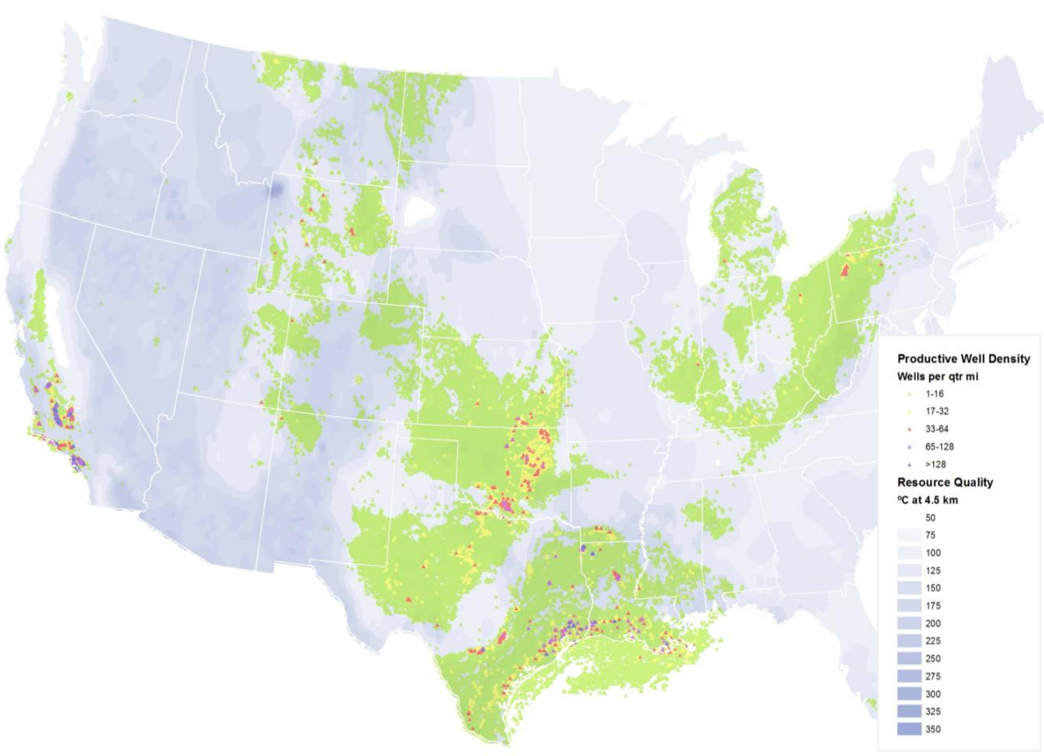
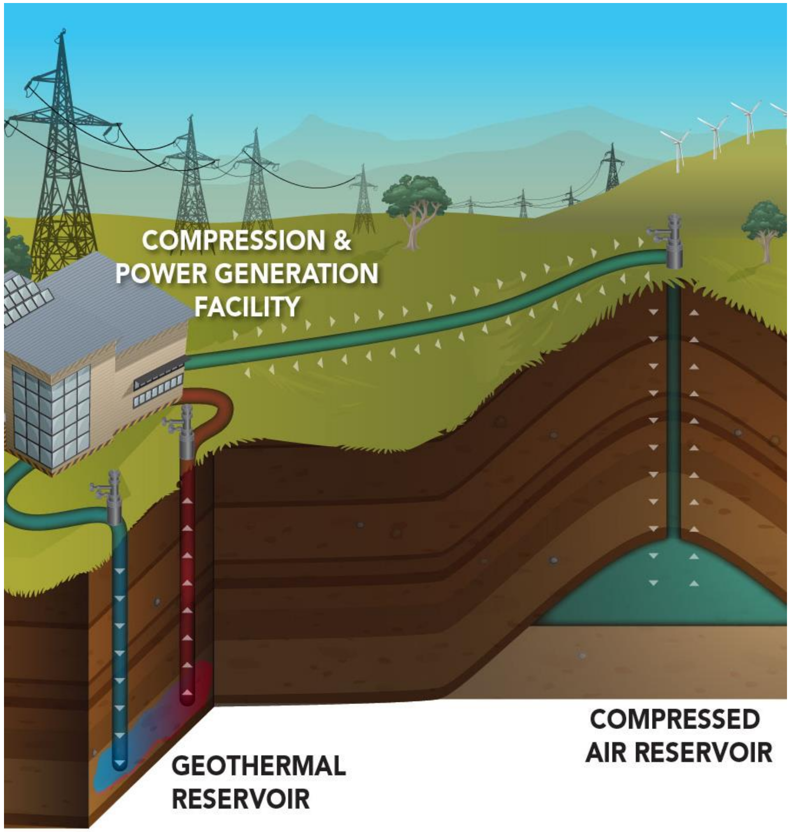




