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Coal To Geothermal:

Engineered Geothermal Systems

Susan Petty
SMU Power Plays
Coal and Geothermal Workshop
January 2018

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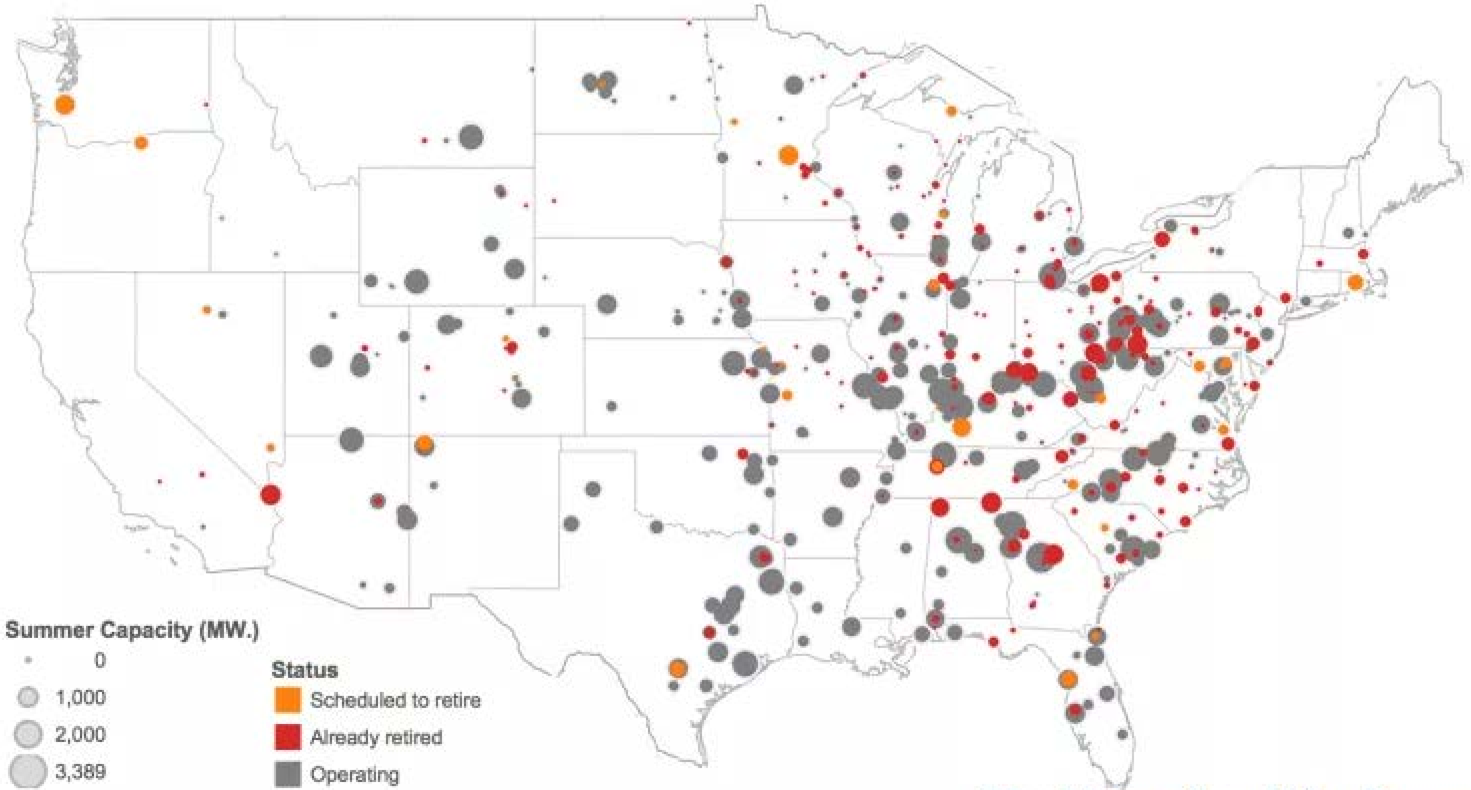
Coal Plant Retirement

Figure 1. Net summer capacity of operating, already retired, and scheduled to be retired coal plants



Source: Brookings analysis of EIA monthly electric generator inventory, Septmber 2016

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EPRI: *Geothermal Management of Coal Plant Waste Water Case Studies*

Plant Name	Location	Operator	Gross Rating (MW)	Disposal Rate (MLD)	Waste Treatment
Mountaineer Power Plant	New Haven, WV	AEP	1300	19	Surface Discharge
North Valmy Generating Station	Valmy, NV	NV Energy	522	2.2	Ponds
Colstrip PPL	Colstrip, MT	Colstrip PPL	2094	1.1	Ponds
Cayuga Generating Station	Lansing, NY	AES	323	26	Surface Discharge
Danskammer Generating Station	Newburgh, NY	Dynegy	537	34	Surface Discharge

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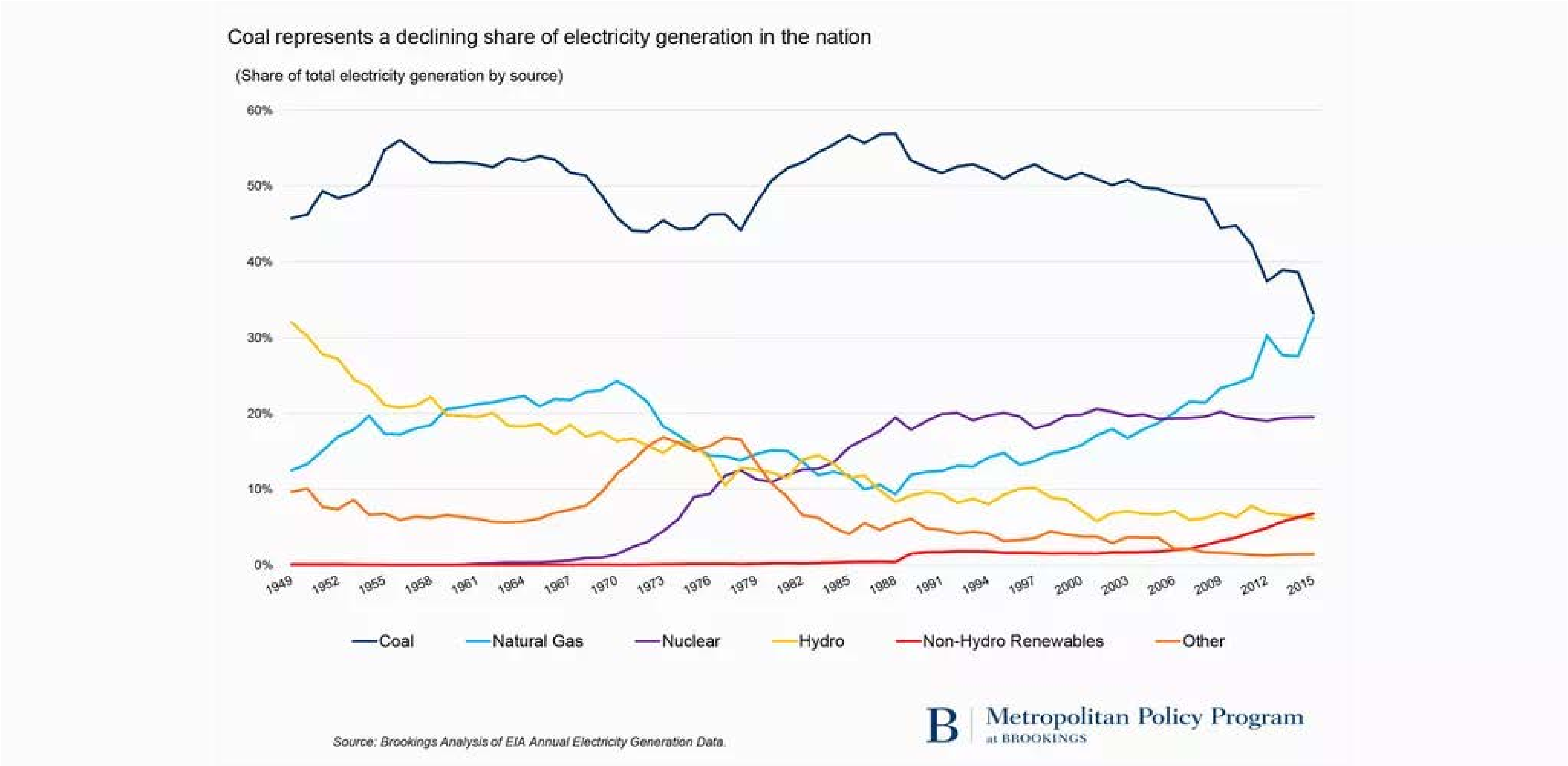
Why Are Coal Plants Retiring?



Coal represents a declining share of electricity generation in the nation

(Share of total electricity generation by source)

Source: Brookings Analysis of EIA Annual Electricity Generation Data.

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Some Factors in Coal Plant Retirement

- Aging coal fleet
  - the median generating station was built in 1966
  - Old plants have lower efficiency
  - Run less often and have poorer economics
- New and proposed EPA regulations
  - Clean Air Transport Rule
  - Proposed Coal Combustion Residuals rule,
  - The proposed Tailoring Rule (covering greenhouse gas emissions),
  - The Ozone NAAQS (National Ambient Air Quality Standards),
  - The forthcoming National Emission Standard for Hazardous Air Pollutants (NESHAPs),
  - Cooling water regulations under section 316(b) of the Clean Water Act. [2][3][4]
- Low prices of power from natural gas plants
- Lower prices for renewables

Aging Plants Are Less Efficient:

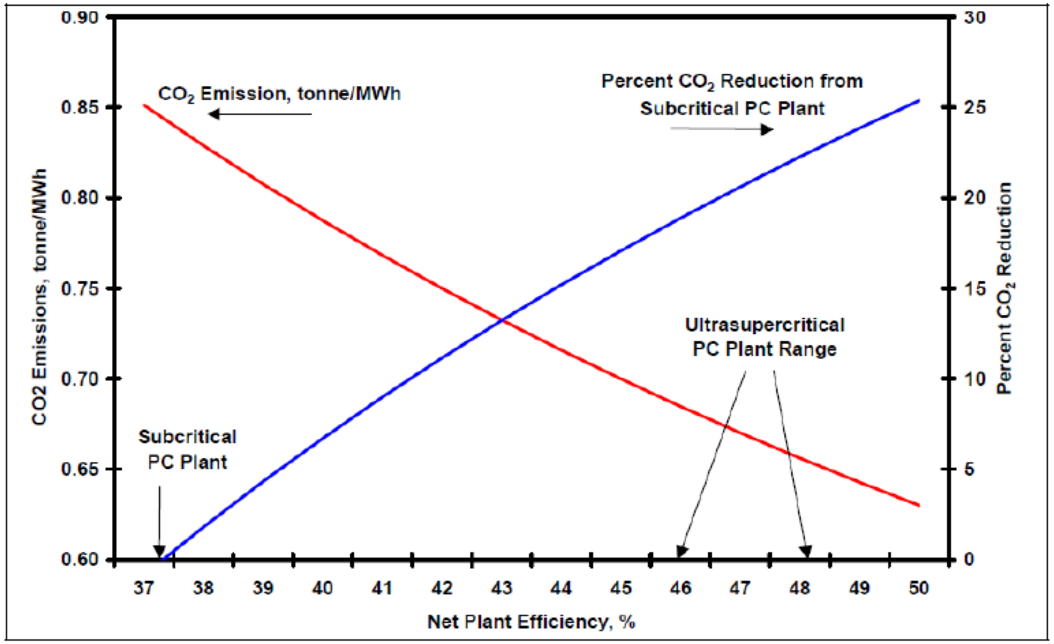
Can't Meet Standards Without Expensive Upgrades

Table 1: Age of U.S. Coal Plants

Years Built	# of Units	Total Capacity (MW)
2005-2009	21	6,785
2000-2004	13	1,382
1995-1999	24	4,372
1990-1994	67	8,638
1985-1989	102	23,734
1980-1984	117	56,105
1975-1979	125	55,879
1970-1974	137	66,466
1965-1969	158	41,656
1960-1964	157	25,310
1955-1959	209	28,883
1950-1954	213	17,518
1940-1949	93	2,583
1930-1939	20	132
1920-1929	10	69
Total	1,466	339,509

Figure 5. Carbon Dioxide Emissions vs. Net Plant Efficiency

Based on Burning Pittsburgh #8 (Bituminous) Coal



Source: Booras, G. and N. Holt, Pulverized Coal and IGCC plant Cost and Performance Estimates, Gasification

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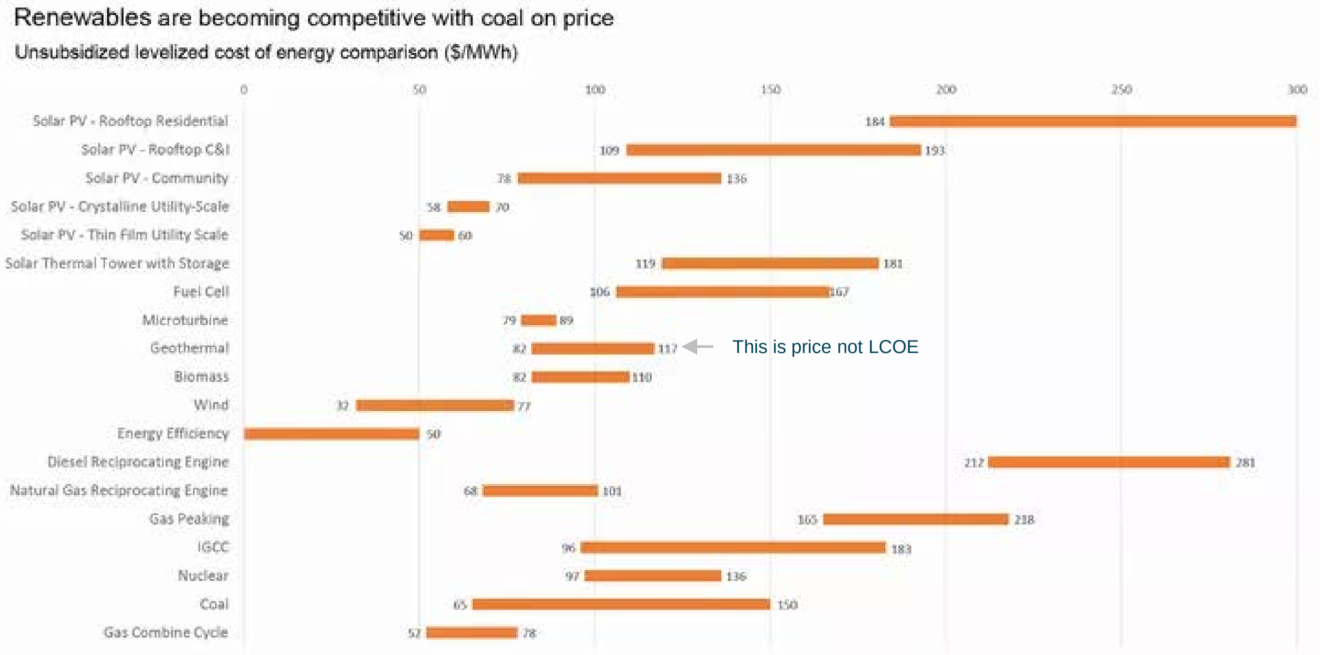
https://www.sourcewatch.org/index.php/Coal_plant_retirements

Renewable Prices are Dropping


Renewables are becoming competitive with coal on price

Unsubsidized levelized cost of energy comparison ($/MWh)

