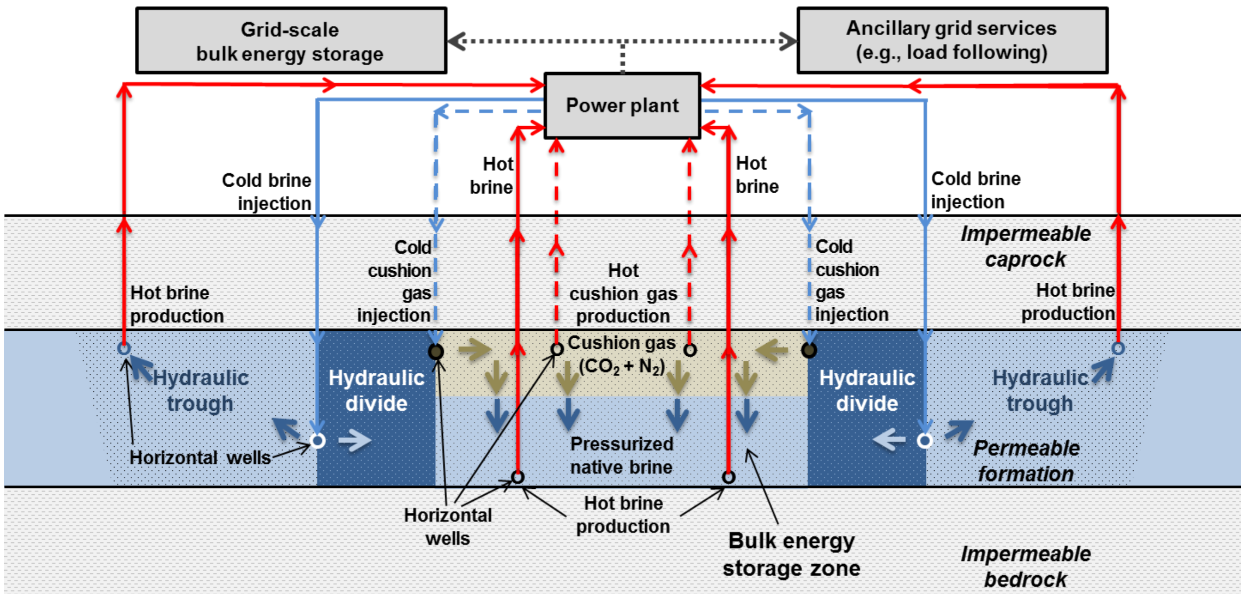


Figure 1. Vertical cross-section of a multi-fluid geo-energy system using only a subsurface geothermal energy source.

Active Management of Integrated Geothermal-CO_2 Storage Reservoirs in Sedimentary Formations

Project Officer: Sean Porse

Total Project Funding: $870k

May 11, 2015

PI: Thomas A. Buscheck

Lawrence Livermore National Laboratory

Track 4: EGS 2

Project Objectives

- Develop/demonstrate an innovative approach (multi-fluid geo-energy systems) with the potential of being commercially viable across much of the United States
  - **More efficient geothermal heat recovery:** using multiple working fluids (CO_2, N_2, and brine) is more flexible than conventional approaches and takes advantage of the thermosiphon effect
  - **More efficient fluid-recirculation:** using a patented well design, we create and store overpressure that pushes fluid to production wells, instead of using downhole pumps
  - **Bulk energy storage/electricity arbitrage:** we take cheap excess power from electric grids when demand is low to time-shift the parasitic load of pressurization, which reduces cost and increases net power when demand is high
    - CO_2 functions as cushion gas that dampens pressure swings during recharge/discharge cycles
  - **Thermal energy storage:** of excess thermal energy from power plants enables the creation of high-quality geothermal resources at shallow depth, and selling electricity when demand is high
- Demonstrate how our approach can be operated to reduce environmental risk
  - **Pressure management:** divert some of the produced brine for consumptive use, instead of reinjecting it, which reduces overpressure and the risks of induced seismicity and CO_2 leakage
- Demonstrate how our approach can be less water intensive
  - **Product water:** use diverted brine for cooling purposes and/or as feedstock for desalination

Project Objectives (continued)

- Monetize the potential value of energy production, bulk energy storage, thermal energy storage, and water production on a per unit of net CO_2-storage basis