Geothermal-Coupled Compressed Air Energy Storage

Project Officer: Tim Reinhardt

Total Project Funding: $460k

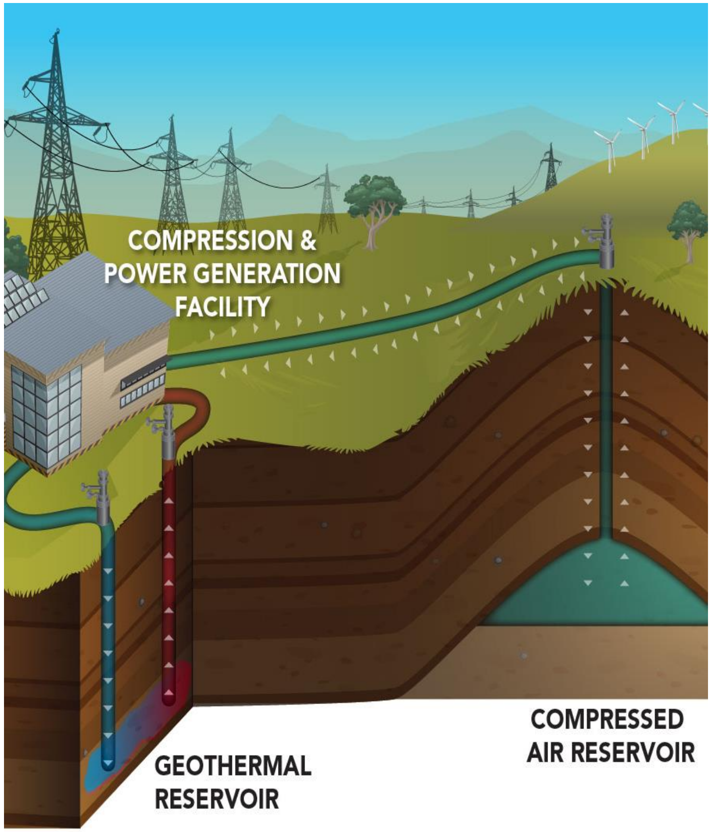
May 12, 2015

PI: B Pete McGrail
Presenter: Casie Davidson
Pacific Northwest National Laboratory

Systems Analysis & Low Temp

PNNL-SA-109815

Assessing technoeconomic feasibility of geothermal-coupled compressed air energy storage (GT-CAES)



- GT-CAES approach investigated here uses geothermal heat during both compression (storage) and expansion (generation) stages
- Benefits of this hybrid system:
  - Expand the use of geothermal resources
  - Enable broader deployment of intermittent renewables
  - Provide large-scale tool to enhance grid stability
  - Geothermal component allows CAES to be used as a zero-emissions system for balancing and/or arbitrage

Key Findings

- Costs for GT-CAES utilizing dome storage range from $1500-$2600/kW for the selected site
  - Geological complexity in good geothermal resource areas makes co-siting reservoir-based CAES challenging
  - Economics may be attractive at locations that offer high-quality geothermal resources and salt domes or suitably thick CAES reservoir
- Preliminary work focused on using existing disused wells for compressed air storage suggests that this approach could be feasibly implemented at suitable scales:
  - 5 MW system from as few as 8 CAES wells (P-110 casing)
  - Widely applicable in areas with large numbers of abandoned oil and gas wells and good geothermal resources (particularly CA, TX)
  - Costs TBD pending site-specific analysis, but comparative configurations and preliminary sizing analysis suggests LCOEs will likely be under the 15 ¢/kWh go/no-go threshold