This is price not LCOE

Source: Lazard's Levelized Cost of Energy Analysis Version 9.0

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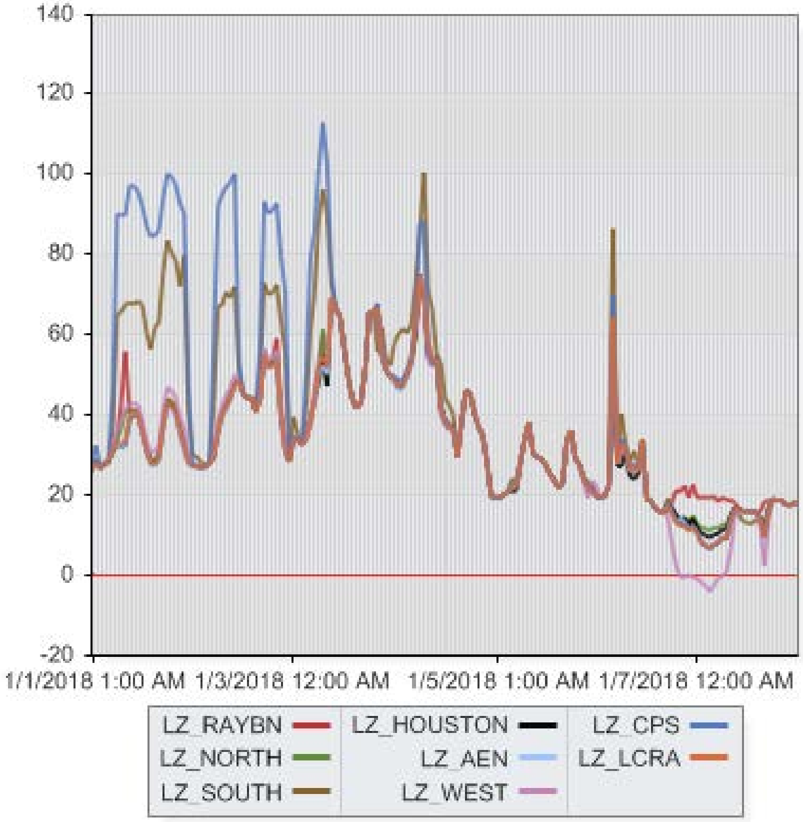
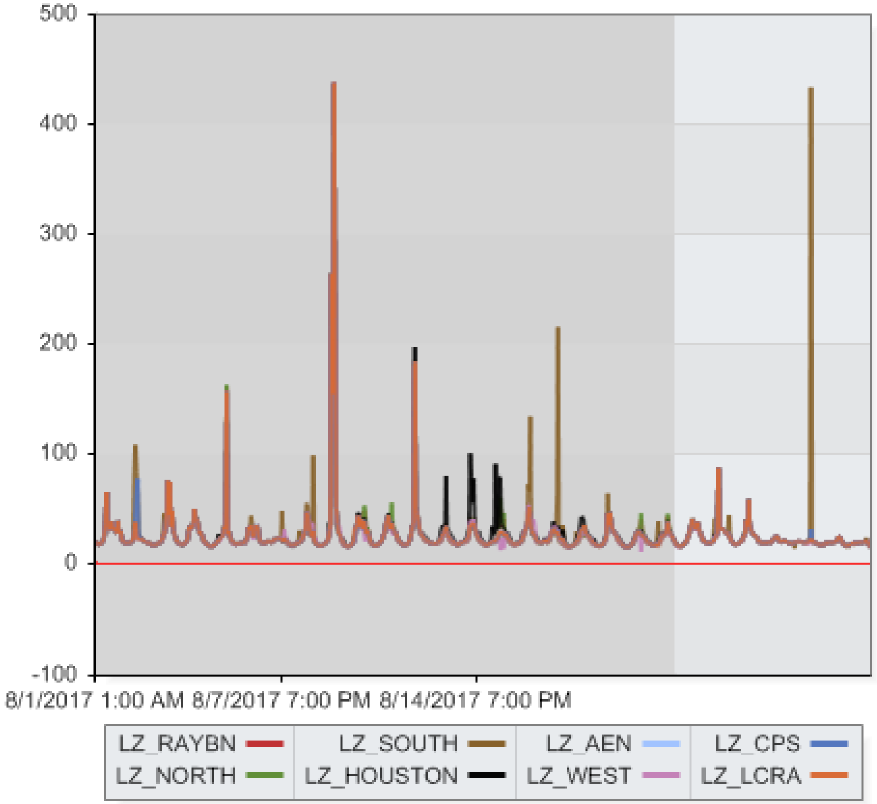
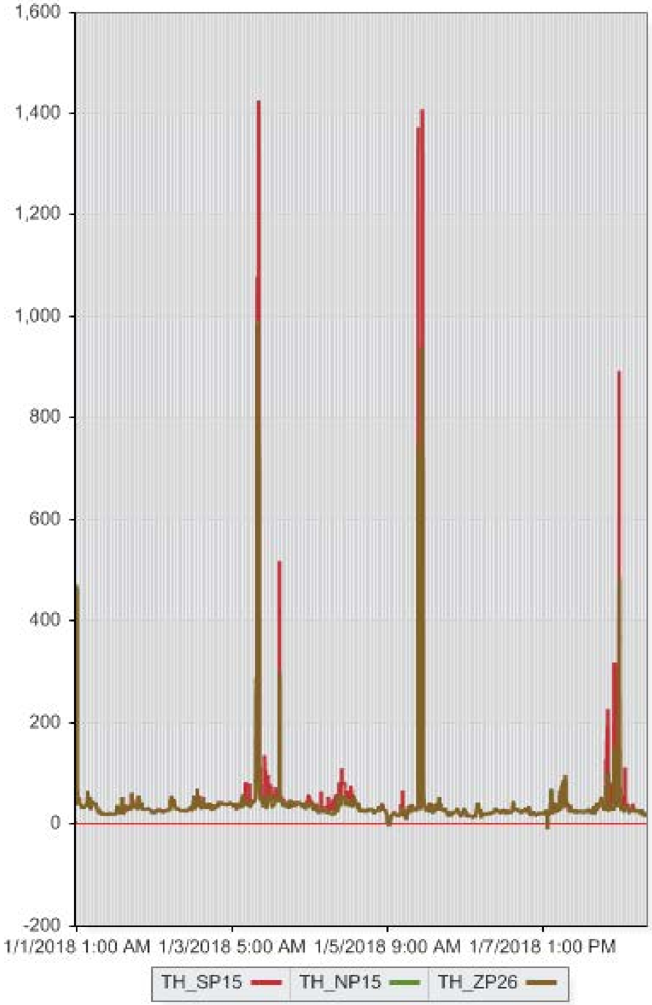
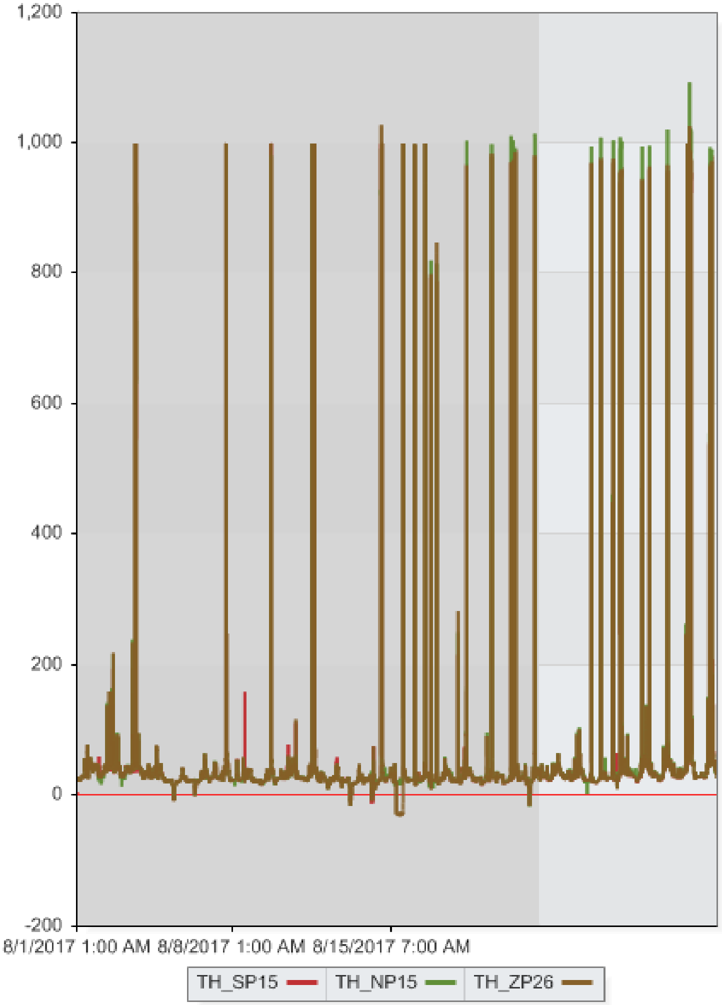
Price Volatility with Increasing Intermittent Renewables: ERCOT





Price Volatility with Increasing Intermittent Renewables: CAISO





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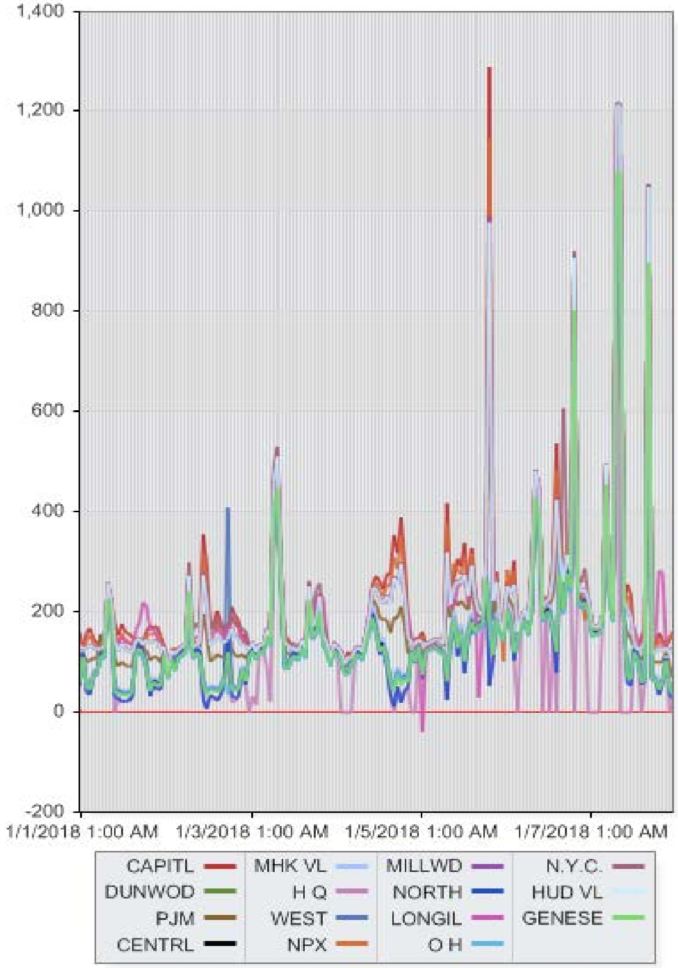
Price Volatility with Increasing Intermittent Renewables: NYISO



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How Can Geothermal Be Part of the Solution?

- Geothermal has no fuel cost
- Operational costs very low
- Baseload power but can provide grid support and load following
- For utility scale projects, capital costs lower than coal
- With EGS technology technically feasible most places.
- We can manage waste water from the coal plant while it continues to operate

Geothermal: The only renewable that can replace coal.

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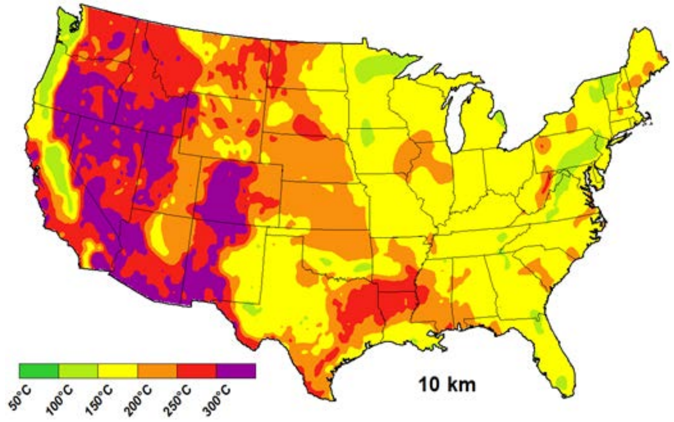
Heat Stored in Rock

200ºC

ΔT=10ºC

1 km^3 Granite



3,490,000 BBL of Oil Equivalent

or

1,360,000 MWh as electricity (155 MWe)

Enhanced Geothermal Systems

What is EGS and how does it does it differ from conventional geothermal

Hydrothermal Systems

- — Natural permeability
- — High flow rates
- — Few big systems
- — Located in Western US
- — Exploration expensive
    - ➢ Must find temperature with permeability
    - ➢ Drilling is needed for exploration
    - ➢ Dry hole rate remains over 30%
- — **<u>Economic even for low temperatures</u>**
    - — 3500 MWe on-line in the US.
    - — >11,500 MWe worldwide
- — ~98% average availability

Enhanced Geothermal Systems (EGS)

- Low or no natural permeability
- Reservoir must be engineered to:
    - – Obtain high flow rates
    - – Develop good heat exchange area
- Exploration risk reduced
- Only Temperature needed
- Drill deeper to get greater temperature for improved efficiency
- Large systems can be developed
- Uses proven state of the art drilling technology
- Fracturing technology developing
- AltaRock technology for multizone stimulation can reduce cost
- Potential for CO2 sequestration

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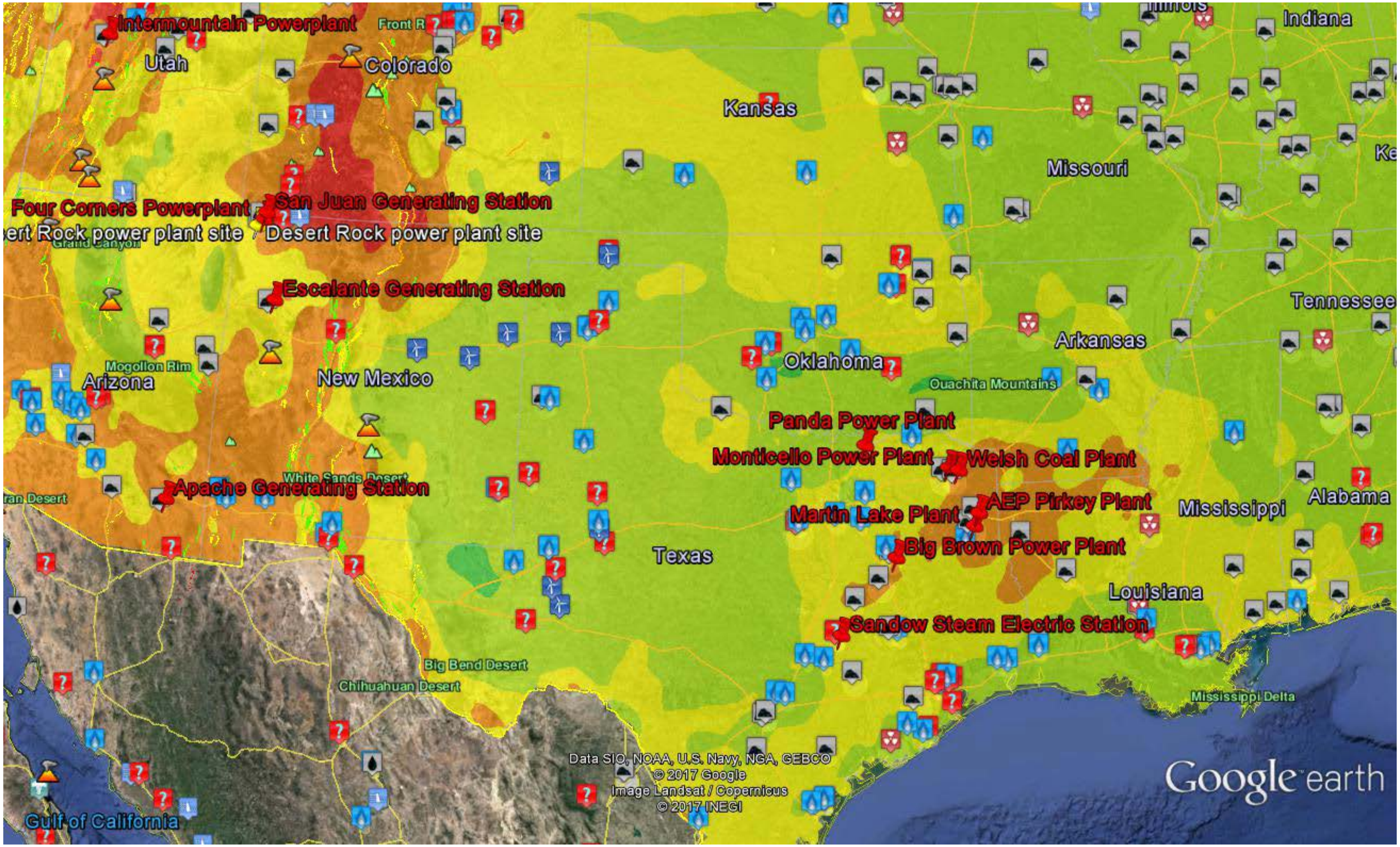
Potential: Coal to Geothermal