Impact on Costs, Performance, Applications, Markets

- Our approach can be deployed in sedimentary basins with lower resource temperatures than most hydrothermal systems, and thus it has the potential to significantly broaden geothermal deployment across the United States
- The added value of bulk energy storage/electricity arbitrage increases the deployment potential of our approach
- The addition of thermal energy storage allows our approach to be deployed where geothermal resources do not exist, which further increases deployment potential, and at shallower depth, which reduces development cost and risk
- Because we use supplemental working fluids, our approach can generate water for cooling purposes, which also increases deployment potential

Multi-fluid geo-energy system approach (Figure 1, Title Page)

- Designed for sedimentary basins suitable for large-scale CO_2 storage
  - Permeable reservoir, overlain by an impermeable caprock (being underlain by an impermeable bedrock is preferred, but not required)
  - Resource temperatures typically range from 100 to 200°C at depths ranging from 3 to 5 km
  - Producers and injectors must be spaced farther apart than is typically done in hydrothermal systems because heat flow is dominated by conduction
  - Wide well spacing is possible because of the large permeability and lateral continuity of sedimentary reservoirs
  - The greater size of the resource target reduces exploration cost and risk
- The well design requires a minimum of four concentric rings of wells (Figure 2)
  - The first (innermost) ring consists of brine/CO_2/N_2 production wells
  - The second ring consists of CO_2/N_2 injectors
  - The third ring consists of brine injectors
  - The fourth (outermost) ring consists of brine production wells
  - This configuration is needed to store/conserve pressure, CO_2 and/or N_2, resulting in artesian flow
    - Brine reinjection can be scheduled to coincide with periods of excess power on grids
    - Pressure can be released when power demand is high, at which time net power is almost equal to gross power

Multi-fluid geo-energy systems: additional innovations

- Thermal energy storage (TES) of excess/waste heat from surface thermal sources
  - Increasing penetration of variable renewables on electric grids is making it difficult for base-load power plants to deliver electricity during periods of over-generation
  - TES can enable time-shifting of energy supply from nonrenewable thermal power plants and concentrating solar power plants
  - TES can effectively result in the equivalent of a high-grade geothermal resource at shallow depths, with the advantages of
    - Reduced well development cost and risk
    - Economic lifetime not being limited by thermal depletion

Project execution

- Reservoir analyses of
  - Power generation and bulk energy storage analyses have been documented in conference papers
  - A well constrained reservoir system will be documented in the Final Report (SMART)
  - A pressure management strategy to mitigate the risks of induced seismicity, caprock leakage, and CO_2 leakage will be documented in a peer-reviewed journal article
- Techno-economic analyses of
  - Power generation and bulk energy storage will be documented in a peer-reviewed journal article

Scientific/Technical Approach

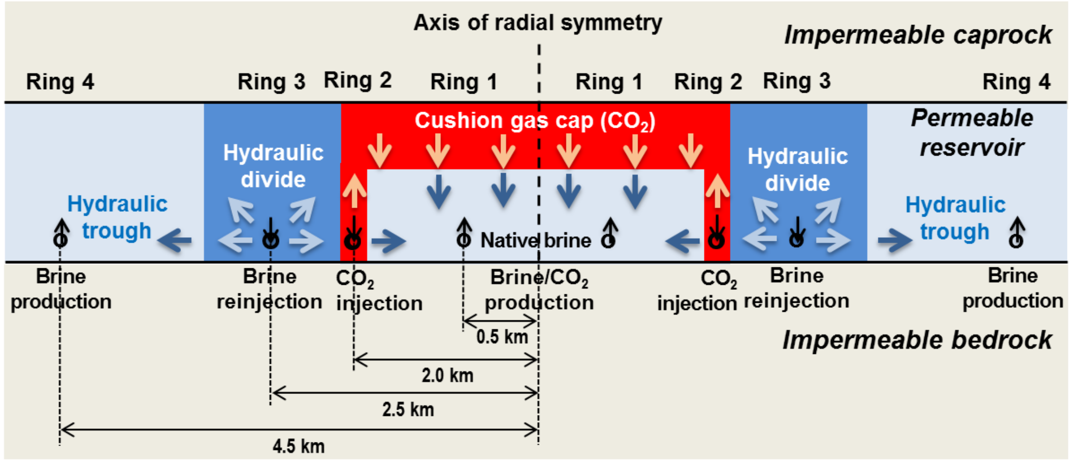


Figure 2. Vertical cross-section of the well configuration used in this presentation.