Technical Approach

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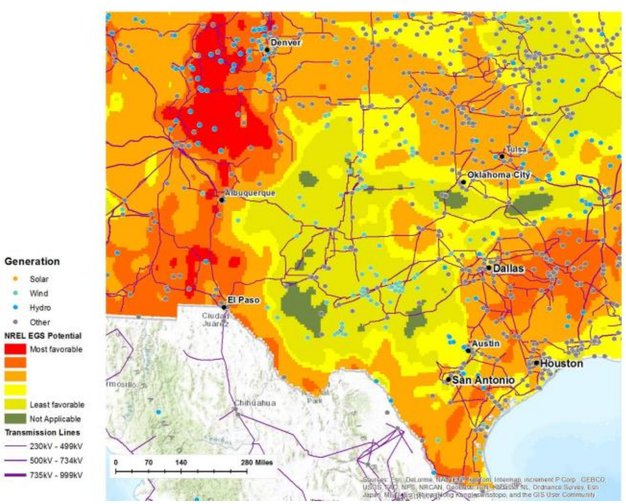
Year 1	Year 2
Geothermal-Coupled Sedimentary CAES	**Geothermal-Coupled Well-Based CAES**
Siting criteria development & screening	
Market evaluation	
Resource evaluation	
Regional down-selection	
Site selection & characterization	
Reservoir parameterization & simulation (STOMP)	
Process design (ASPEN)	
Technoeconomic evaluation	
Report preparation	
	Siting criteria development
	Regional down-selection
	Site selection & characterization
	Process design & modeling (ASPEN)
	Technoeconomic evaluation
	Demo project partnering discussions
	Report preparation
	Journal paper preparation

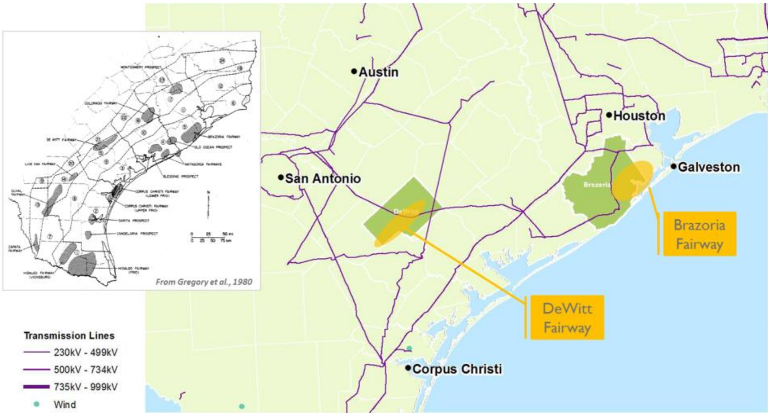


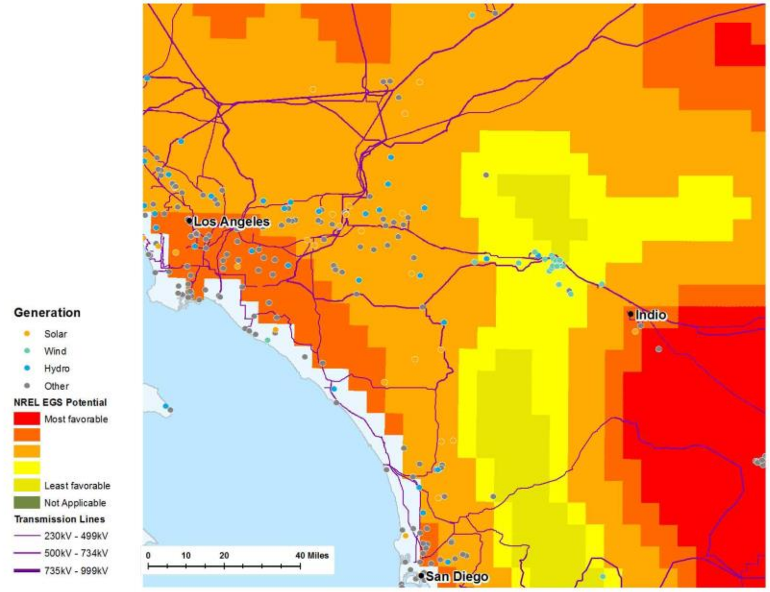
Technoeconomic assessment leverages PNNL's expertise in:

- Siting of complex subsurface projects
- Reservoir modeling
- Process simulation
- Grid stability & energy market dynamics
- Systems engineering and economics

Addressing barriers & knowledge gaps: Year 1

- Novel application of geothermal energy developed under previous project to address site-specific limitations, but could it be used more broadly?
- Concept applicability
  - Co-location of geothermal resource and suitable CAES reservoirs
  - Presence of requisite infrastructure
  - Market need for energy storage
- Site downselection & evaluation
  - Modeling completed for sites in TX
  - Limited overlap of geothermal and CAES storage resources