- 50,000 MW of aging coal fired generation in the US alone needs to be repowered or shut down because it can't meet current emissions standards
- World wide efforts to reduce coal fired generation. China closing oldest plants. EU closing 10,000 MW over next 5 years. More planned for future.
- *Clean Power Plan (if implemented), state RPS, and COP21 commitments will increase this.*
- *Repowering with natural gas doesn't solve the problem of greenhouse gas emissions and many of these plants need expensive gas pipelines to provide enough supply to repower with gas*
- *Need a Smart Retirement Strategy that maintains jobs, community value and infrastructure to generate new power*
- *Repowering with EGS takes advantage of existing infrastructure, means zero emissions with very low cost to operate and keeps jobs.*

The Southwest



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Southwest Coal Plants

- Planned for Retirement in Texas
  - Big Brown – 2018
  - Sandown – 2018
  - Monticello- 2018
  - Deely-2018

"Sustained low wholesale power prices, an oversupplied renewable generation market, and low natural gas prices, along with other factors."

  - Four Corners, NM – 3 Units closed
  - San Juan Generating Station - 2022
  - Navajo Generating Station, AZ - 2019

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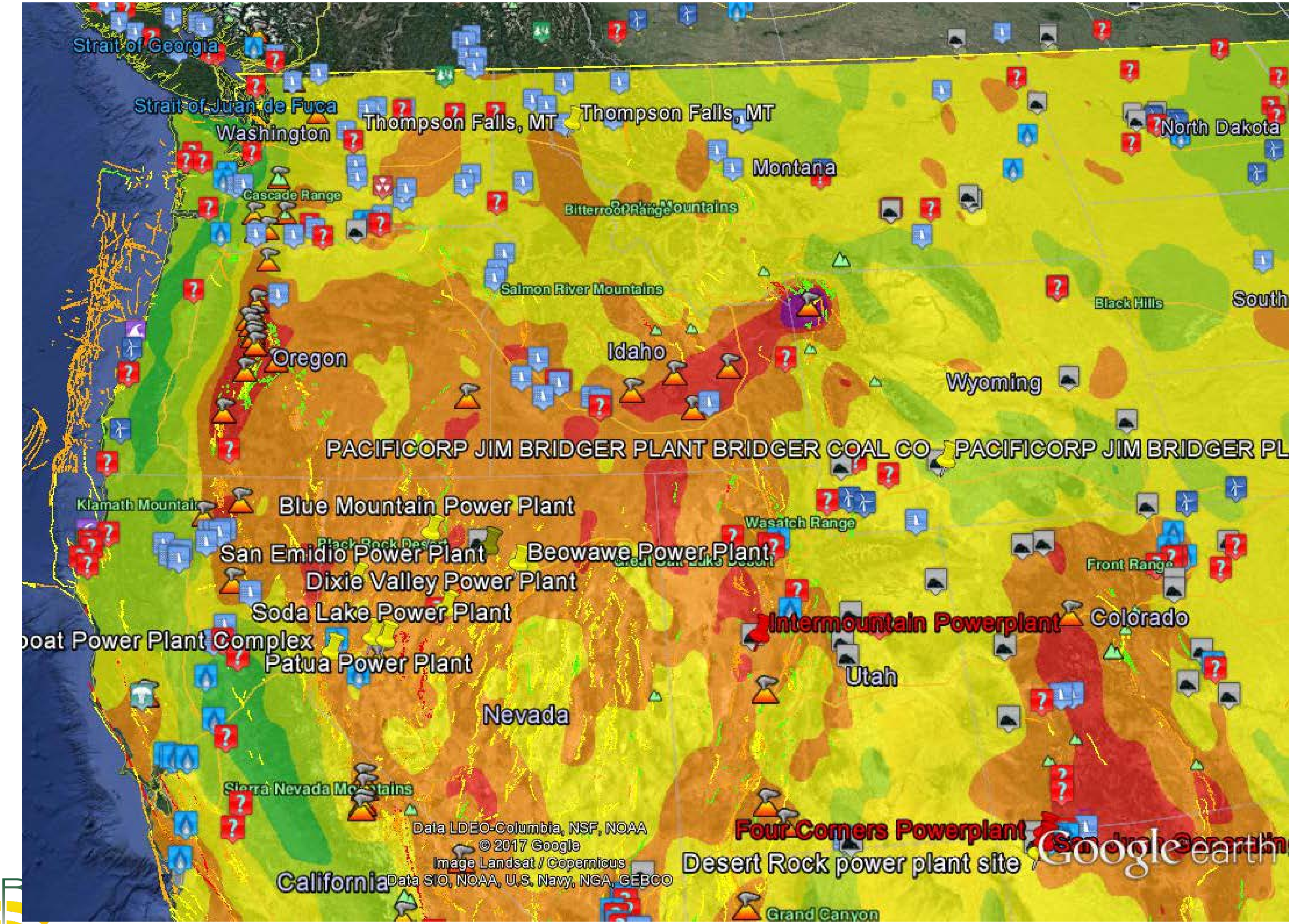
The Pacific Northwest



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Pacific Northwest Coal Plants

- Planned for Retirement
  - Centralia – 2025
  - Boardman – 2020
  - Colstrip Units 1 & 2 - 2020

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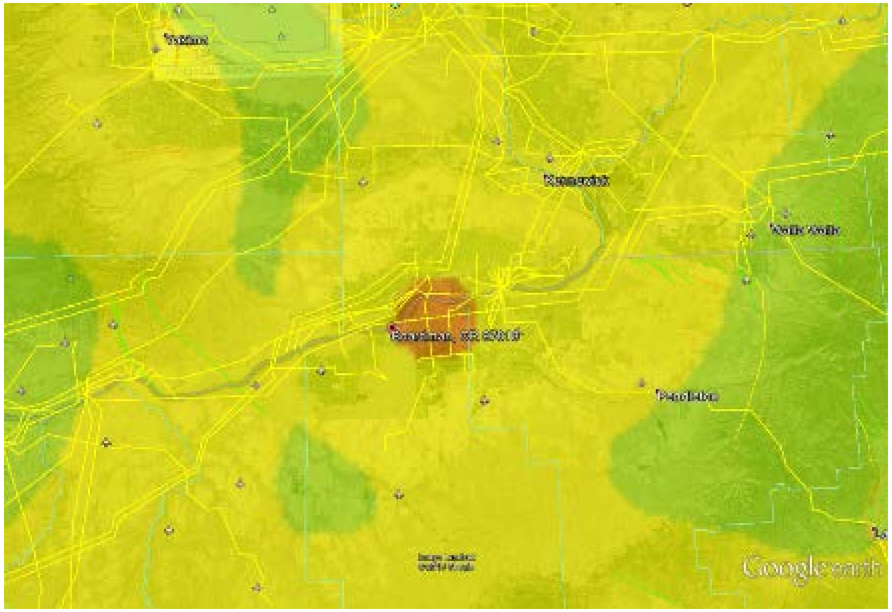
Coal to Geothermal: Boardman

- Area near Boardman plant has elevated temperature gradient – 200C at 5 km.
- Stress regime is favorable for reservoir creation.
- Water for cooling, existing transmission intertie and water for reservoir fill up available on site.
- Natural gas production probable. Could be used to boost water temperature
- Plant scheduled for shut-down 2025. Must be replaced with renewables.
- MOU with PGE in discussion



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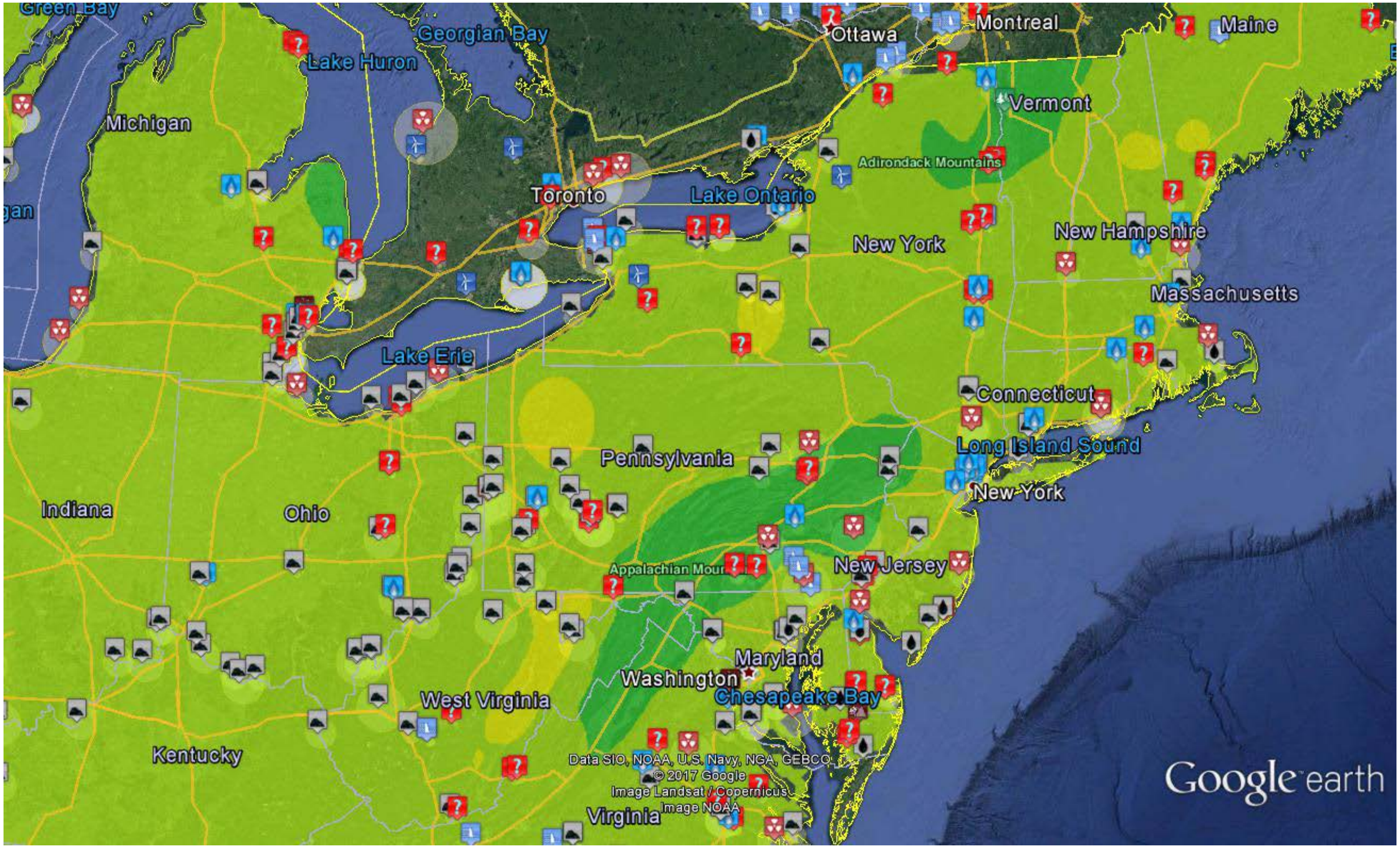
The Northeast



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Northeast Coal Plants

- Planned for Retirement
  - Cayuga, NY – 2019
  - Albright, WV – 2020
  - Kammer, WV - 2020

Natural gas will replace coal plants in PA

- Armstrong – 2017
- Hunlock – 2020
- Mitchell- 2020

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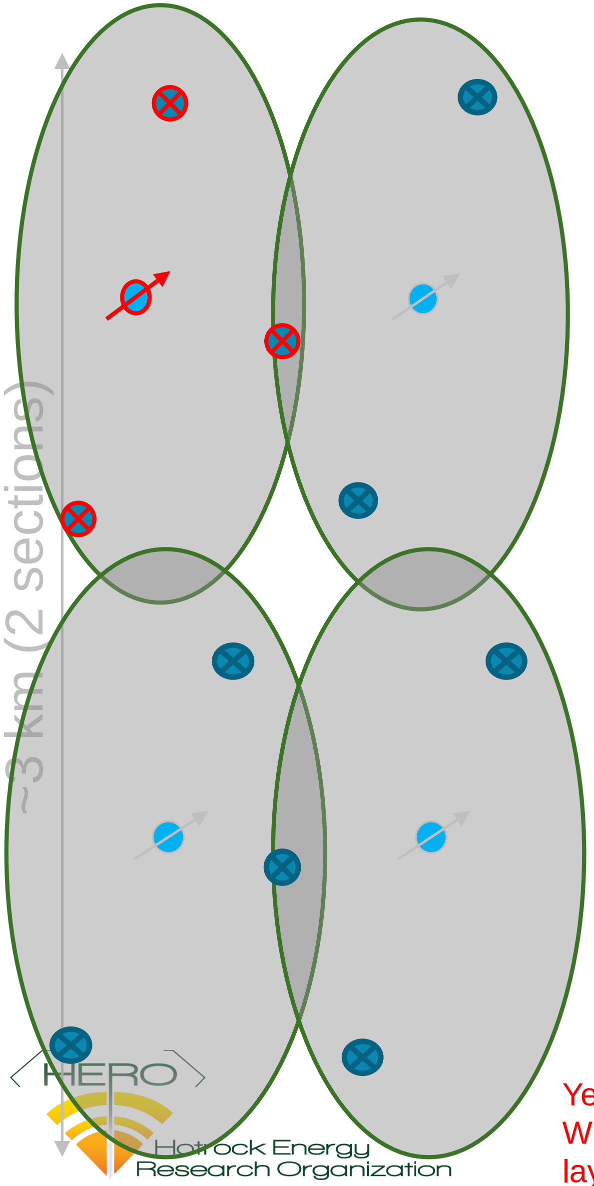
How Would EGS Work at a Typical Site?