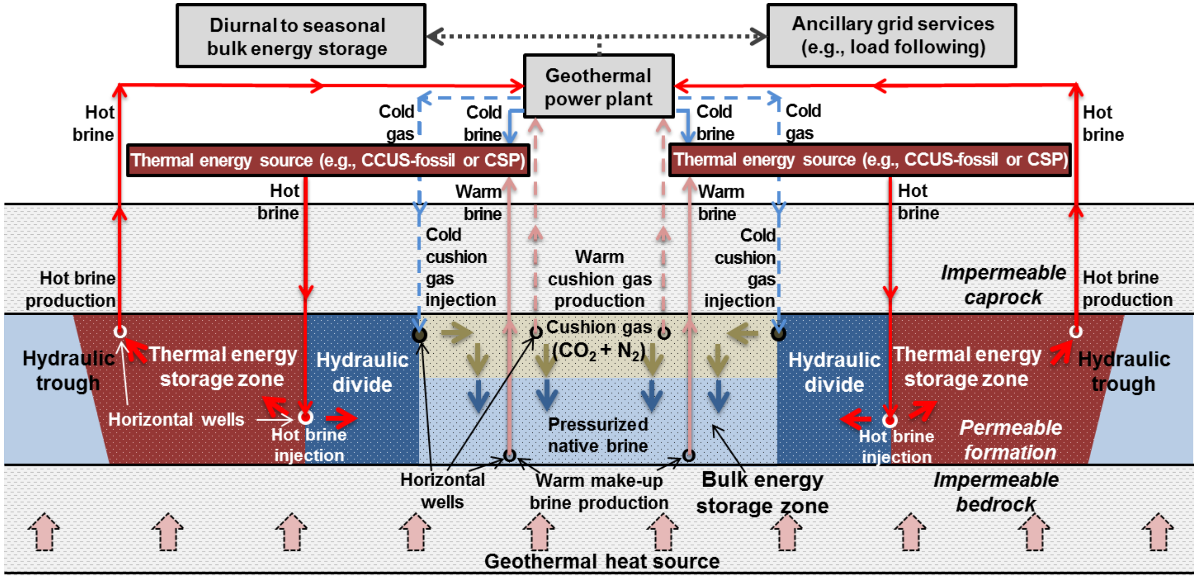
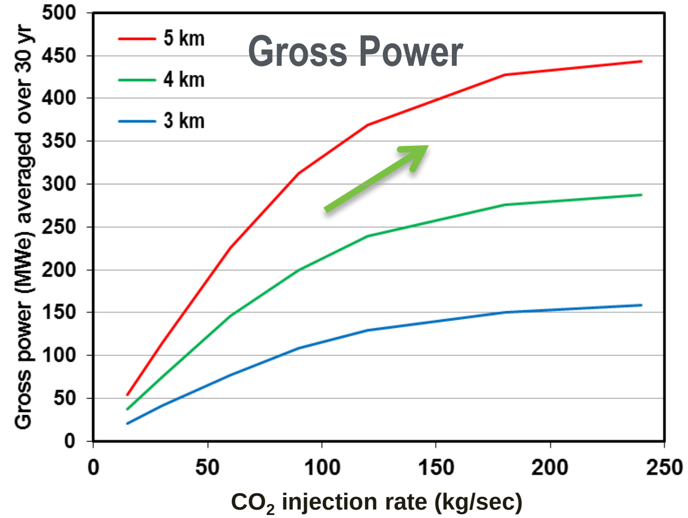
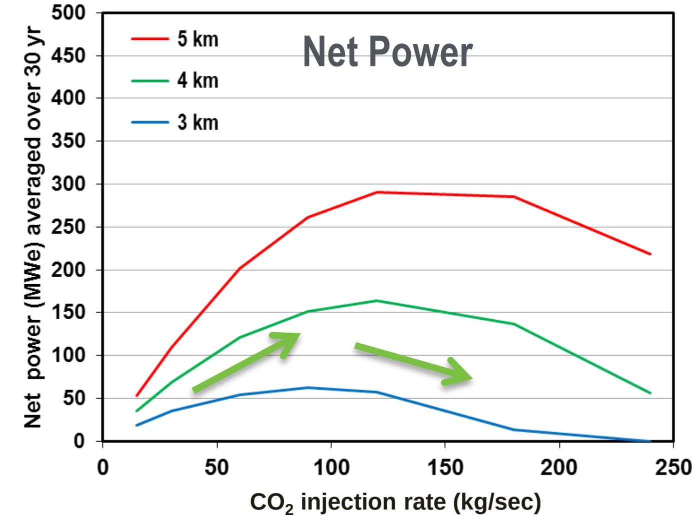
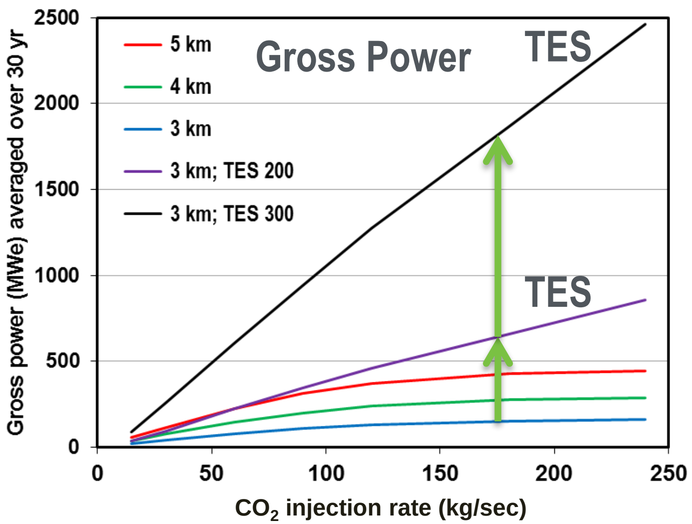