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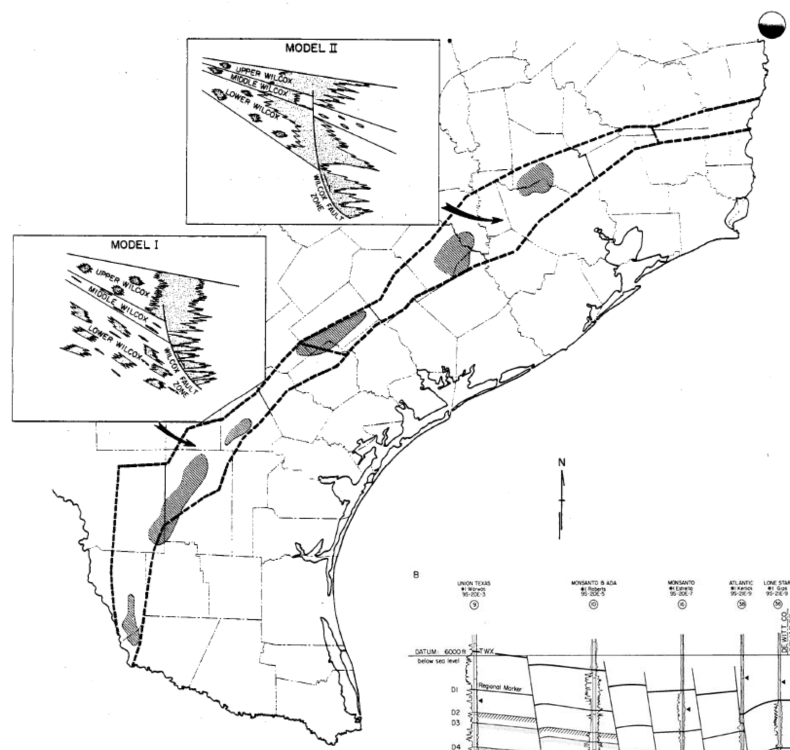
Technoeconomic viability assessment: Texas sites

- Texas chosen for site downselection and evaluation
- Attractive overlap of geothermal resources and potentially suitable storage reservoirs
- More attractive geothermal resources coincide with complex reservoir geology in TX
  - Transgressive / regressive sequences
  - High degree of extensional faulting
  - Entire Gulf Coast reflects a structure that plunges steeply toward the Gulf, making sites nearer the population centers on the coast more expensive (deeper drill depths)



Reservoir models for the Wilcox Group, Texas.

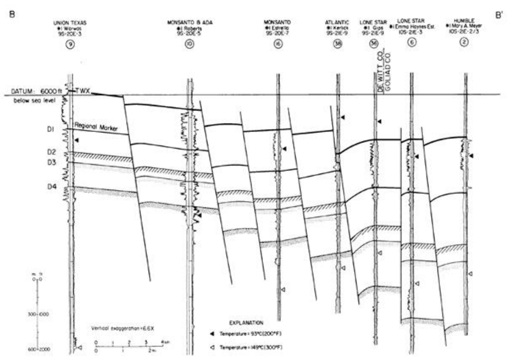
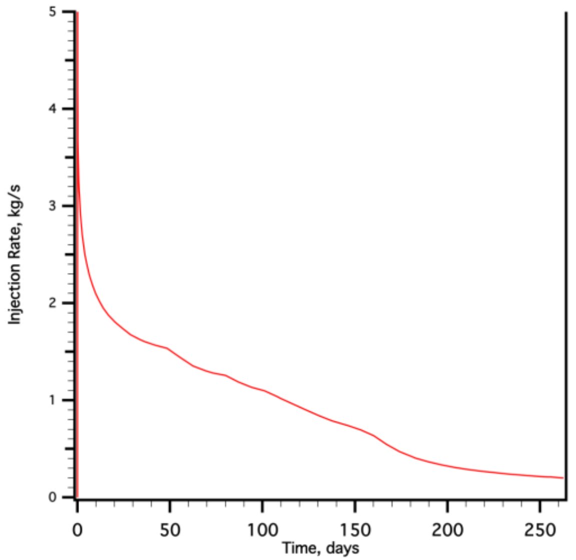
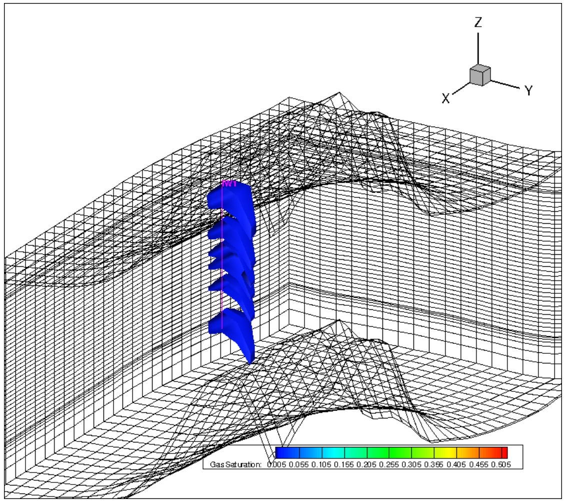