- Create EGS reservoirs through cold water stimulation using AltaRock TZIM technology to fill reservoir with stored waste water
- Once EGS reservoir is operating, water loss to rock managed to dispose of all waste water from coal plant
- Reduce coal fired generation as geothermal project expands
- Two options:
  - 2-5 km (8000-16,000 ft) deep wells in Sedimentary Basin
    - Temperature known – 302ºF (150ºC)
    - Binary power plant with wet cooling
    - Water losses to rock higher due to natural permeability in sediments
    - 3-5 MW per well so for 100 MW plant 24 production wells, 18 injection wells
  - 3-7.5 km (10,000-25,000 ft) deep wells in crystalline basement rocks
    - Temperature (>225ºC, 440ºF) projected from shallower wells
    - Better conversion efficiency means more power per well even with lower flow rates
    - Flash plant with evaporative cooling or hybrid flash/binary plant with air cooling
    - Water losses: evaporation in cooling tower and loss to reservoir rock
    - 5-9 MW per well for 100 MW plant need 12 producers, 7 injectors

EGS Project: Moderate Temperature



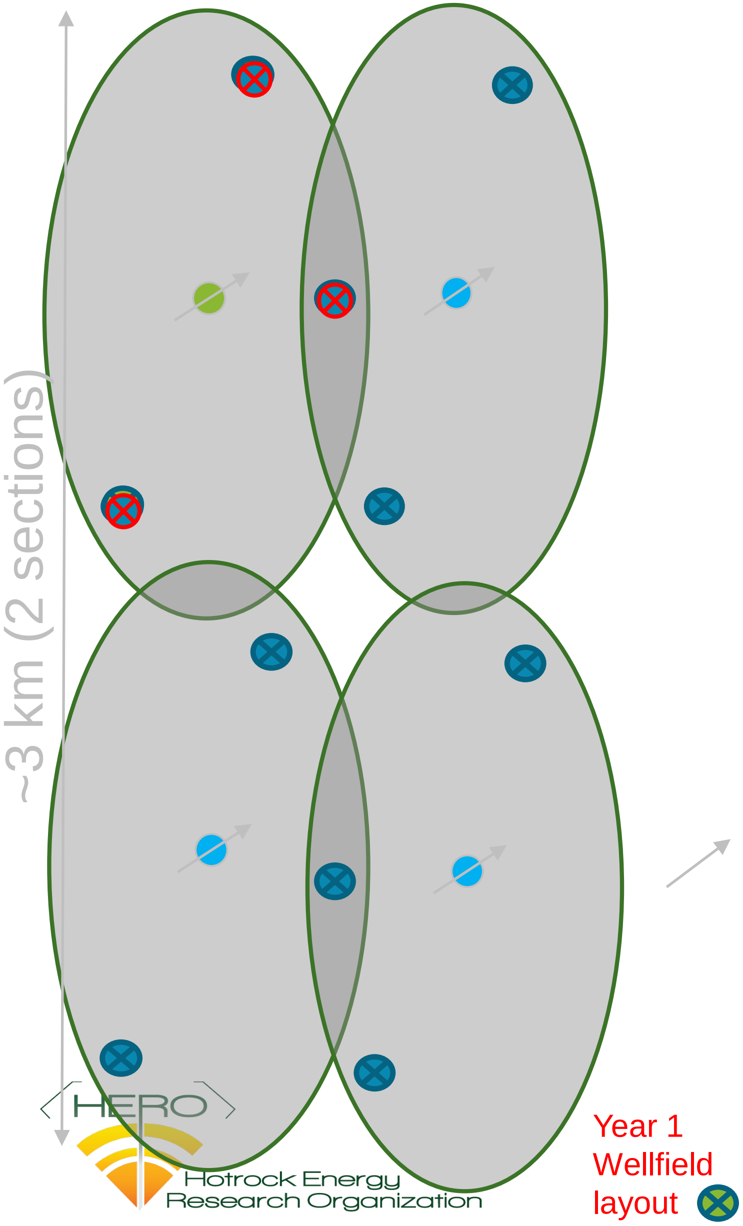
Year 1 Wellfield layout - ⊗

Water use during EGS Reservoir Creation

Year	New Wells	Annual Water Loss from Operations (Mgal)	Annual Water Loss from Stimulation (Mgal)
1	13	344	518
2	12	661	478
3	10	926	398
4	8	1,138	319
5	8	1,349	319
6	6	1,508	239
7	6	1,667	239

- 15,000 ft wells
- 320ºF resource temperature
- Average 3.5-5 MW per producer using TZIM stimulation
- 740 acres can yield 50 MW with little surface disturbance

EGS project – High Temperature



Year 1 Wellfield layout ⊗

Water use during EGS Reservoir Creation

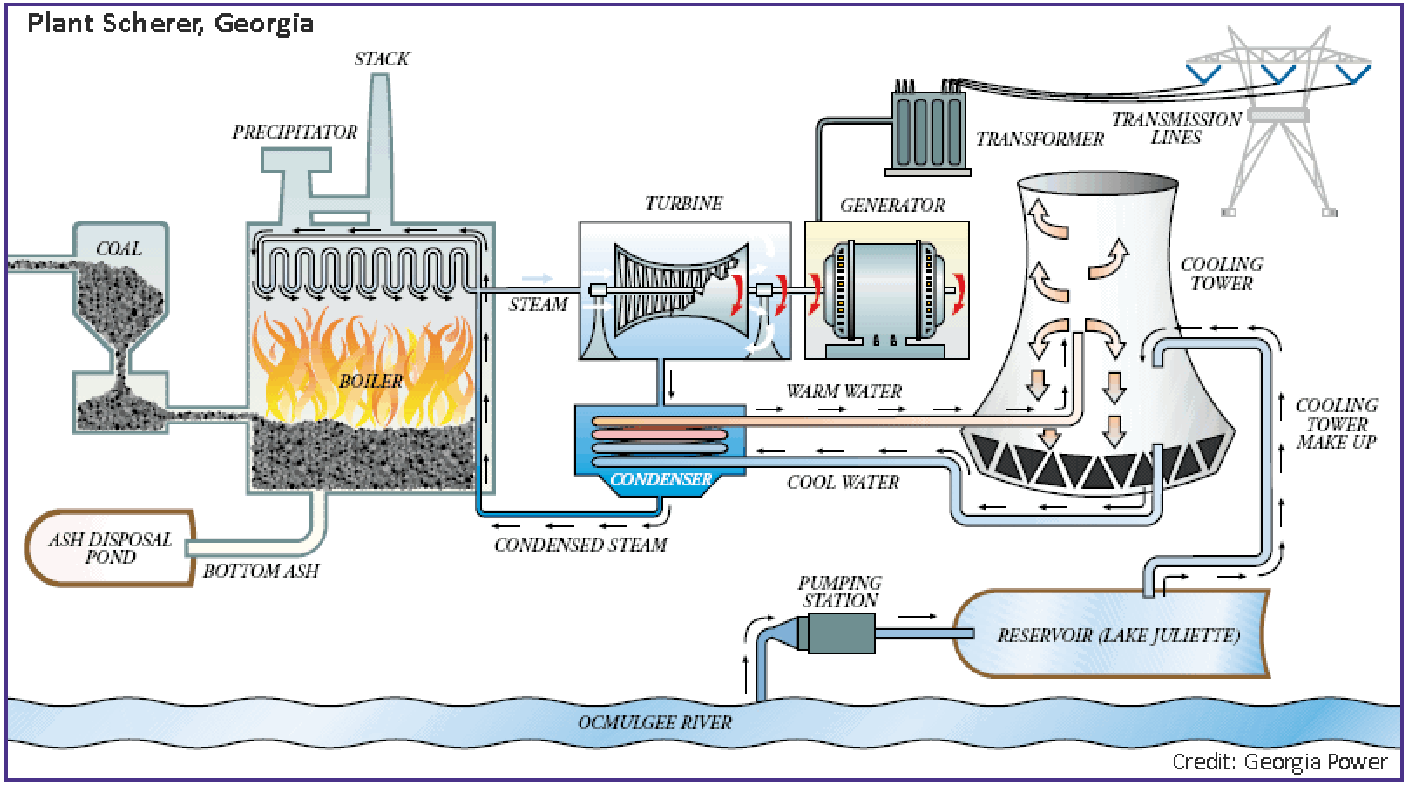
Year	New Wells	Annual Water Loss from Operations (Mgal)	Annual Water Loss from Stimulation (Mgal)
1	12	741	418
2	8	1235	279
3	8	1728	279
4	6	2099	209
5	4	2346	139
6	4	2592	139
7	0	2592	

- 11,150-16,000 ft wells in basement
- 480ºF resource temperature
- Average 6-8 MW per producer using TZIM stimulation
- 740 acres can yield 80 MW

Surface Facilities:

How Do We Generate Electricity with Coal?

How Much of the Coal Plant Can I Use for My Geothermal Project?



Plant Scherer, Georgia

Credit: Georgia Power

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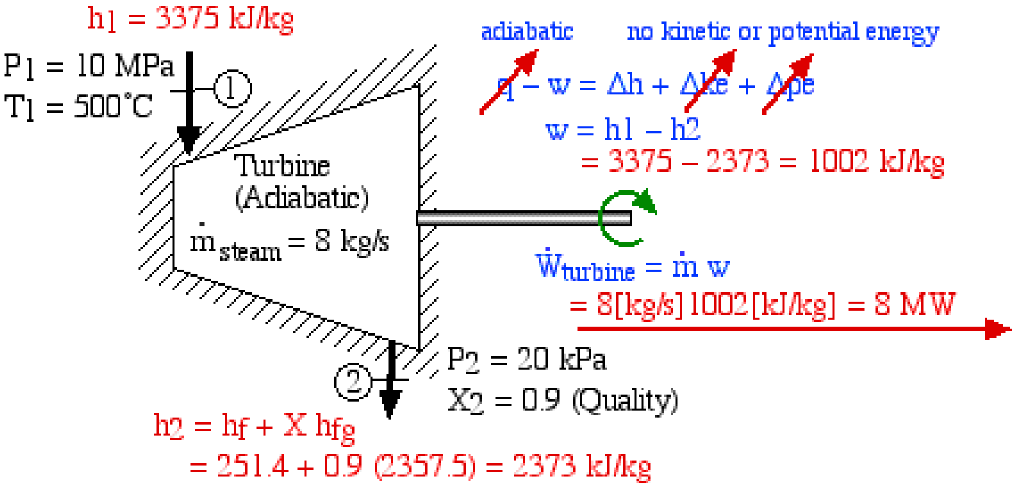
Cycle Efficiency



$h_1 = 3375$ kJ/kg

$P_1 = 10$ MPa

$T_1 = 500^\circ$C

$\dot{m}_{steam} = 8$ kg/s

$\cancel{q} - w = \Delta h + \cancel{\Delta ke} + \cancel{\Delta pe}$

$w = h_1 - h_2$

$= 3375 - 2373 = 1002$ kJ/kg

$\dot{W}_{turbine} = \dot{m}\, w$

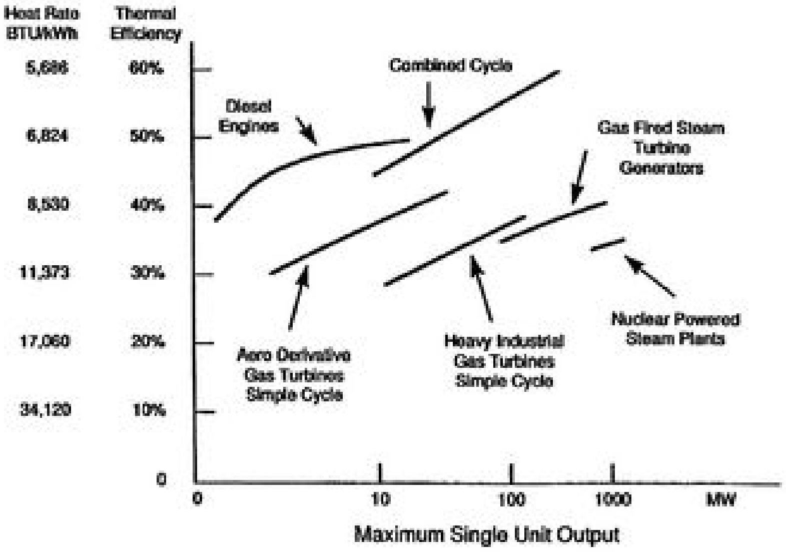
$= 8[\text{kg/s}]\, 1002[\text{kJ/kg}] = 8$ MW

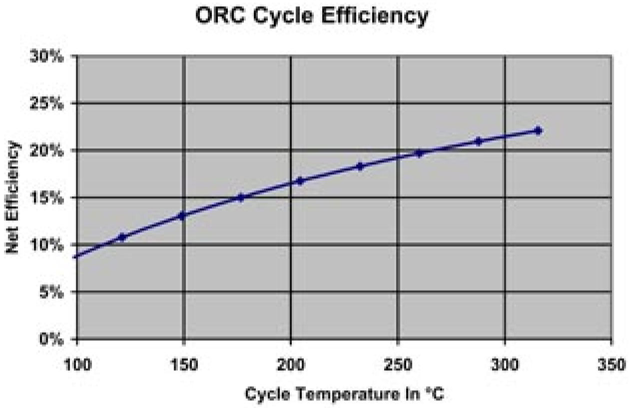
$P_2 = 20$ kPa

$X_2 = 0.9$ (Quality)

$h_2 = h_f + X\, h_{fg}$

$= 251.4 + 0.9\ (2357.5) = 2373$ kJ/kg




ORC Cycle Efficiency

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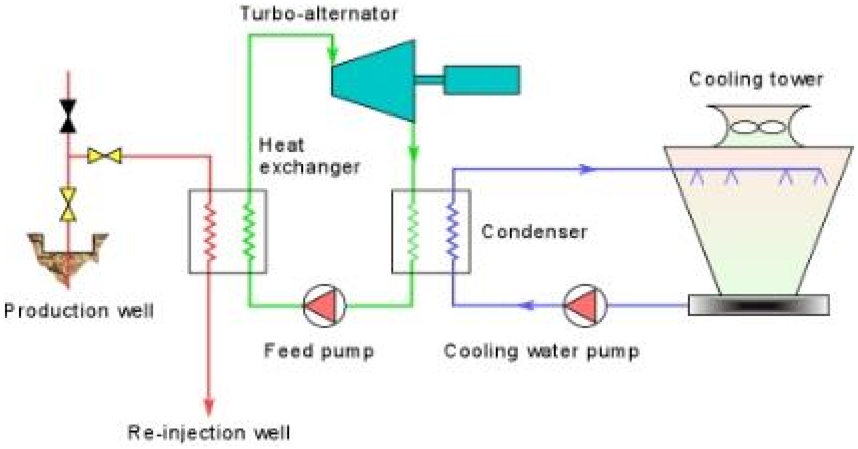
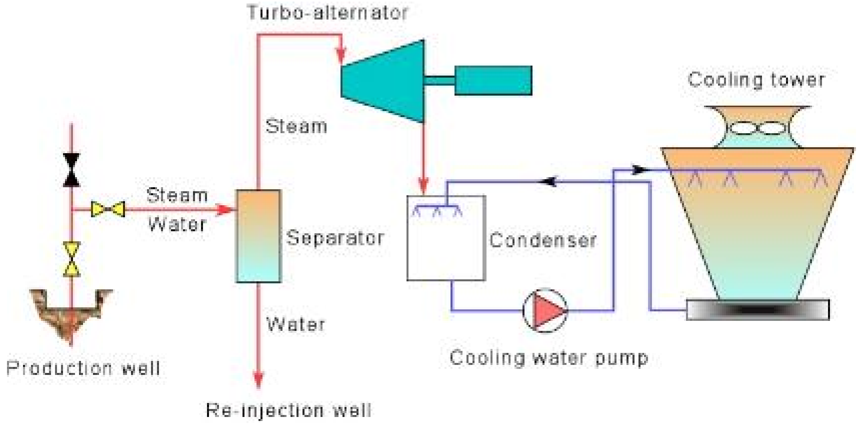
How Do We Generate Power With Geothermal?

