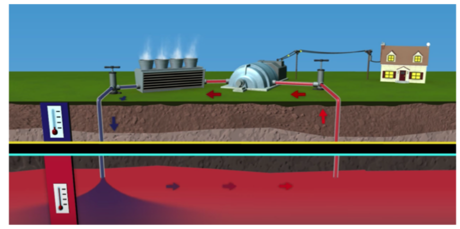
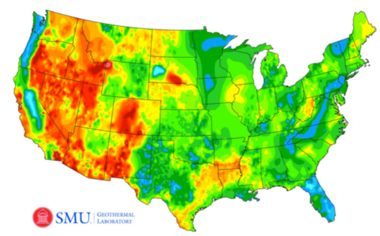
Don't Emit, Use It: CO_2-Enabled Geothermal Energy Production and Storage

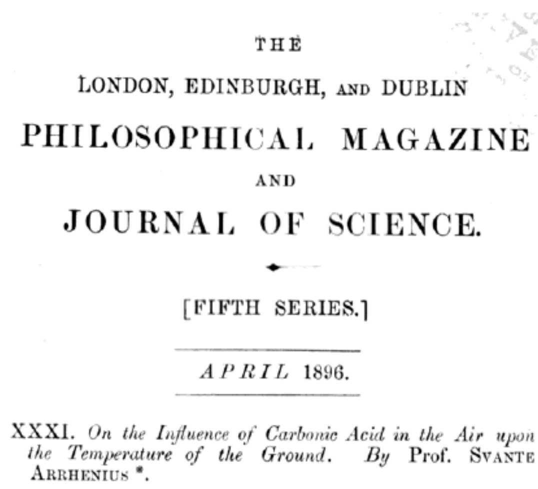




Prof. Jeffrey M. Bielicki
Department of Civil, Environmental, and Geodetic Engineering
John Glenn College of Public Affairs
Environmental Science Graduate Program
Ohio State University

Geothermal Frontiers Forum | Energy Options Network and Clean Air Task Force | Center for the National Interest | May 7, 2019

118 years after:


THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

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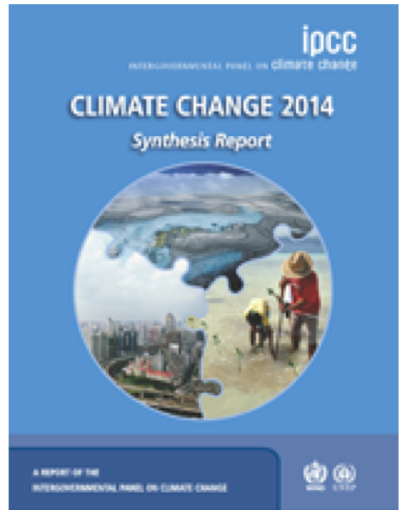
118 years after:



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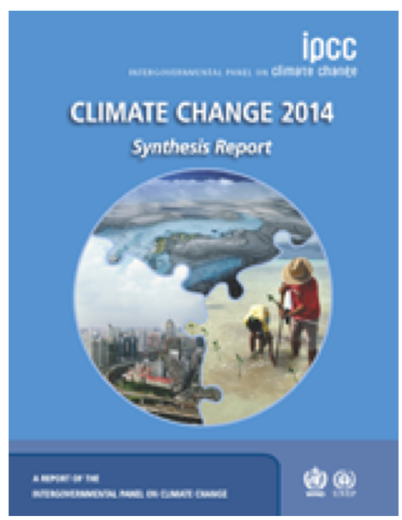
Intergovernmental Panel on Climate Change

"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history….

… Recent climate changes have had widespread impacts on human and natural systems."