Figure 82. Structural dip section B-B', De Witt Fairway.

Site evaluation: DeWitt County

- CAES in Upper Yegua Fmn, 4500 ft deep
- 500' thickness, ~100 ft net sand interbedded with sandy shales
- Utilized 6 stacked sand intervals, typical of the cyclic deltaic depositional systems of this part of TX; average permeability ~200 mD
- STOMP reservoir simulation used to assess maximum injection rate for sizing CAES system, subject to TX statutory frac gradient limits (0.5 psi/ft min)
- Max rate of 5 kg/s sustainable for only a very short period of time
- Even at this highest rate, the ultimate size of the storage system would be prohibitively small (< 1 MW)

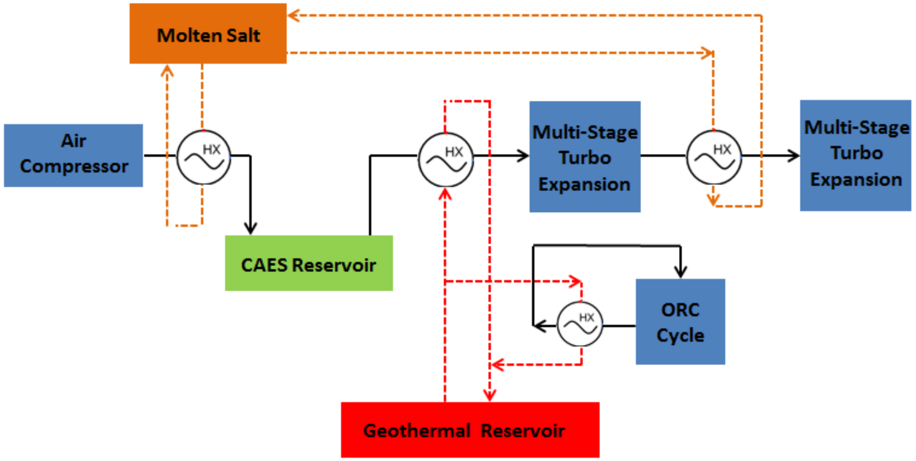




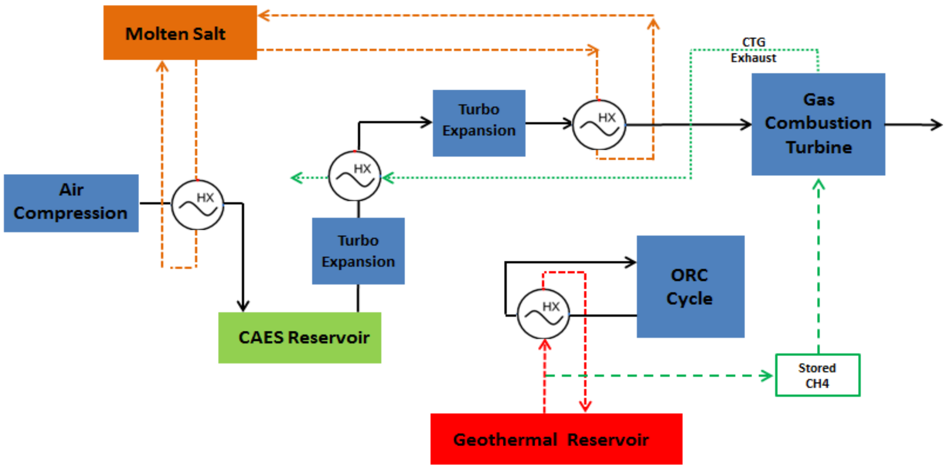
Site evaluation: Brazoria County

- While a CAES reservoir in the Goliad sandstone was selected that had properties significantly better than those for the DeWitt, we chose to model a salt dome as the storage reservoir for Brazoria Co
- Proven geothermal resource at the site with excellent data (Pleasant Bayou #2)
- Because of the demonstrated presence of methane in the geothermal fluid at this site, we also chose to model on-site combustion of produced methane