Binary Plant



Flash Plant



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Equipment Used in Geothermal Power Generations

- Single flash plants are simple but inefficient
- Multi-stage, HP/IP/LP much better efficiency
- Binary power generation favored in arid areas due to ability to use air cooling
- Most new binary plants used at moderate temperatures from 125C-170C.
- Efficient power generation needed, particularly important for deep, expensive wells used for EGS
- Plants need to adapt easily to changing temperature/pressure conditions

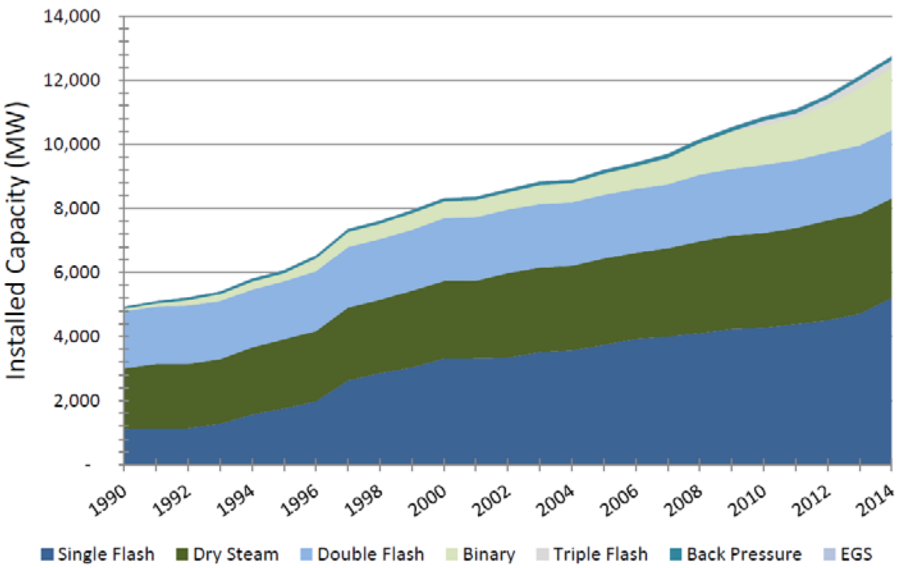
Figure 9: Operating Capacity by Technology Type

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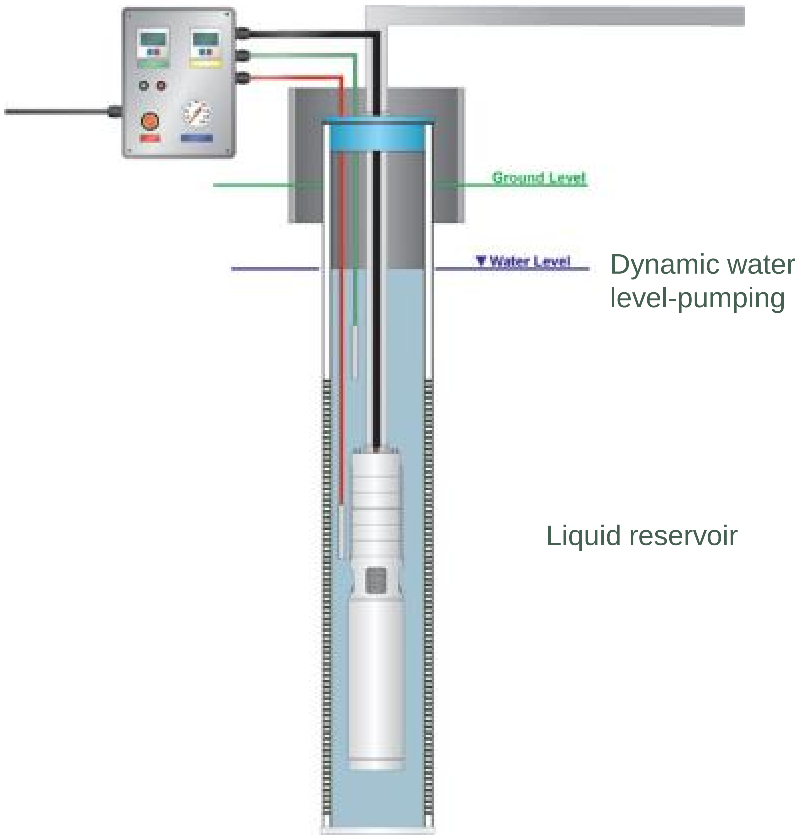
How Do We Produce Geothermal Wells

Moderate Temperature: 125C-170C

- We need REALLY high flow rates
- Wells pumped to binary power plant
- Pumps are general lineshaft, but some ESP
- Net thermal efficiency between 8%-15%
- Very high flow rates needed: 60-120 kg/s

ESP Pumped Well



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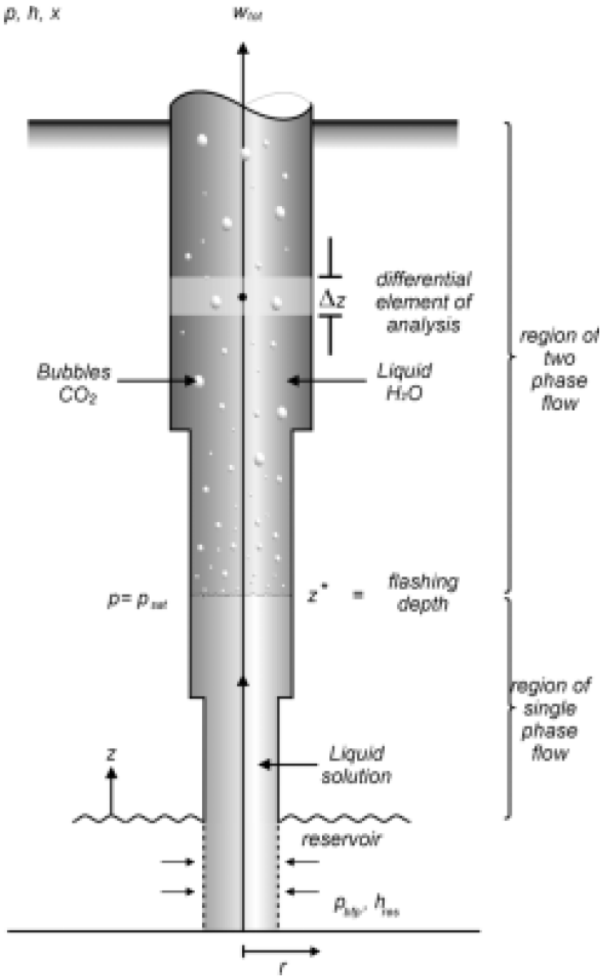
How Do We Produce Geothermal Wells

Well flowed by boiling

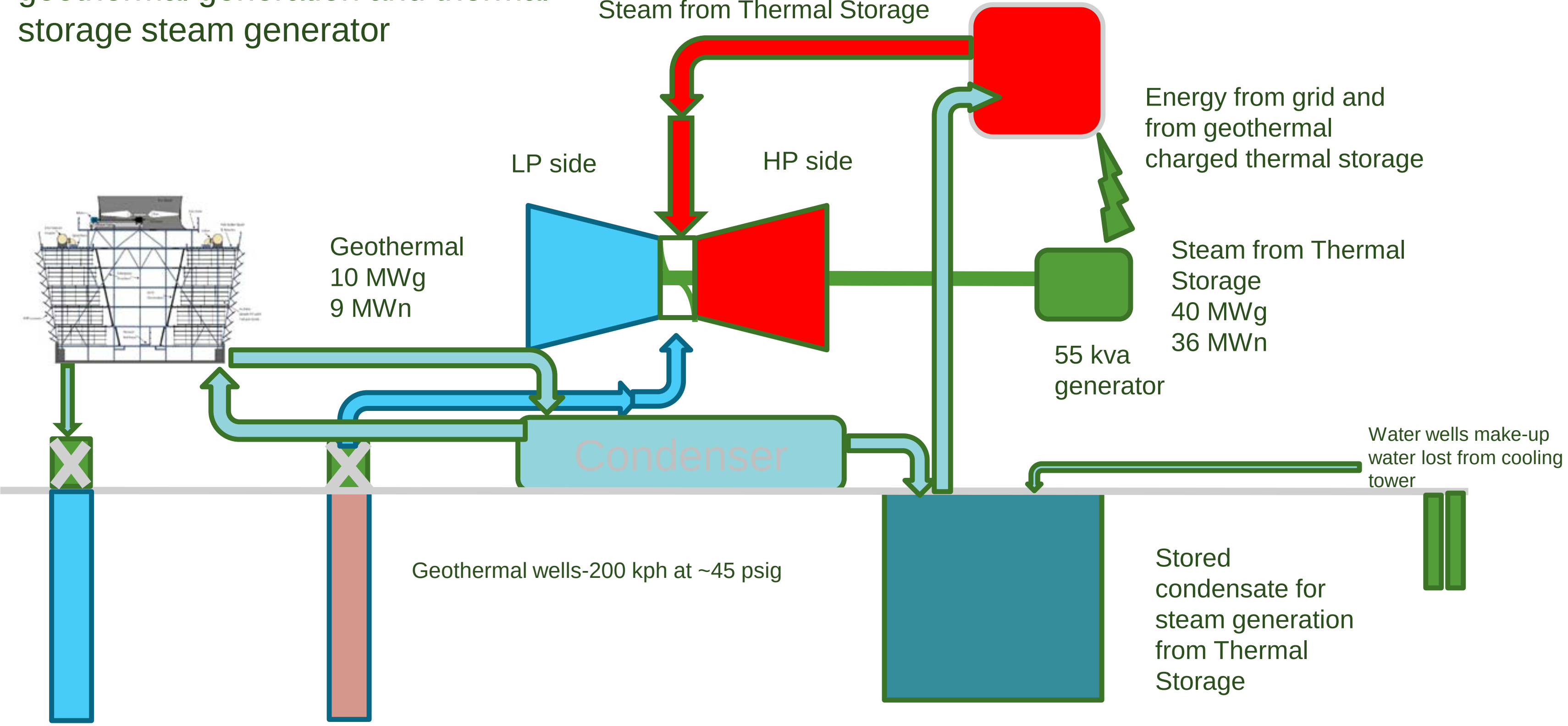


High Temperature: >170C

- Wells pumped between 170C-200C
- Above 200C, no pumps available.
  - Too hot for ESP
  - Deep set depth needed to provide sufficient head over pump, so usually too deep for line shaft pumps
- Wells self flow by density gradient through boiling
- Water and steam reaches surface at saturation temperature for controlled wellhead pressure

Adding Thermal Storage

Thermal energy storage with HP steam discharge - use refurbished used HP/LP steam turbine for both geothermal generation and thermal storage steam generator



Steam from Thermal Storage

Energy from grid and from geothermal charged thermal storage

LP side

HP side

Geothermal
10 MWg
9 MWn

Steam from Thermal Storage
40 MWg
36 MWn

55 kva generator

Condenser

Water wells make-up water lost from cooling tower

Geothermal wells-200 kph at ~45 psig

Stored condensate for steam generation from Thermal Storage

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Western States Coal Plants

Example: NV Energy North Valmy Generating station.

- Valmy plant slated to close between 2019-2025
- High geothermal gradient with ample data.
- Potential for conventional geothermal project as first phase
- Holding residual waste water in holding/evaporation ponds.

Eastern States Coal Plants

Example: Cayuga Power Plant near Lansing, New York.

- Plant is located in one of the best areas for geothermal energy in the east.
- Slated to close in Feb., 2015 but governor stopped closure to preserve jobs/property taxes
- Gas repower would need expensive pipeline the public doesn't want
- Utility wants to build new T-line, shut down the plant and buy power from the market
- Looking for a solution that makes sense.

Estimated Project Water Use

Reservoir stimulation/make-up water

- Water use is one of the most important environmental issues for EGS
- Need about 215-370 acre-feet (70-120 million gallons) of water for initial hydroshearing stimulation per 5-18 MW
- Lose 1-10% of water to rock during operation of field. Pressure controls magnitude of losses
- Can be managed to lose more or less water with production and injection pressures.
- Water can be minimally treated to remove particulates, but dissolved solids are not usually an issue.
- Closed loop operation prevents escape of contaminants into environment

Cooling water make-up

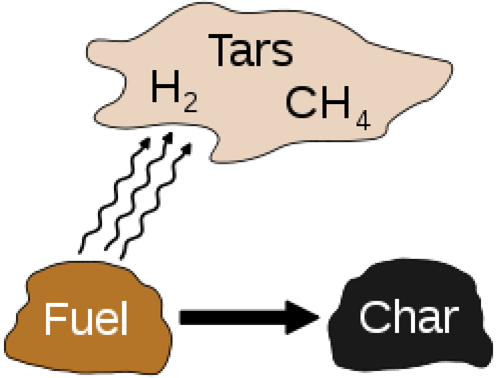
- Need ~400 gpm circulating water per MW
- Lose ~10% to evaporation in evaporative cooling tower
- Binary plants can use dry cooling, but efficiency is reduced
- Overall conversion efficiency has impact on EGS costs
- Hybrid systems possible
- Innovative cooling systems under development
- Water quality for cooling needs is higher than for circulating in the EGS reservoir

Proposed Work:

- Coal Transition Funding from TransAlta for Centralia coal plant
  - Feasibility study with detailed engineering design. Not funded
  - Re-propose as combined biomass/geothermal project with TSI?
  - Washington State Clean Energy Fund supplement to Coal Transition Funding for Centralia
  - Total $1.8M for lead up to pilot project. Request $1.3M from Centralia fund
  - $500k to supplement drilling on ARE lands leased from Weyerhauser
- Pilot project at Centralia, Boardman or Colstrip
  - Total $30M pilot plant - $10M-$15M from Transalta.
  - Need $15M from HERO through foundation funding or impact investment
- Cornell University: Deep Earth Resource EGS projec
  - HERO performs feasibility study
  - AltaRock provides EGS technology
- R&D
  - Flow test at Newberry
  - Drilling at Mt. St. Helens through Play Fairway/WA Clean
  - Seismic calibration and passive seismic monitoring

Centralia Biomass/Geothermal Hybrid

- Proposal to Coal Transition Grant Fund not accepted
- Reapply with Emphasis on maintaining jobs favors biomass and natural gas
- TSI, Inc. in Lynnwood- Torrefaction method that can produce wood waste biomass that can be directly used in coal plant
- Combined with geothermal could reduce energy requirements for biomass drying
- Produce power from geothermal and dry biomass from wood waste
- Need to understand:
  - Biomass supply
  - Geothermal project costs
  - Worker training for biomass operation
  - Schedule for transition
  - Demand for baseload power



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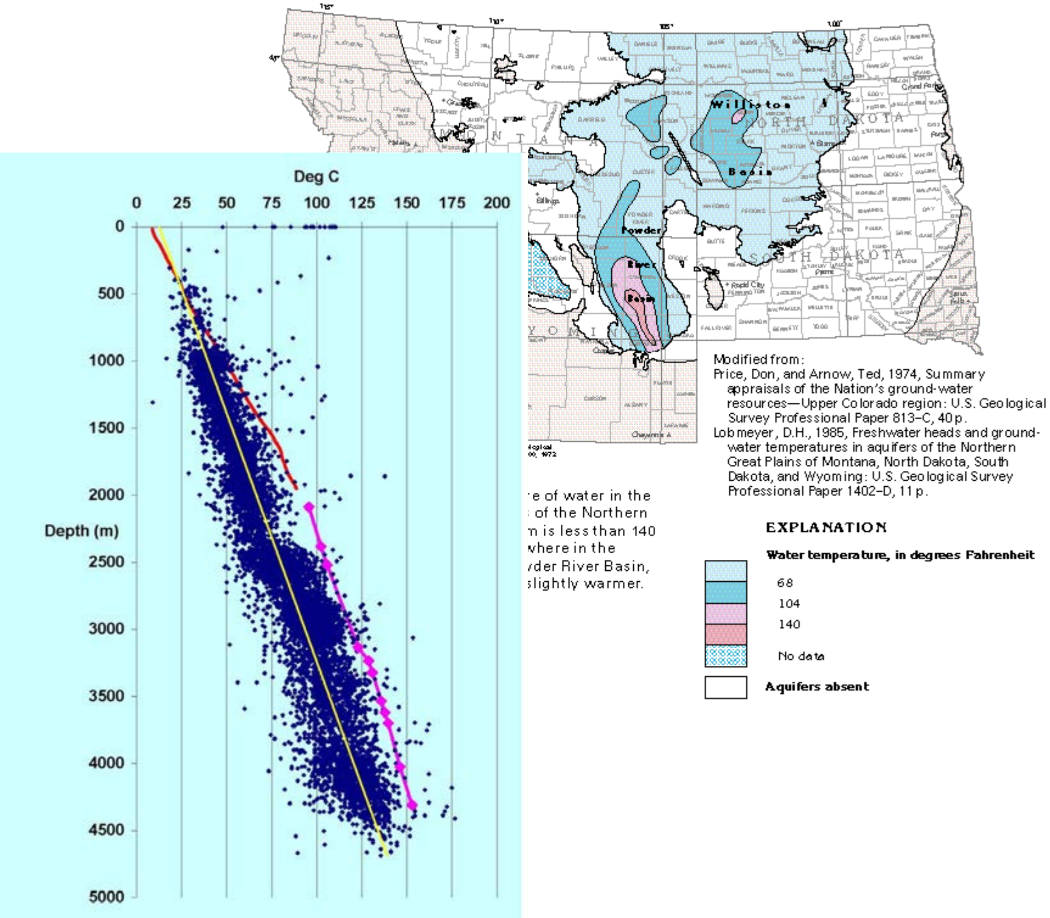
Colstrip in Central Montana: High Temperature Gradients

- Deep sedimentary basins with ample data from oil wells
- Williston Basin oil wells have demonstrated elevated temperatures with depth
- Best sites for deep hot water
- Coal fired power plants across the area
- Temperature gradients above 45ºC/km
- Deep disposal well drilled for Colstrip plant found good temperatures for EGS geothermal
- Waste water disposal an issue



e of water in the
of the Northern
n is less than 140
vhere in the
der River Basin,
slightly warmer.