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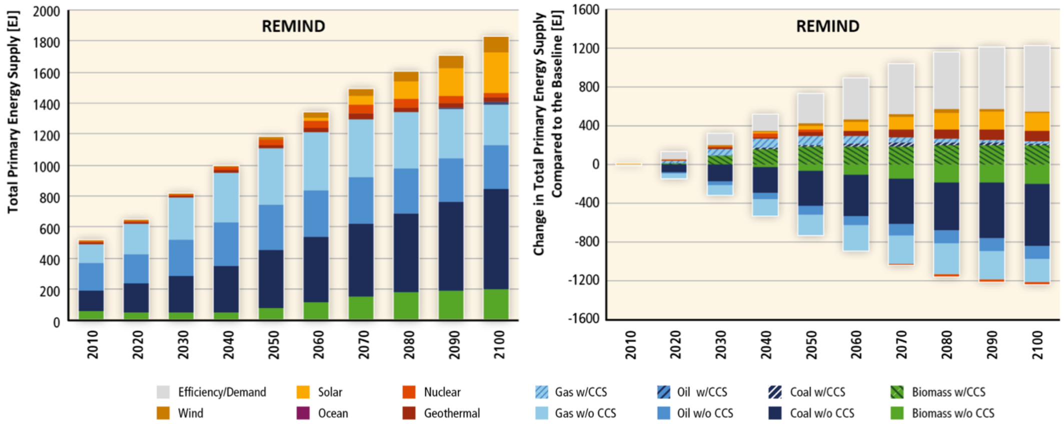
Illustrative Primary Energy Projections



Primary Energy Production

Changes in Primary Energy Production

(for 430 – 530 ppm)

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IPCC (2017)

Challenges for Modern Energy Systems

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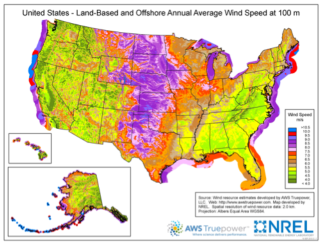
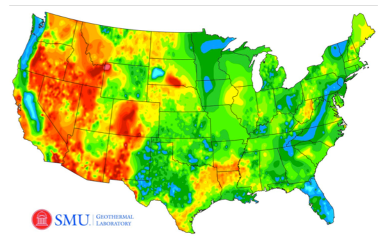
Renewable Resource Bases

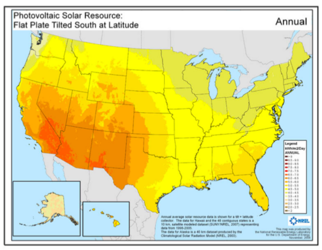
Wind



Heat



Sun



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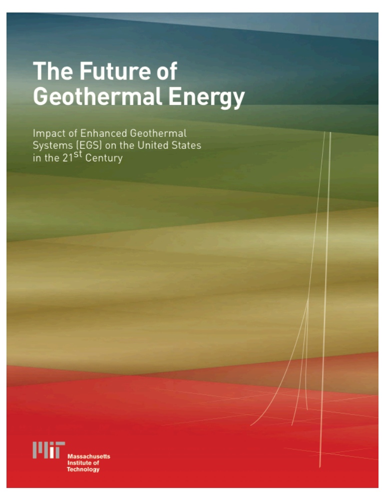
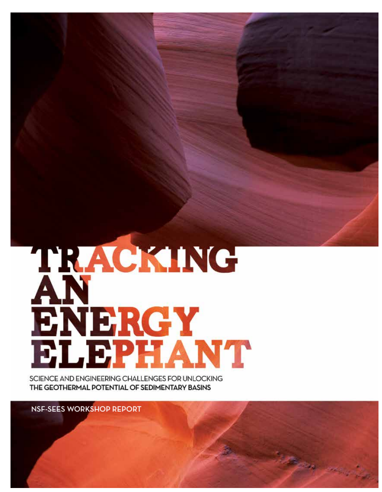
[1]Natcarb Atlas IV(2013)

Pathways for Geothermal

MIT (2006) Report on EGS

NSF SedHeat RCN (2013) report on sedimentary basin opportunities





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Pathways for Geothermal

MIT (2006) Report on EGS

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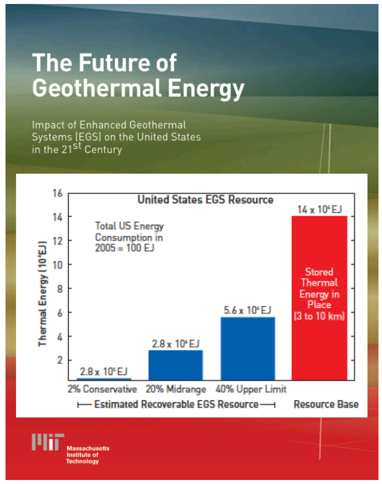