Baseline Configuration, Plus Thermal Energy Storage (RTE, 74%)



Baseline, Plus Thermal Energy Storage and CH4 Combustion (RTE, 96%)



Findings, Year 1

Phase 1 Report, FY14

At the end of Year 1, we produced a report detailing our findings on the co-location of geothermal resources, air storage reservoirs, supporting infrastructure and near-term market needs for energy storage projects. A detailed analysis around a promising geothermal site in Texas was completed. This Phase 1 report also includes details on subsurface modeling and surface facility design, as well as providing several potential project configurations with associated levelized costs of electricity. In Year 2, we are preparing this work for publication in a peer reviewed journal, and intend to prepare a white paper detailing our assessment of the well-based air storage configuration.

Table 6.9. Total Direct and Total Project Costs for GT-CAES Plant Configurations

Area Estimate			GT-CAES (24 MW)	GT-CAES + thermal storage (32 MW)	GT-CAES + thermal storage + methane combustion (44 MW)
Air Compression and Injection			$ 11.66	$ 14.60	$ 14.60
Geothermal Wellhead, Extraction, and Injection			$ 3.37	$ 3.37	$ 3.37
ORC			$ 2.48	$ 2.48	$ 2.48
Cooling Tower and BOP			$ 0.99	$ 0.99	$ 0.99
Power and Recovery			$ 10.04	$ 10.35	$ 10.36
Molten Salt (thermal storage)			NA	$ 2.11	$ 2.11
	Total Direct Cost		$ 28.54	$ 33.90	$ 33.91
Project Indirect Costs	Engineering	10%			
	Contingency	18%			
	Home Office	20%			
	Freight, Tax	2%			
	Fee and Profit	5%			
	Total Direct and Indirect Plant Cost		$ 44.2	$ 52.5	$ 52.6
	Total Well and Reservoir		$ 17.1	$ 17.1	$ 17.1
	Total Project Cost		$ 61.3	$ 69.6	$ 69.7
	Cost per kW		$ 2,554/kW	$ 2,175/kW	$1,584 /kW

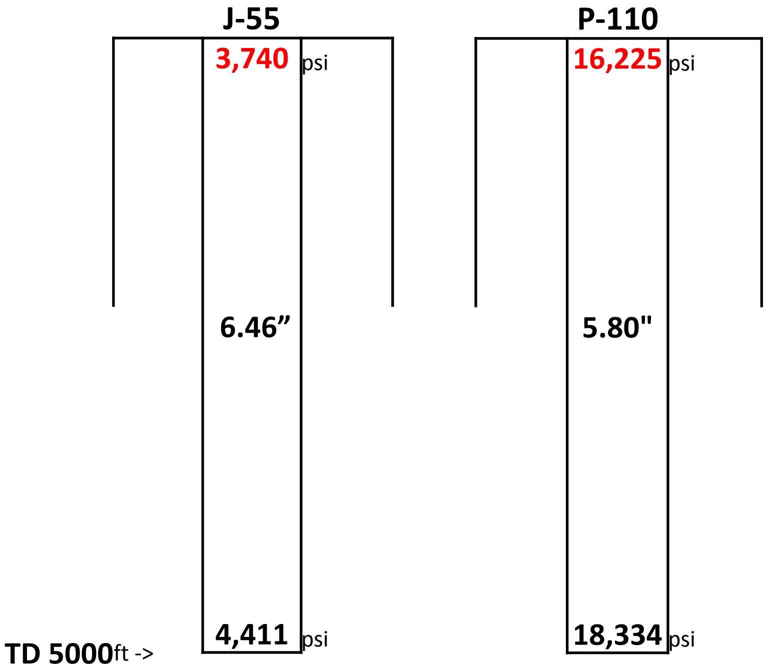
from Davidson, CL, J Cabe, M Bearden, J Horner, M Chamness, and BP McGrail. 2014. *Preliminary Siting and Feasibility Evaluation of Geothermal-Coupled Compressed Air Energy Storage,* PNNL-SA- 84046, Pacific Northwest National Laboratory, Richland, Washington.