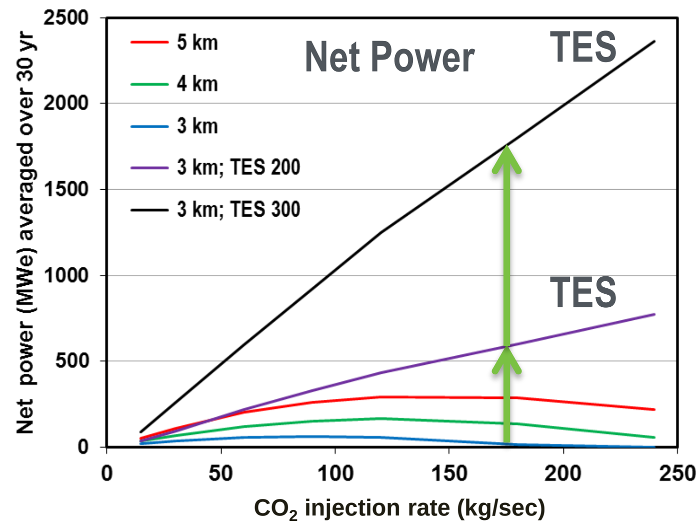
Figure 3. Vertical cross-section of a multi-fluid geo-energy system using both surface and subsurface energy sources.