Modified from:
Price, Don, and Arnow, Ted, 1974, Summary appraisals of the Nation's ground-water resources—Upper Colorado region: U.S. Geological Survey Professional Paper 813–C, 40 p.
Lobmeyer, D.H., 1985, Freshwater heads and ground-water temperatures in aquifers of the Northern Great Plains of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–D, 11 p.

Steps To Transition of Coal to Geothermal:

Phased approach reduces risk. Transitions jobs

- Phase 1 – Detailed engineering feasibility study
  - Site assessment – geologic, geophysical, seismic temperature and project data evaluation using existing data.
  - Gap analysis with plan for collecting additional data including core hole and additional geophysics
  - Environmental and regulatory compliance assessment
  - Public outreach – webinars, public meetings and conference to educate stakeholders
  - Drill deep core-hole to acquire data on temperature with depth, rock stresses, rock type and drilling conditions
  - Detailed engineering study including well design, stimulation design and cost analysis.
  - Economic analysis including power markets and financing potential

- Phase 2 – Demonstration project
  - Obtain project financing
  - Permitting and regulatory compliance
  - Modify temporary seismic array as indicated from Phase 1 studies.
  - Modify project plan using data.
  - Drill 1 injector and up to three producers and create a stimulated reservoir for small scale power project as demonstration.
  - Construct demonstration power plant
  - Operate facility while designing expansion project
- **Go/No-go decision on Full Scale Expansion**
- Phase 3 – Expansion to utility scale project
  - Obtain project financing
  - Permitting and regulatory compliance
  - Determine from Phase 2 project data the potential for total development of project site
  - Adjust plan using Phase 1 data to optimize project economics
  - Run multiple rigs to drill project wells
  - Stimulate wells
  - Construct full scale power plant

Pilot Project Proposal

Goal: Develop a pilot project at Boardman using EGS technology at Boardman

Phase I	Preparatory Phase		Pre
	Task 1.1	Project management	$ 97,120
	Task 1.2	Public outreach	$ 31,536
	Task 1.3	Data collection, review and assessment (e.g., PNNL BWIP data)(Gap analysis)	$ 52,480
	Task 1.4	Geophysical analysis and conceptual modeling: gravity, MT, and/or passive seismic (basement depth??)	$ 181,200
	Task 1.5	Permitting, regulatory and compliance matrix	$ 34,200
	Task 1.6	Permit fees and well drilling bonds	$ 123,000
	Task 1.7	Induced seismicity risk assessment - assuming stimulation	$ 64,280
	Task 1.8	Exploration plan design and drilling plan	$ 194,400
	Task 1.9	Initial economic analysis (including natural gas potential)	$ 143,152
	Task 1.10	Fundraising/financing for demo project	$ 50,528
	Task 1.11	Reporting and presentations , include recommendations and Phase II budget	$ 25,636
	Go/No-Go decision point - Proceed to Phase II		

Deliverable: Cost & Risk Analysis Report with preliminary engineering design

- Go/No-Go Decision: Is development at Boardman feasible?

If Go, continue to Phase 2: Drill and Stimulate First Well

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Decisions From Phase 1

- Target depth
- Likely lithology at target (sediments or basement?)
- Fluid pressure – overpressures >5000 psi possible
- Porosity & permeability at target
- Well design (bit & casing sizes)
- Drilling cost
- Preliminary pilot plant design and cost
- Preliminary economic analysis
- Resource potential of Boardman site
- Natural gas production possible?
- Permitting and regulatory compliance matrix and permitting for first well

Reducing the natural gas risk with geothermal (and geopressure)
Reducing the geothermal risk with natural gas.

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Phase 2 – Drill/Stimulate 1st Well

Phase II	**Drill and Stimulate Exploration/Production Well**		**$ 11,846,431**
	Task 2.1	Project management	$ 130,920
	Task 2.2	Public outreach	$ 40,632
	Task 2.3	Permitting, installation, and monitoring of MSA	$ 282,800
	Task 2.4	Wellfield and reservoir creation design and engineering and planning	$ 418,920
	Task 2.5	Drill 15,000 - 17,000 deep exploration/production well	$ 8,700,022
	Task 2.6	Well logging and completion	$ 258,144
	Task 2.7	Well stimulation including microseismic fracture mapping	$ 1,282,182
	Task 2.8	Well testing	$ 119,462
	Task 2.9	Second (injection) well design based on results	$ 87,360
	Task 2.10	Pilot plant preliminary design and permitting	$ 473,200
	Task 2.11	Updated economic analysis of Boardman	$ 52,788
	Go/No-Go decision point - Proceed to Phase III		

Deliverable: First EGS well with testing. Costing update. Final plan for second well.

- Go/No-Go Decision: Drill second well?

If Go, continue to Phase 3: Drill and Stimulate Second Well

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Decisions From Phase 2

- Design of second well
- Preliminary power plant design
- Updated economics
- Permitting and regulatory compliance update

Reducing the natural gas risk with geothermal (and geopressure)
Reducing the geothermal risk with natural gas.

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Phase 3 – Drill/Stimulate 2nd Well

Phase III	**Drill and Stimulate Second (Injection) Well**		**$ 13,658,630**
	Task 3.1	Project management	$ 181,248
	Task 3.2	Public outreach	$ 32,640
	Task 3.3	Stimulation plan design based on results	$ 256,572
	Task 3.4	Pilot power plant design completion and permitting	$ 131,712
	Task 3.5	Drill second well (low scenario)	$ 6,363,616
	Task 3.6	Drill second well (added for high scenario)	$ 4,218,712
	Task 3.7	Stimulate second well	$ 956,243
	Task 3.8	Post stimulation well testing	$ 267,846
	Task 3.9	Preliminary power plant design and engineering, transmission and interconnection design	$ 1,161,600
	Task 3.10	Update project economics and risk analysis	$ 39,737
	Task 3.11	Reporting and presentations	$ 48,704
	Go/No-Go decision point - Proceed to Phase IV		

Deliverable: Second EGS well with circulation testing. Power plant design and construction plan. Final permitting for pilot plant.

- Go/No-Go Decision: Construct pilot plant?

If Go, continue to Phase 4: Construct pilot plant

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Decisions From Phase 3

- Final pilot plant design with engineering and risk analysis update
- Updated economics
- Permitting and regulatory compliance update
- Final resource assessment for utility scale power potential

Reducing the natural gas risk with geothermal (and geopressure)
Reducing the geothermal risk with natural gas.

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Phase 4 – Construct Pilot Plant

Phase IV	**Pilot Power Plant Construction**		**$ 13,162,544**
	Task 4.1	Project management	$ 578,048
	Task 4.2	Public outreach	$ 20,000
	Task 4.3	Regulatory compliance and permitting - including EFSC operating permit modification	$ 69,680
	Task 4.4	Final facility layout, design & cost estimate	$ 571,620
	Task 4.5	Transmission interconnection planning	$ 34,256
	Task 4.6	Detailed design procurement	$ 311,040
	Task 4.7	Major equipment manufacturing	$ 8,603,424
	Task 4.8	Pilot plant construction and commissioning	$ 2,912,512
	Task 4.9	Start-up operation	$ 13,168
	Task 4.10	Financing plan for utility scale project	$ 16,754
	Task 4.11	Reporting and presentations	$ 32,043
	Go/No-Go decision point - Expand to utility scale project		

Deliverable: Operating pilot plant. Plan for utility scale project. Operating report.

- Go/No-Go Decision: Plan for utility scale project?

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Boardman Summary and Questions

What Will We Find

- Underlain by thick layer of Columbia River Basalt
- Geothermal resource is most likely sandstone, with stored hot water
- Natural gas may be by-product of water production

What Do We Need to Find

- Would well stimulation be able to develop sufficient production/injection?
- Is the land position at Boardman large enough to expand to utility scale using EGS technology?
- Could the Boardman site be developed along with another site such as Newberry to provide the demand supplied now by the coal plant?

How Do We Work Together?

- HERO, AltaRock Energy, GE Global Research, Blade Energy Partners, Portland General Electric
- Joint Venture
- Build/Operate/Transfer
- HERO can assist with pilot plant financing
- AltaRock can provide project development experience
- Blade Energy can provide drilling technology and large scale resource project experience
- GE Global Research can provide power plant innovative design for pilot plant

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Questions for PGE

- How much baseload power at Boardman needs to be replaced?
- What is the value of load-following?
  - Geothermal plants can load follow but can’t be turned on and off
  - Blue Mountain ramps at about 6 MW/min
  - Summer decrease in output can be mitigated with solar thermal.
  - Thermal storage is possible in EGS projects
- What is the timeline for power replacement?
- How much replacement can come from conservation? Intermittent resources like wind and solar?

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Development Scenario

Year	Rigs	New Wells	Total Wells Prod/Inj	MWe
2016-17	1	2	1 / 1	3+ (Pilot plant)
2018	3	12	9/3	25 (1st unit)
2019	4	18	24 / 6	60 (units 2-3)
2020	3	12	33 / 9	100 (units 4-5)

Assumptions
4-5 wells per rig per year
3-4 producers per injector
3-5 MWnet per producer

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Boardman Geothermal Potential

APPENDIX A

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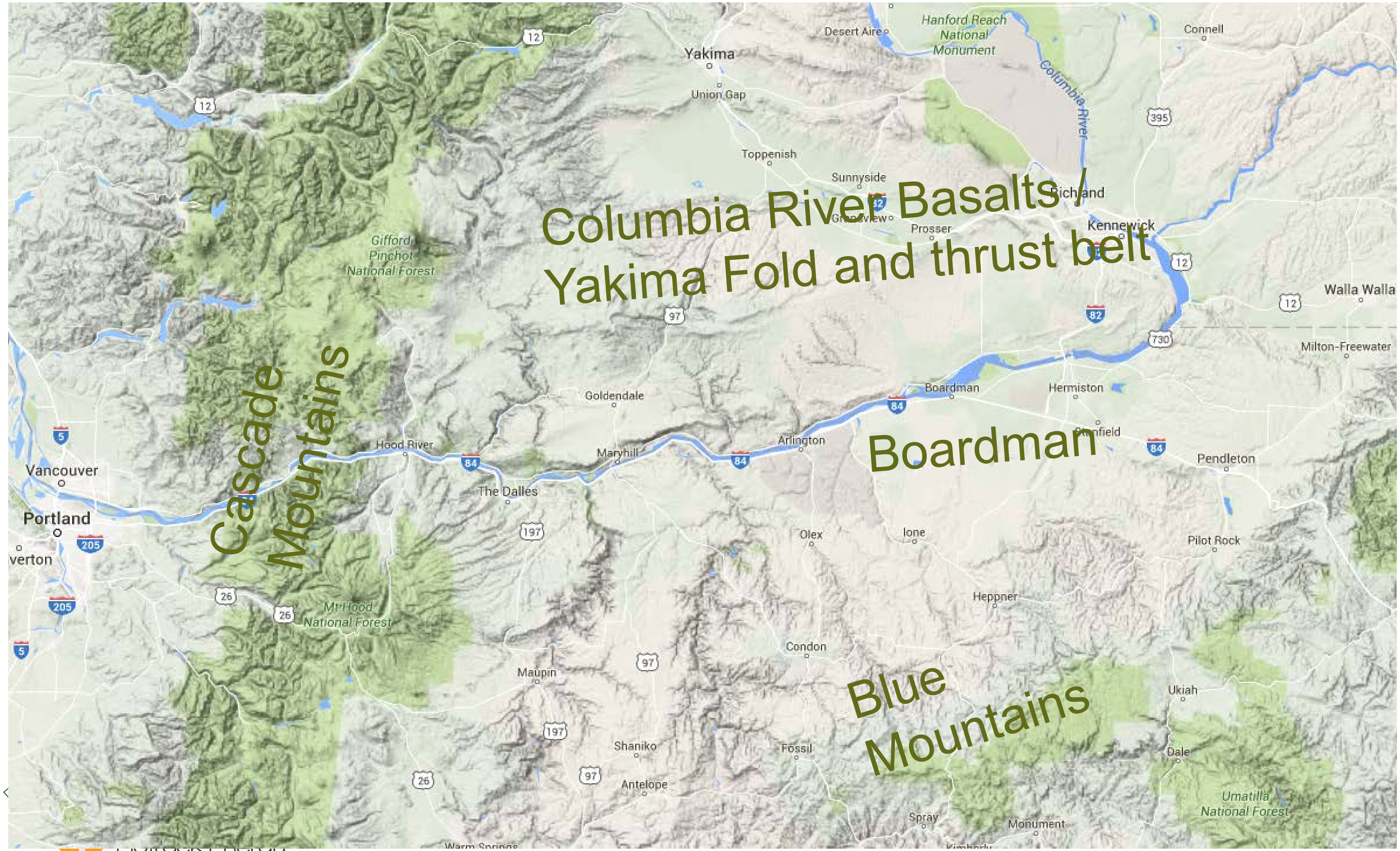
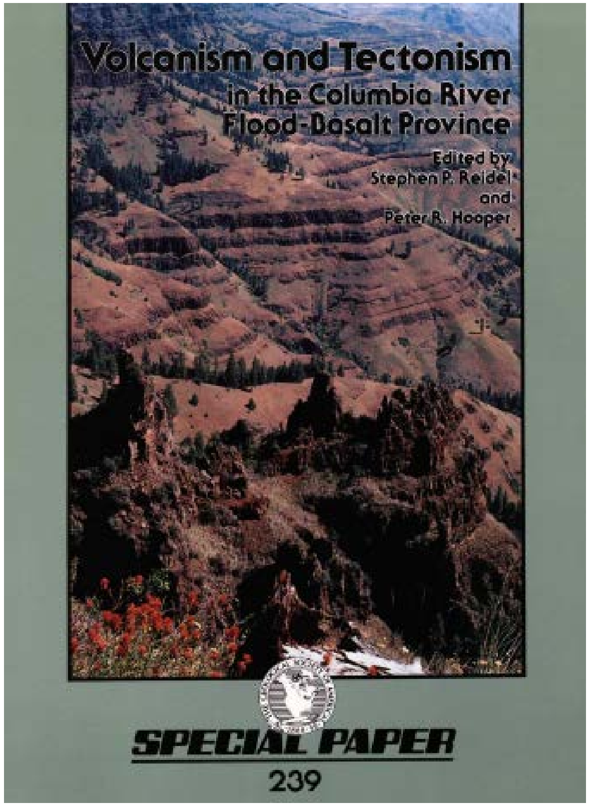
Boardman: Tectonic Setting