Addressing Barriers & Knowledge Gaps: Year 2

- Applying GT-CAES using sedimentary reservoir rocks for the compressed air storage of the project poses challenges for siting
  - Places where these two resources overlap typically pose other siting issues including lack of infrastructure availability, lack of market need for energy storage, or lack of available data
  - While economically feasible and possibly even attractive, particularly in parts of Texas where salt domes can provide low-risk air storage options, the use of sedimentary reservoirs for CAES is likely to be limited by complex geology in areas with significant geothermal resources
- However, the coupling of geothermal and CAES technologies appears to be applicable where these criteria are met
- In order to ease the air storage reservoir criteria and broaden the applicability of this hybrid approach, FY15 is focused on evaluating existing wells as compressed air storage resources

Utilizing wells for compressed air storage

- J-55 and P-110 as representative endmembers for casing strength to determine pressure envelope
- 7” nominal casing (outer dia), 5000’ well depth
- Compression for 12 h per daily cycle; expansion for 4 h/d
- Outlet air heated to 145ºC with 150ºC geothermal fluid, and after each expansion stage
- Preliminary modeling doesn’t include geothermal use for compressor cooling
- Based on our previous modeling, we expect an efficiency improvement of 20-30% when thermal energy storage (TES) is included in next iteration of modeling work



	J-55	P-110
Compression electricity (load), kWh	1763	5493
Expansion electricity (generation), kWh	860	2546
Round-trip efficiency (without TES)	48.8%	46.3%

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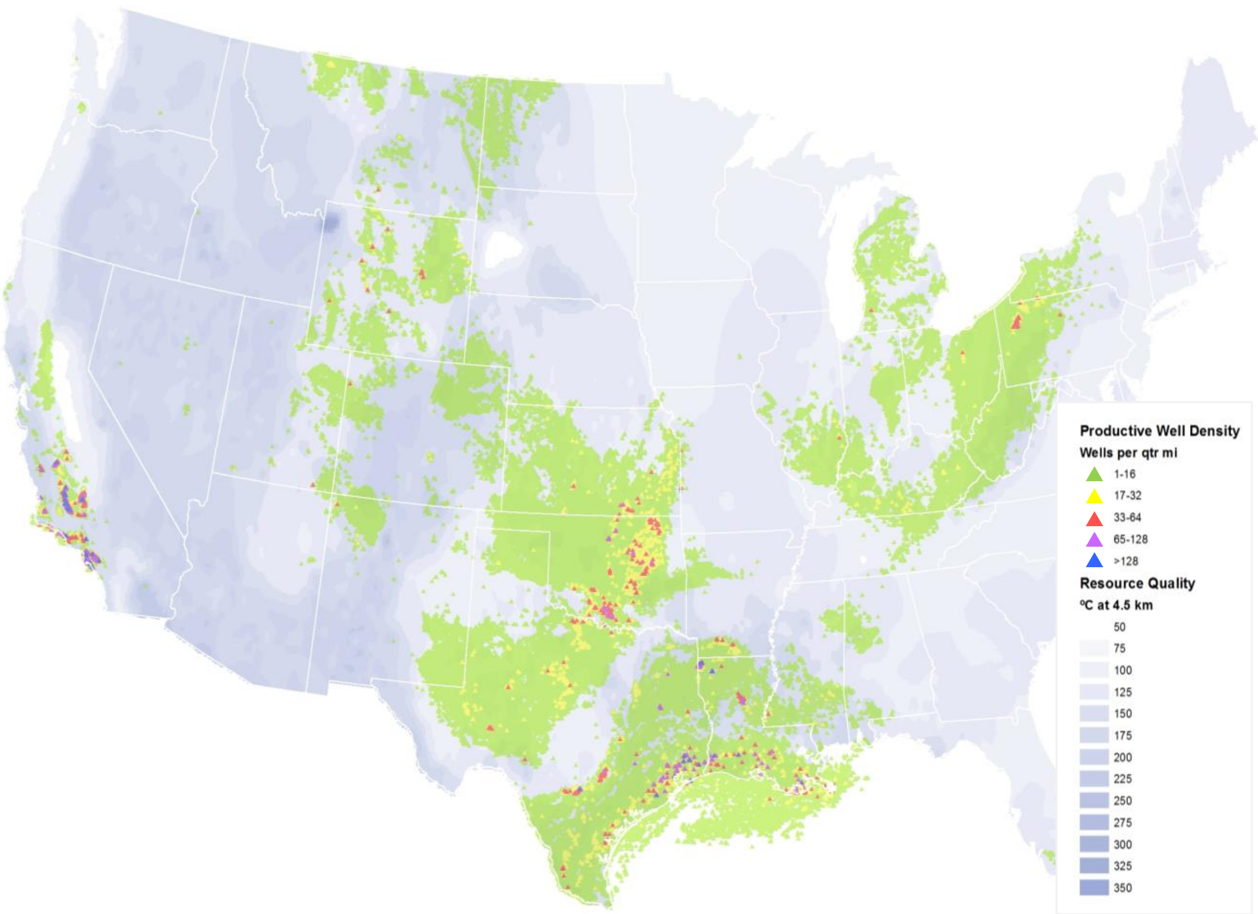
Selecting a site for detailed system modeling