Scientific/Technical Approach

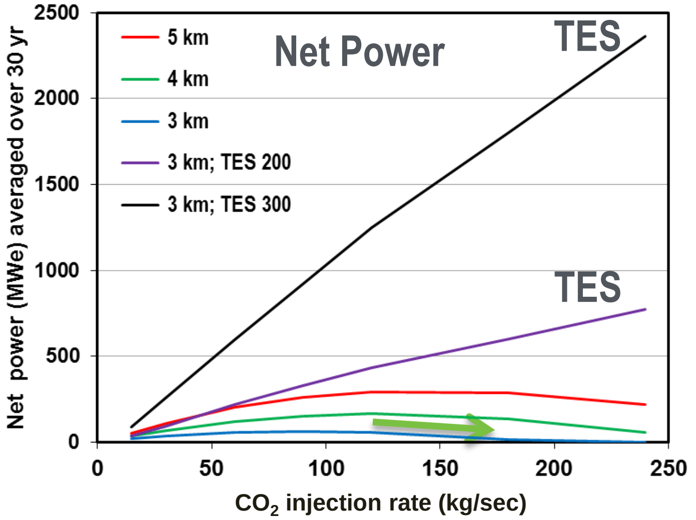


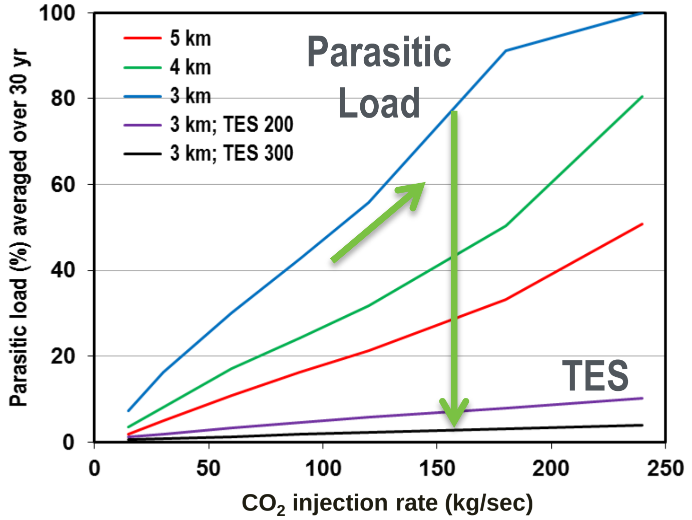


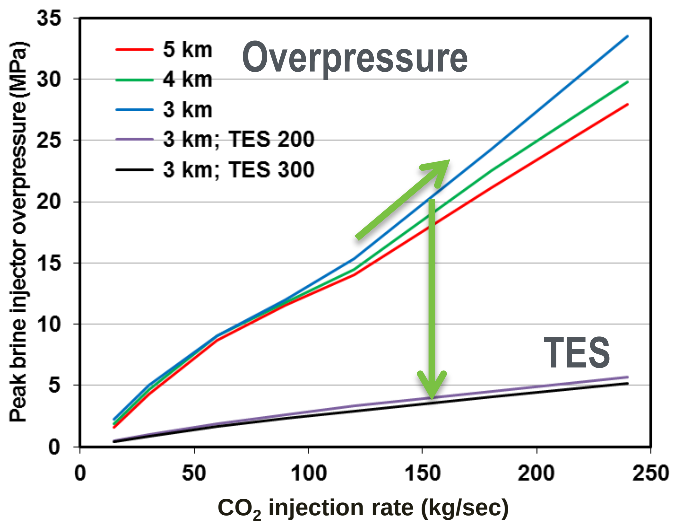


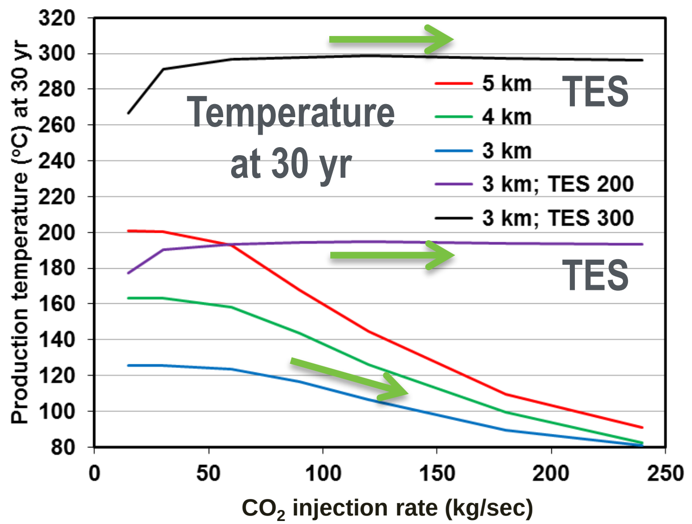


Scientific/Technical Approach