Past studies

- Columbia River Flood Basalt Province Special Paper (1989)
- USGS Report on Gas Potential (2006)
  - 5,000 – 10,000 ft of sediments (source and reservoir)
  - Overlain by 4,000 – 13,800ft of Columbia River Basalt
  - Rattlesnake Hills gas field (1.3 BCFG, 1930-1941)



Volcanism and Tectonism in the Columbia River Flood-Basalt Province

Edited by
Stephen P. Reidel
and
Peter R. Hooper

SPECIAL PAPER
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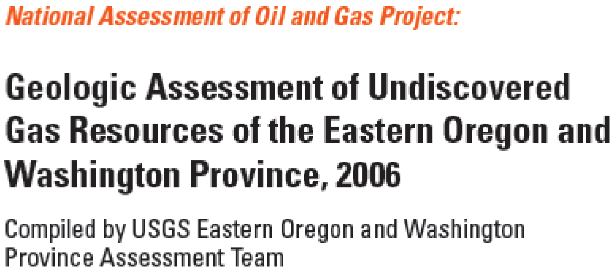

National Assessment of Oil and Gas Project:

Geologic Assessment of Undiscovered Gas Resources of the Eastern Oregon and Washington Province, 2006

Compiled by USGS Eastern Oregon and Washington Province Assessment Team

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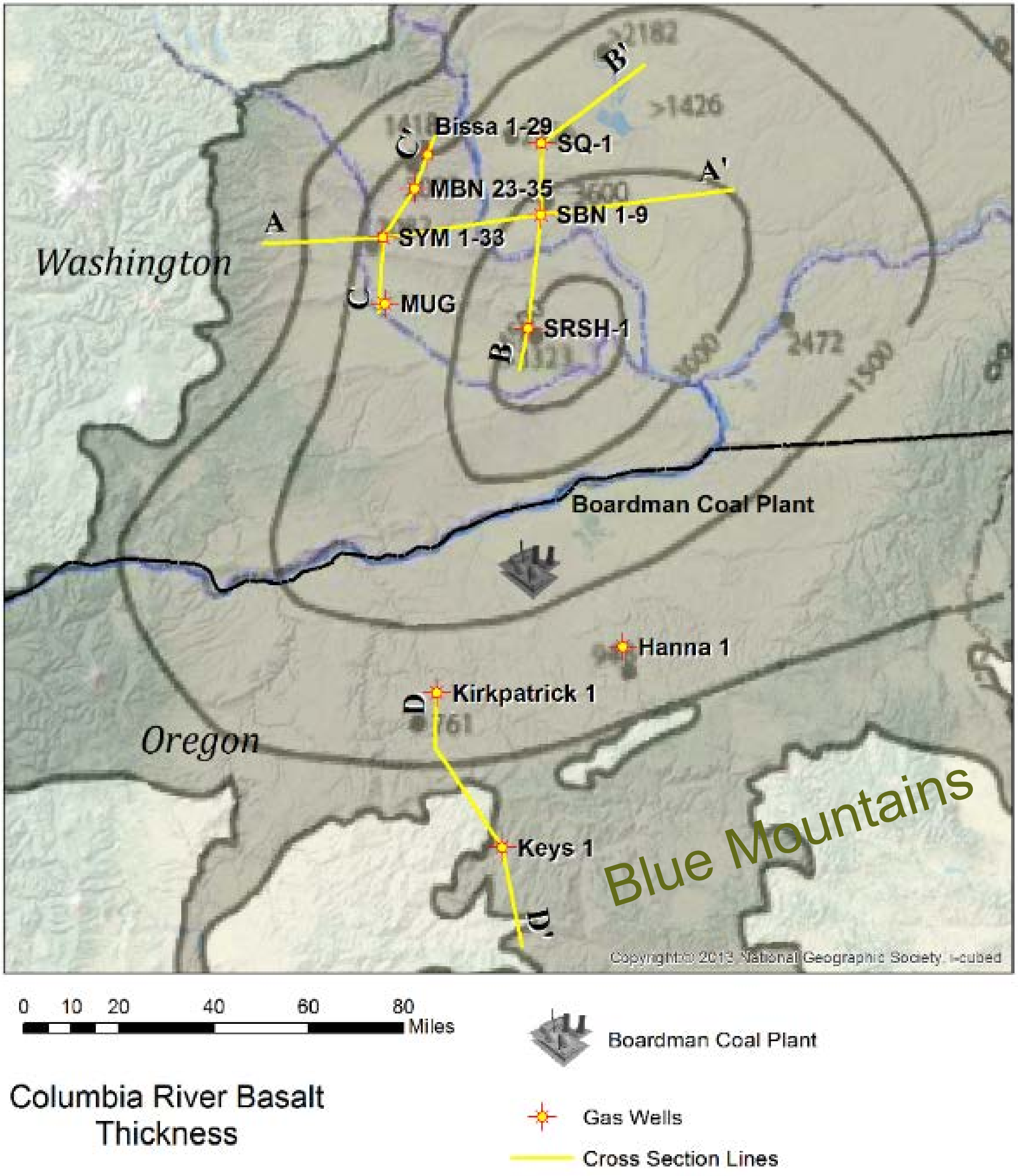
Regional Deep Wells



Columbia River Basalt Thickness

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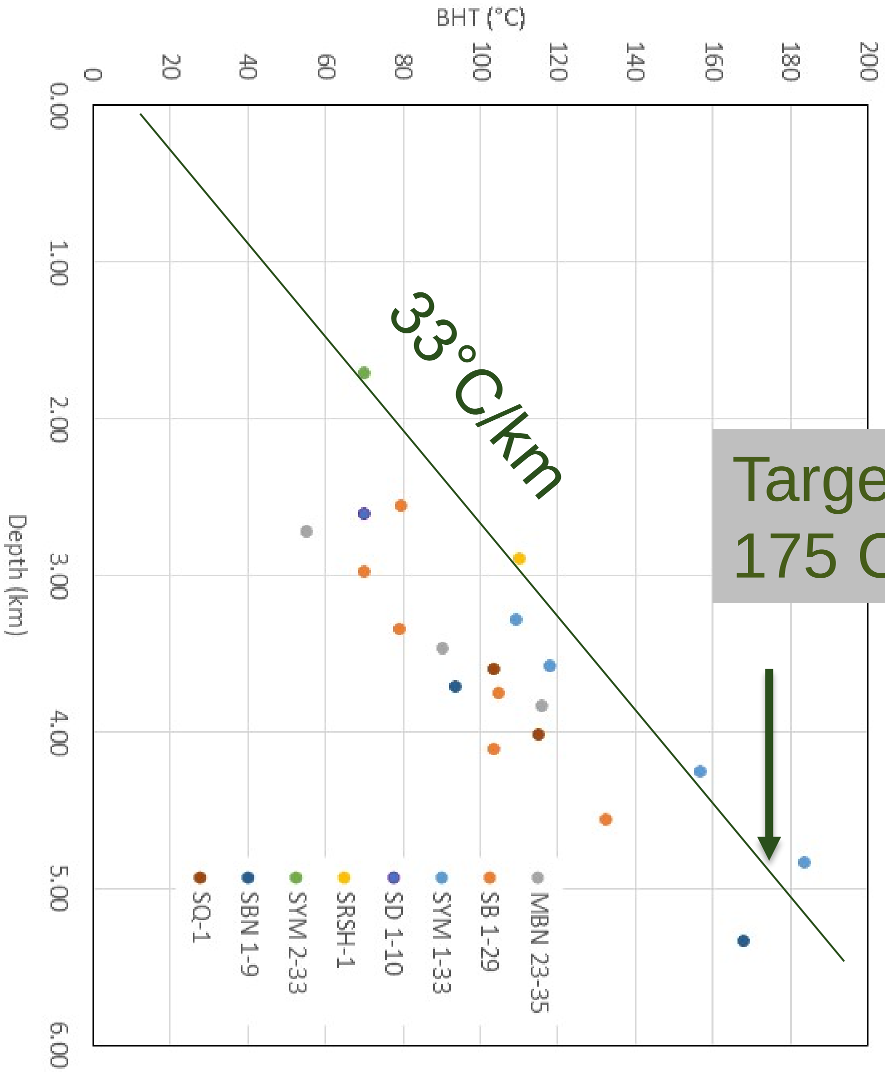
Temperatures at Depth

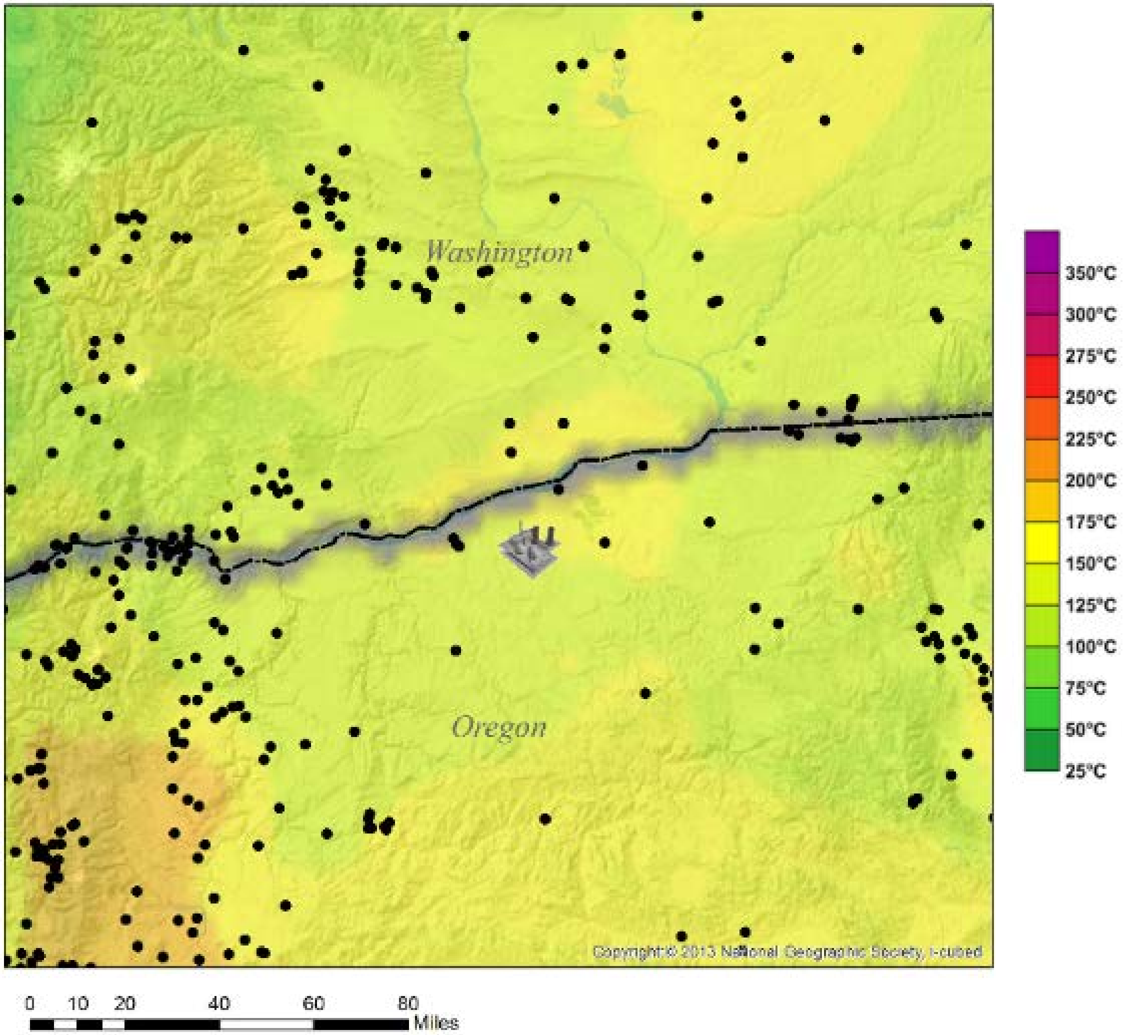
Based on exploration wells drilled below CRB



Target temp
175 C, 350 F

Temperature at 4.5 km (15,000ft) depth

Based on thermal modeling and SMU data base



SMU Geothermal Laboratory
Temperatures at 4.5 km

Boardman CoalPlant

● SMU TG/heatflow wells

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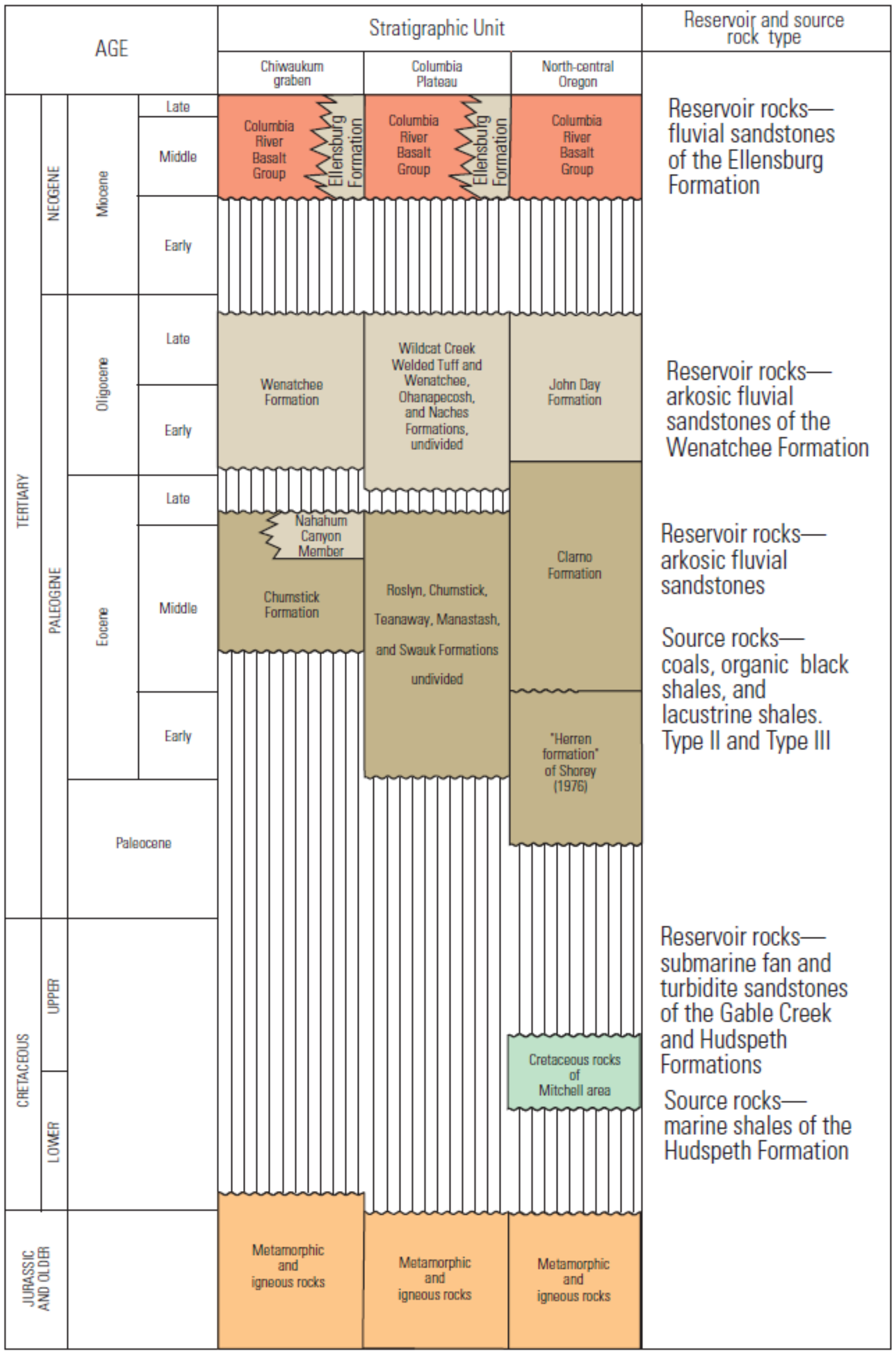
Stratigraphy