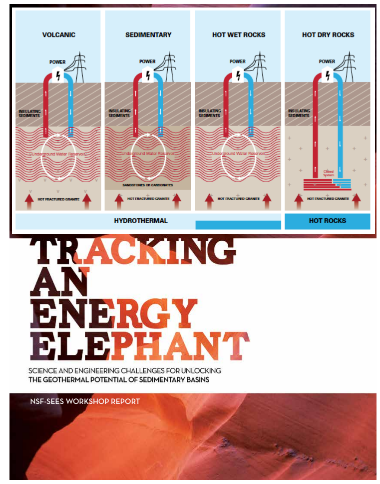

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PROCEEDINGS, Twenty-Fifth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 24-26, 2000
SGP-TR-165

A HOT DRY ROCK GEOTHERMAL ENERGY CONCEPT UTILIZING SUPERCRITICAL CO_2 INSTEAD OF WATER

Donald W. Brown
Earth and Environmental Sciences Division
Los Alamos National Laboratory

Proposed the use of CO_2 as fracturing fluid and as heat extraction fluid.

Subsequent modeling studies illustrated the effectiveness of such a CO_2-EGS approach (Atrens et al., 2009, 2010, Pruess, 2006, 2008).

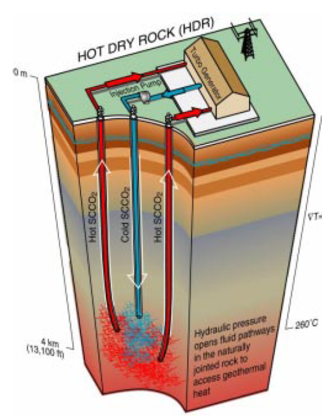

Figure 2: HDR–SCCO$_2$. A System Engineered for Geothermal Heat Mining Using Supercritical CO$_2$.

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(Some) Benefits of Supercritical CO_2 over Brine

1. **Reductions in water requirements (especially in arid regions)**
2. **Potential for enhanced fracturing and fracture propagation**
3. **Substantially lower kinematic viscosity: higher fluid mobility**
4. **Higher heat advection rates within reservoirs**
5. **Temperature-dependent density: self-convecting thermosiphon**
6. **Lower mineral solubility: limits the leaching and transport of minerals, likely reduction of scaling in pipes and turbomachinery.**

(Adams et al., 2014, 2015; Atrens et al., 2009, 2010; Brown, 2000; Luhmann et al., 2014; Tutolo et al., 2014, 2015)

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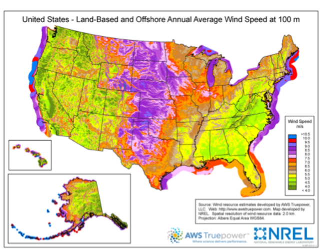
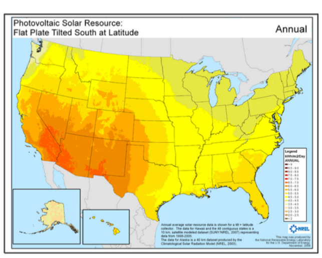
Resource Bases

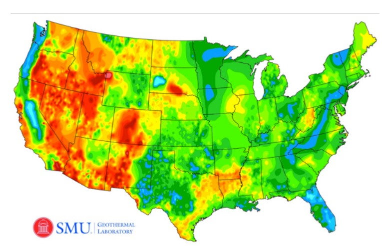
Wind



Sun

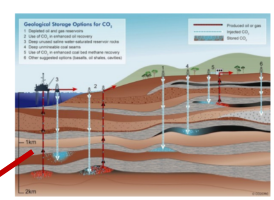


Heat



Storage

Geologic CO_2 Storage



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[1]Natcarb Atlas IV(2013)