Scientific/Technical Approach

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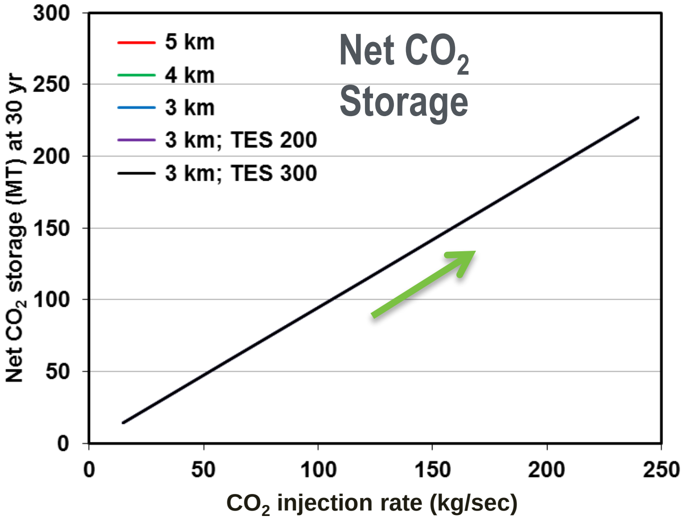
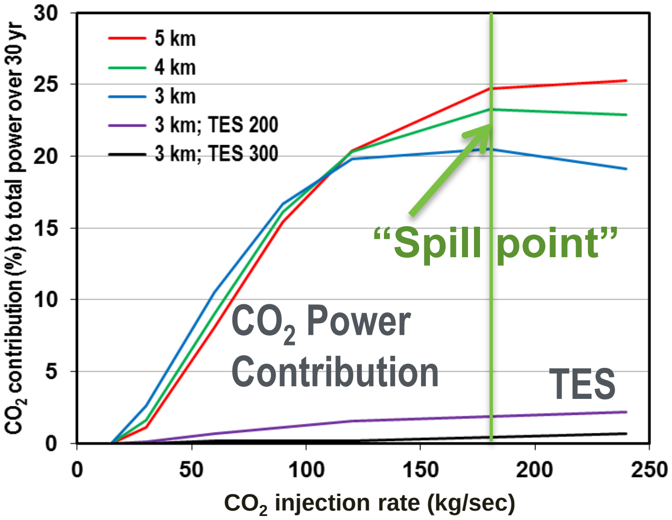
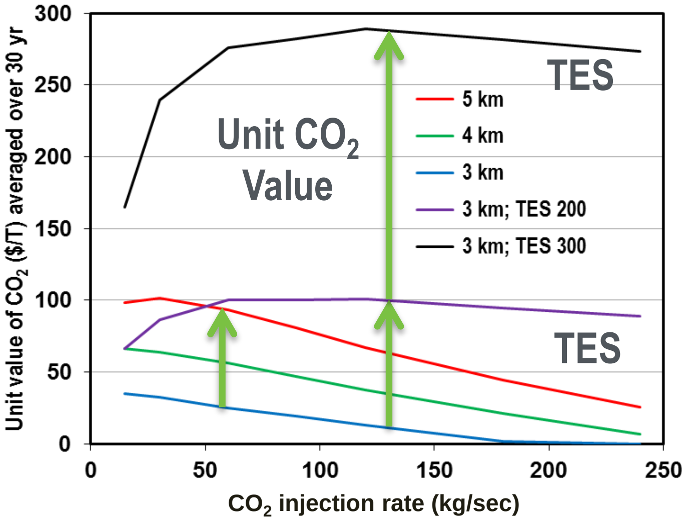