Formation	Rock Type / Age	Depth at site (top)	Porosity
Columbia River Basalts (CRB)	Basalts	0	NA
Wenatchee, Ohanapecosh, John Day	Volcanics / Oligocene	2200 m	9 to 17%
Chumstick, Rosyln, Swauk, Clarno, Herren	Sand-stones / Eocene	>3000 m	5 to 8%
Hudspeth	Marine Sediments / Cretaceous	??	?
Basement (exotic terrain)	Granite / Gneiss	>4000 m	Fracture



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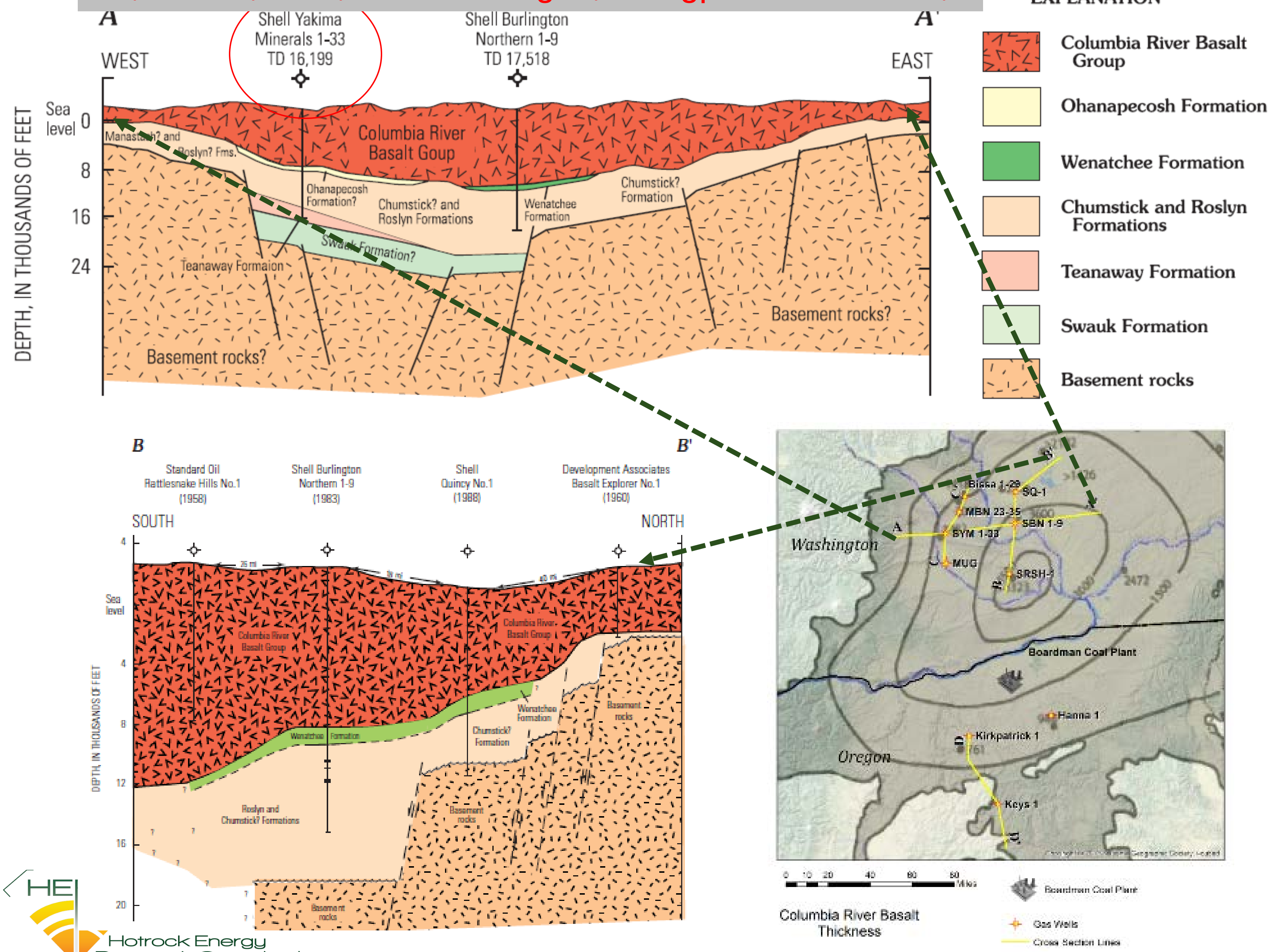
13,000-13,600ft, 570 MCFD gas, 160 gpm 314 F water,



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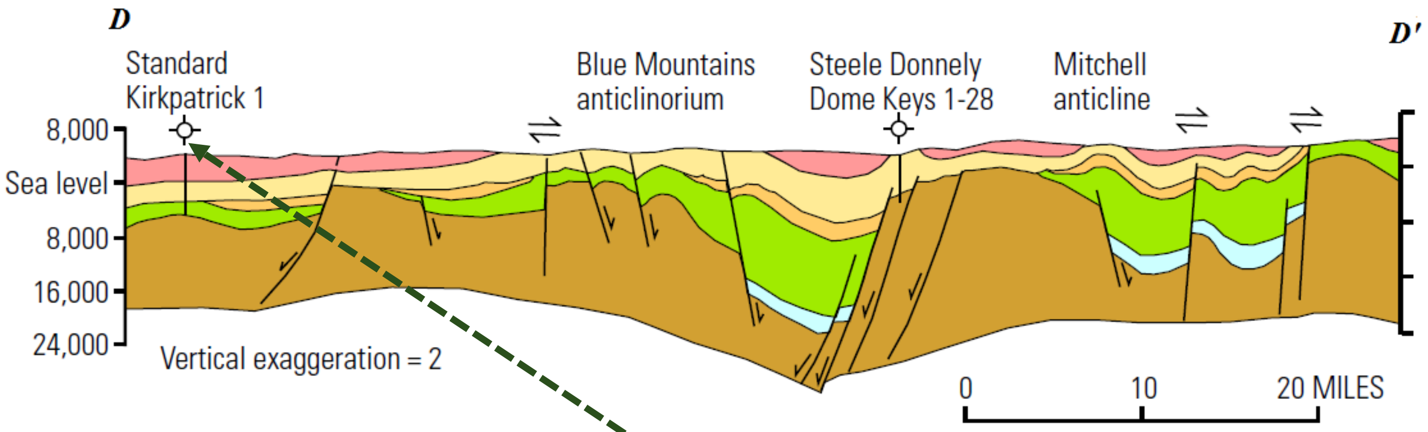
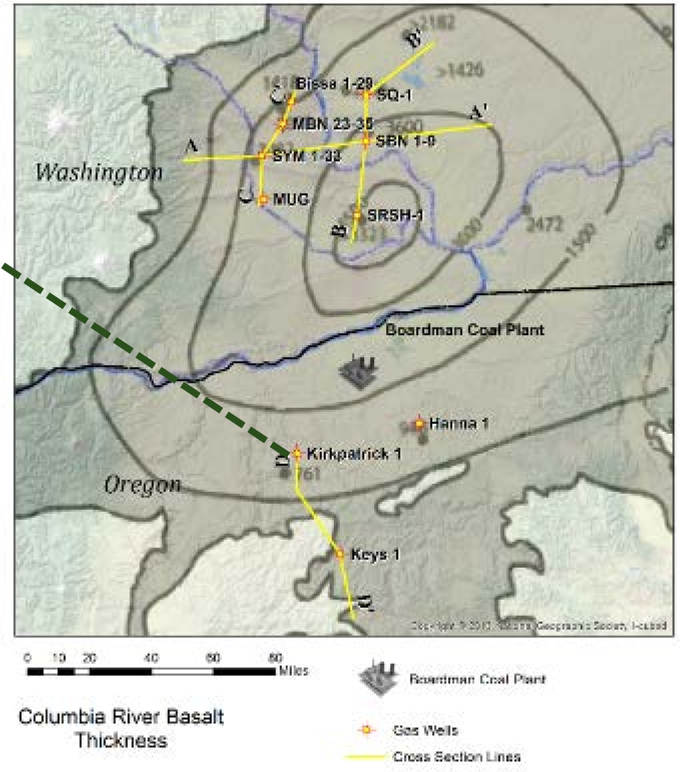


EXPLANATION

- 🟥 Columbia River Basalt Group and John Day Formation
- 🟨 Clarno Formation
- 🟧 "Herren formation" of Shorey (1976)
- 🟩 Gable Creek and Hudspeth of the Mitchell area
- ▢ Triassic and Jurassic rocks
- 🟫 Basement



Columbia River Basalt Thickness

EGS in basement vs Hot sedimentary aquifers

EGS

- Rock type = crystalline (granite, gneiss)
- Permeability = enhanced fracture
- Examples
  - Newberry, Oregon
  - Cooper Basin (Australia)
  - Soultz, France
  - Landau, Germany
  - South Hungary EGS
  - Finland Deep Heat

Hot Sediments

- Rock type = sandstones, mudstones, shale
- Permeability = matrix, natural fracture permeability +/- fracture enhancement
- Examples
  - Bavarian region, Germany - limestone
  - Grosse Schoenbeck, Germany – sandstone and basalts

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Other Geothermal Prospects in Oregon

APPENDIX B

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Other geothermal prospects in OR

Other Possible EGS Resources

- Compare costs to alternative geothermal sites:
  - Newberry Volcano
  - Mt. Hood
  - Warm Springs
  - Mount St. Helens
  - Wind River, WA
  - Klamath and southern Oregon
- DOE risk reduction through Play Fairway studies in Oregon and Washington: Untapped Cascade resource.
- Basin and Range resources in OR

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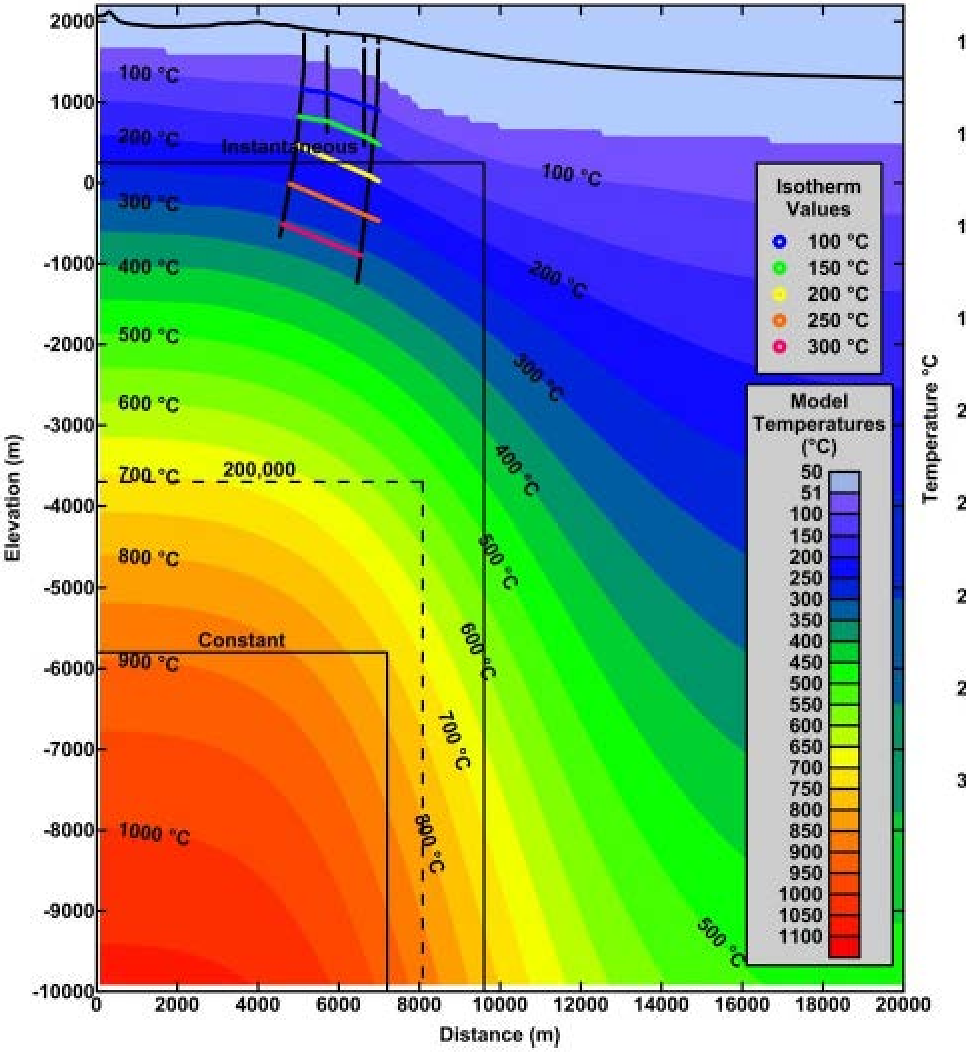
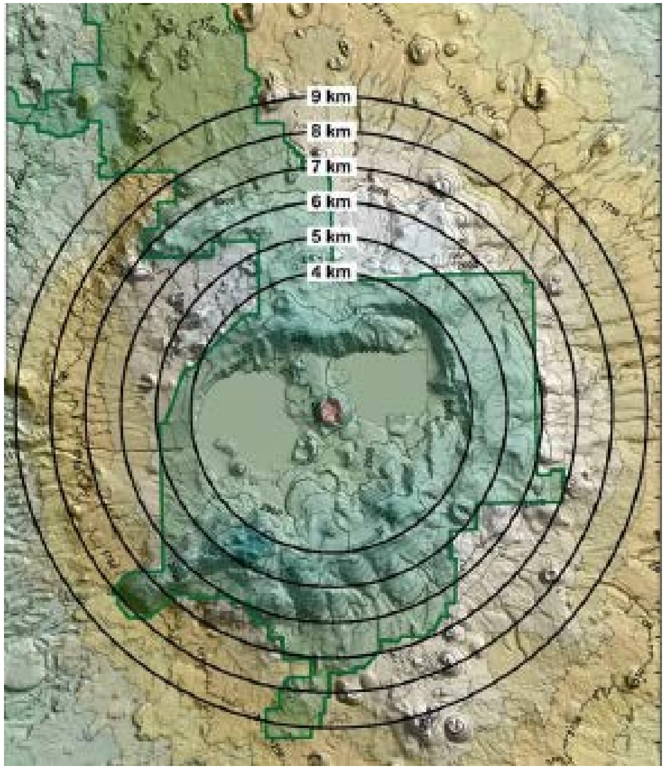
Conductive heat resource at Newberry





Accessible EGS Resource:

4-9 km from caldera center

Depth < 3.5 km,

> 2.4 GW for 30 years

40% of Oregon's current average use!!

Frone, PHD Thesis, SMU, 2015

Newberry EGS reservoir Production Well Course and Target