- Using wells for the air storage portion of a GT-CAES project offers a broader range of sites
- This allows for a greater focus on quality of the geothermal resource and market applicability for the storage project
- Because stored air is kept in the well itself, there is no substantive impact to reservoir rocks or stress regimes, buying down risk
- A large amount of data exist on wellfields in the U.S., easing data availability issues for siting

Key Findings

- Costs for GT-CAES utilizing dome storage range from $1500-$2600/kW for the selected site
  - Geological complexity in good geothermal resource areas makes co-siting reservoir-based CAES challenging
  - Economics may be attractive at locations that offer high-quality geothermal resources and salt domes or suitably thick CAES reservoir
- Preliminary work focused on using existing disused wells for compressed air storage suggests that this approach could be feasibly implemented at suitable scales:
  - 5 MW system from as few as 8 CAES wells (P-110 casing)
  - Widely applicable in areas with large numbers of abandoned oil and gas wells and good geothermal resources (particularly CA, TX)
  - Cost TBD but low capital costs for CAES portion suggest LCOEs below 15 ¢/kWh

Accomplishments, Results and Progress

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Planned Milestone	Actual Accomplishment		Date Completed
Evaluation of energy storage markets, geothermal resources, CAES-specific geology and electricity transmission infrastructure; regional down-selection	As planned	Complete	Q1 FY14
Site selection; preliminary model parametrization	As planned	Complete	Q2 FY14
Geologic reservoir simulation domain realization; plant configuration development	As planned, though because of the lack of geologic data available on some of the CAES reservoirs in the geothermal resource areas of interest, reservoir modeling took longer than expected	Complete	Q2 – Q3 FY14
CAES reservoir simulation finalization; integrated facility modeling; submittal of final report	As planned for the DeWitt site. However, due to the poor results at DeWitt, we chose to model air storage in a salt dome at the Brazoria site, so full simulations were not carried out for the Goliad ss as we had intended. Also, report was issued as a draft to allow for incorporation of additional analysis undertaken in FY15Q1.	Complete	Q4 FY14 – Q1 FY15
Go/No-Go: projected LCOE at one of the candidate sites of less than $0.15/kWh	Funding delays resulted in work stoppages through Q2, so this was moved out to Q3 and is on track (see next slide)	On Track	In progress

STATUS KEY: Complete | On Track | At Risk | Missed

Future Directions

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- In FY15, we are working to understand the economics and technical feasibility of using existing cased wellbores for compressed air storage with future work focused on:
  - Down-selection to a final site for deeper data development and system modeling
  - LCOE estimation for a set of site-specific configurations
  - Interest from previous industrial partners in field demo; exploring these opportunities for next FY

Milestone or Go/No-Go		Status & Expected Completion Date
Go/No-Go: projected LCOE at one of the candidate sites of less than $0.15/kWh		On track for completion in Q3 – originally planned for completion in Q2 but funding delays resulted in work stoppages through Q2
Milestone: Draft report on hybrid geothermal CAES siting and LCOE analysis		On track for completion in Q4 FY15
Milestone: Journal article on GT-CAES analysis with optimized designs for hybrid plants		On track for completion in Q1 FY16

STATUS KEY: Complete | On Track | At Risk | Missed

Summary

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- Geothermal-coupled compressed air energy storage appears to be technically and economically feasible, where geothermal resources, suitable CAES reservoirs, transmission infrastructure and market needs overlap.
- Increasing the types of geologic systems that could be used for the CAES portion of a GT-coupled energy storage project could greatly increase the areas across which this approach might be applicable, and could allow for greater utilization of higher-quality geothermal resources.
- GT-CAES provides a novel non-baseload value proposition for geothermal energy extraction that had not received attention prior to this work.
- Planned scope will allow for improvements in both the qualitative and quantitative assessment of the degree to which this coupled approach could help spur geothermal development while at the same time increasing the deployment of wind generation in the U.S.