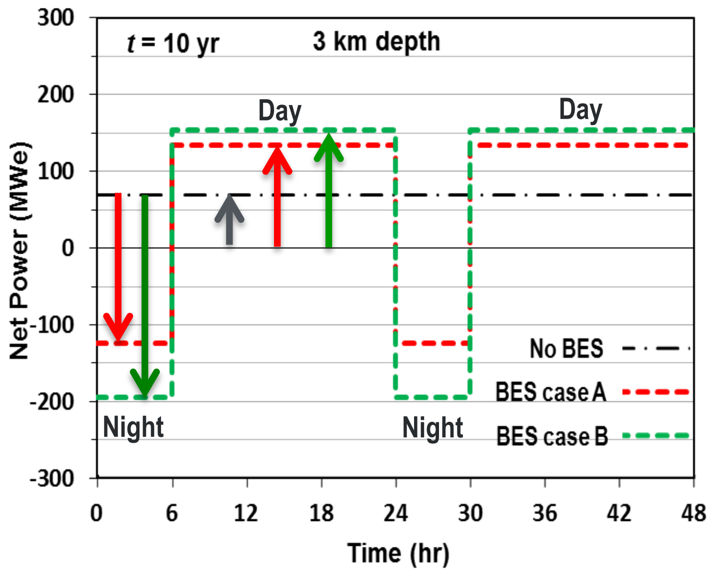




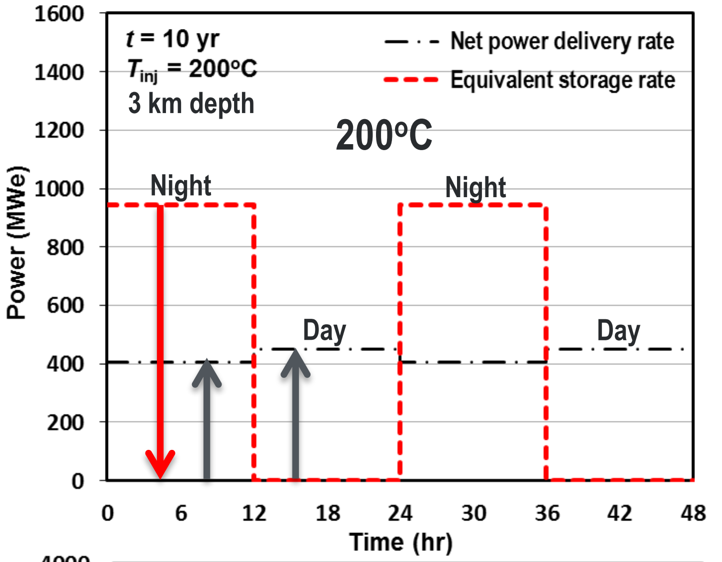
- Net CO_2 storage increases with CO_2 injection rate
- Contribution of CO_2 production to total power increases with CO_2 injection rate up to the "spill point", which corresponds to when CO_2 breaks through the hydraulic divide
- Unit value of CO_2 increases with resource temperature
- Unit value of CO_2 increases with the temperature of thermal energy storage

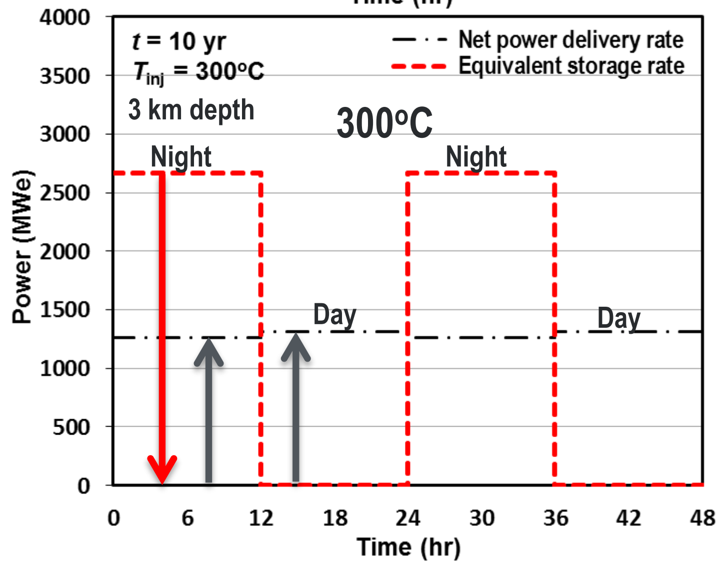
Scientific/Technical Approach

Bulk Energy Storage (BES)



Thermal Energy Storage (TES)





- With synchronous parasitic loading, net power is constant
- With asynchronous parasitic loading of brine pumping, cheap excess power can be taken off the grid
- When demand is high, more power can be dispatched
- If production is reduced when demand is low, even more power can be taken from the grid and more power is available when demand is high
- Excess thermal energy can be stored from surface sources
- TES can levelize power generated from surface thermal sources or time-shift power diurnally or even seasonally

Accomplishments/Progress

- Our patented technology, multi-fluid geo-energy systems, is a unique approach to recovering geothermal energy and storing energy
  - By using as many as three working fluids and having options for bulk and thermal energy storage, it is a versatile approach that can adapt to local conditions
  - Includes a pressure management strategy that generates water as a byproduct
  - Designed to interface with surface electricity systems
  - Documented and presented extensively: one published peer-reviewed paper, one peer-reviewed paper in preparation, 11 conference papers, and 4 additional conference presentations
  - IP is protected by two US patent applications, for which a renewable energy company has signed option agreements
- Special recognitions/awards
  - Best presentation award (only 10 out of >500 were selected) at the 11th Annual Conference on Carbon Capture, Utilization, and Storage
  - Invited papers in Greenhouse Gases: Science and Technology and Geosphere
  - Best paper awards at the 2012, 2013, and 2014 Geothermal Resources Council Annual Meetings
  - Our research has been the subject of numerous internet articles
  - The 2015 European Geophysical Union General Assembly Meeting held a press conference that included a member of our team talking about this work
  - Several venture capital investors have reached out to us to help guide us in the process of developing a marketing plan and business model that can lead to commercialization

