform a site-specific lithography and resource analysis of a candidate site
  - Specific resource temp and flows
  - Regional lithography for detailed cost analysis of well drilling/stimulation
- Work with plant for optimal hybridization strategies of geothermal integration
  - Cooling inlet air or the booster air compressor by integration with the heat exchange network to reduce the main air compressor horsepower
  - Reduction of cooling water temp for increased vacuum in the condenser
  - Using geothermal steam in the coal-plant's low-pressure steam turbine

Milestone or Go/No-Go	Status & Expected Completion Date
Complete detailed geothermal resource report	Started, 6/30/2015
Revised process simulation with site conditions	In progress, 6/30/2015
Completion of final techno-economic analysis	N/A, 9/30/2015

*This program is translatable to other large–scale systems such as natural gas plants and biorefineries. Potential for carbon sequestration with CO_2 as working fluid.

Mandatory Summary Slide

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Results from FY14 ASPEN Plus modeling and Cost Analyzer:

- Direct-use hybridization generates more power to a coal-fired powerplant than stand alone heat pumps
  - 19 MWe for 150 ˚C water at 5,400 gpm (2.7 million lb/h) VS 9 MWe ORC at the same flow rate

- Hybridization is projected to reduce the COE of coal-fired power plants 5.93 cents/kWh (from 6.02) without CCS, and 10.72 cents/kWh (from 11.01) for coal plants with CCS

Additional Information

	No Carbon Capture (Case 9 reference: Subcritical PC)			With Carbon Capture (Case 10 reference: Subcritical PC with MEA capture solvent)					
Fuel Costs	**Case 9 Only (recreated)**	**Case 9 with geothermal for BFW heating**	**Case 9 with geothermal for BFW, but through ORC [i-Butane] first**	**Case 10 Only (recreated)**	**Case 10 with geothermal for BFW, but for 7% of reboiler first**	**Case 10 with geothermal for BFW, but for 100% of reboiler first**	**Case 10 with low viscosity CO2BOLs solvent vs. MEA (no geothermal)**	**Case 10 w/ CO2BOLs, BFW via geothermal but for 90% of reboiler first**	**Assumptions (list below)**
TOTAL (STEAM TURBINE) POWER, kWe	574,331	597,822	588,505	668,950	695,453	830,588	760,890	807,486	1
Portion of Total Power from ORC, kWe			15,767						
AUXILIARY LOAD SUMMARY, kWe									
Coal Feed, Boiler and Auxiliaries	21,360	21,360	21,360	30,470	30,470	30,470	30,470	30,470	5
CO2 Capture Plant Auxiliaries				19,231	19,268	19,584	27,660	19,584	1
CO2 Compression				48,790	48,790	48,790	48,790	48,790	9
Condensate Pumps	516	514	512	405	432	723	405	707	1
Circulating Water Pumps	4,963	5,844	5,896	10,199	10,984	14,221	10,199	13,486	5
Ground Water Pumps	540	636	641	930	1,001	1,296	930	1,229	1
Cooling Tower Fans	2,770	3,262	3,291	7,791	8,383	10,854	7,791	10,293	1
Transformer Loss	1,804	1,878	1,848	2,337	2,429	2,901	2,337	2,821	1
Geothermal Well Injection Pumps		3,039	3,039		3,039	50,879		7,954	1
TOTAL AUXILIARIES, kWe	31,953	36,532	36,587	120,152	124,796	179,718	128,581	135,333	2
NET POWER, kWe	542,379	561,289	551,918	548,799	570,657	650,870	632,309	672,153	2
Net Plant Efficiency (HHV)	36.3%	37.5%	36.9%	26.1%	27.1%	31.0%	30.1%	32.0%	2
Net Plant Heat Rate (Btu/kWh)	9,408	9,091	9,245	13,074	12,573	11,023	11,347	10,674	2
As-Received Coal Feed (kg/h)	198,391	198,391	198,391	278,956	278,956	278,956	278,956	278,956	5
Thermal Input, kWt	1,495,379	1,495,379	1,495,379	2,102,643	2,102,643	2,102,643	2,102,643	2,102,643	5
Total CO2 Production Rate (kg/h)	471,116	471,116	471,116	695,954	695,954	695,954	695,954	695,954	5
Percent CO2 Captured	0%	0%	0%	90%	90%	90%	90%	90%	5
Geothermal Water Flow (lb/hr)	0	2,695,600	2,695,600	0	2,695,600	37,000,000	0	10,000,000	1
Total Geothermal Duty (MMBtu/hr)	0	517	517	0	517	2,577	0	1,605	1
Annual Fuel Cost ($MM/year)	$62.2	$62.2	$62.2	$87.4	$87.4	$87.4	$87.4	$62.2	2
Utilization Factor	85%	85%	85%	85%	85%	85%	85%	85%	5
Fuel Cost (¢/kWe-hr)	1.54	1.49	1.51	2.14	2.06	1.80	1.86	1.24	2

Assumptions: 1) From Aspen Plus Simulation, 2) Calculated from Table Values, 3) From Aspen Economic Analyzer, 4) Average well cost estimates, 5) Same as Case 9 or Case 10, 6) Assumes 23% of TPC, 7) MEA from Case 10, CO_2BOLs from PNNL report, 8) Same as Case 9 or Case 10 normalized to new net power.