Accomplishments, Results and Progress

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- We have built a strong team: The Ohio State University, University of Minnesota, and ETH Zürich
- Performance variances
  - Milestones have been delayed in part due to extended medical leave by the PI

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Preliminary techno-economic analyses	In preparation and to be submitted in an invited peer-reviewed paper	Original:12/31/14 Proposed revised: 6/1/15
Preliminary environmental risk assessment	A pressure management strategy has been developed to reduce the risk of induced seismicity, caprock fracture, and CO_2 leakage. Analyses of this strategy are being documented in an invited peer-reviewed paper	Original: 3/31/15 Proposed revised: 6/1/15
Analysis of power generation and bulk energy storage	Documented in two conference papers to be presented at the 2015 World Geothermal Congress	Original: 6/30/15 No change
Final report (SMART)	Reservoir analyses and techno-economic analyses are being conducted for a promising, constrained reservoir system	Original: 6/30/15 Proposed revised: 7/31/15

Future Directions

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FY15 activities

- Complete techno-economic analyses of power generation and bulk energy storage
- Complete risk assessment/mitigation analyses
- Finish and submit an invited peer-reviewed journal article to Geosphere that includes the techno-economic and risk mitigation analyses
- Continue discussions with a renewable energy company with the goal of establishing a CRADA that can lead to a pilot project

Post-project activities

- Seek funding opportunities to continue bulk energy storage and thermal energy storage research, including the integration with existing power systems
- Analyze a binary-power approach where heat is transferred from the produced brine to the produced CO_2
- Work with venture capital mentors at the Livermore Valley i-GATE innovation hub to develop a marketing strategy and business model that can lead to commercialization

Milestone or Go/No-Go	Status & Expected Completion Date
Reservoir economic benefit	In progress, scheduled for 6/30/15

Summary

- Our project has evolved to focus on two key challenges for mitigating climate change
  - Energy storage
  - Economically viable CO_2 capture, utilization, and storage (CCUS)
- Technology solutions that address these challenges can increase the use of renewable and low-carbon nonrenewable energy
- The results of our study indicate that multi-fluid geo-energy systems have the potential of generating enough revenues to make CCUS an attractive commercial opportunity, particularly where
  - Resource temperatures are high enough (>150^{o}C) and bulk energy storage is used
    - resulting in broader geographic deployment potential than hydrothermal systems
  - Bulk and thermal energy storage are used
    - resulting in very broad geographic deployment potential
- The next major step is a pilot project, conducted in a staged manner
- Proving our approach in the field can lead to much wider deployment of geothermal energy systems

Publications, Presentations, and Intellectual Property

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Peer Reviewed Papers

Elliot TR, Buscheck TA, Celia MA, 2013. Active CO_2 reservoir management for sustainable geothermal energy extraction and reduced leakage, *Greenhouse Gases: Science and Technology*, **1**, 1-16.

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Conference Presentations

Elliot TR, Buscheck TA, and Celia MA, 2012. Active CO_2 reservoir management: A two-stage approach for sustainable geothermal energy production with reduced risk of brine leakage and increased CO_2 security, proceedings of the 11th Annual Conference on Carbon Capture, Utilization, and Sequestration, Apr 30–May 3, Pittsburgh, PA, USA.

Buscheck TA, Bielicki JM, Randolph JB, Chen M, Hao Y, and Sun, Y, 2013. Multi-fluid geothermal energy systems: Utilizing CO_2 for dispatchable renewable power generation and grid stabilization, 2013d, *American Geophysical Union Fall Meeting*: Dec 9-13, San Francisco, CA, USA.

Bielicki JM, Buscheck TA, Chen M, Sun Y, Hao Y, Saar MO, and Randolph JB, 2014. Engineering sedimentary geothermal resources for large-scale dispatchable renewable electricity, *European Geosciences Union General Assembly 2014*: Apr 27–May 2, Vienna, Australia.

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