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Department of Earth Sciences
University of Minnesota

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TerraCOH, LLC
University of Minnesota

Sustainable Energy Pathways Program (Grant 1230691)

U.S. DEPARTMENT OF ENERGY
Geothermal Technologies Office (DE-FOA-0000336)

SUSTAINABLE AND RESILIENT ECONOMY
INTEGRATED SCIENCE: PEOPLE, PROCESS, PLANET

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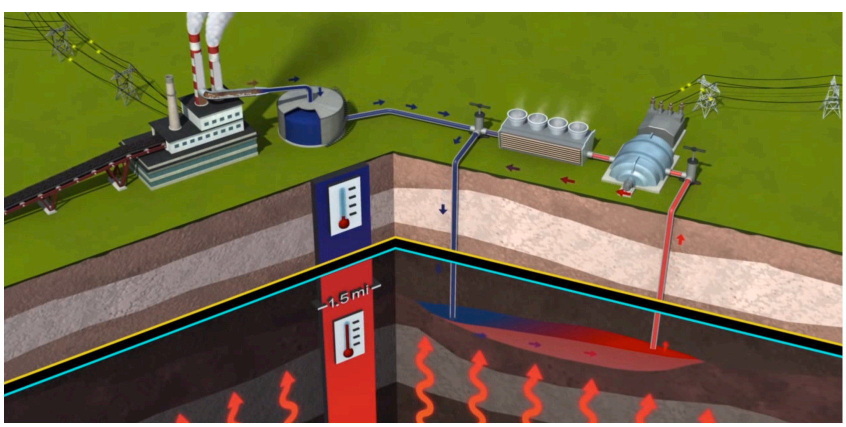
Use CO_2 Geologically Stored in Sedimentary Basin Geothermal Resources to Store and Produce Electricity



www.energypathways.org

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Using Sedimentary Basin Geothermal Resources

Can we generate electricity using geologically stored CO_2?
… and expand areas where geothermal energy production is cost effective?

Can we time-shift the oversupply of renewable energy and dispatch it when demanded?
… and enable changes in dispatch that improve environmental performance?
… and cost-effectively transport renewable energy large distances?

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Geothermal Energy Reservoirs and Fluids

	Energy Extraction Working Fluid	
Type of Reservoir	Water	CO_2
Sedimentary Basin (large-scale, naturally permeable, typically lower temperature)	Conventional Hydrothermal System	CO_2-Plume Geothermal (CPG) System
Enhanced Geothermal System (EGS) (small-scale, relatively impermeable prior to stimulation, typically higher temperature)	Conventional EGS	CO_2-based EGS

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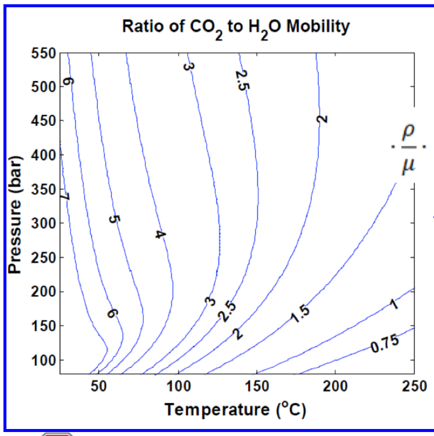
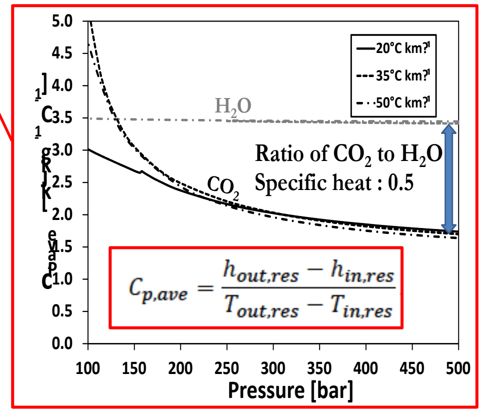
Thermophysical Properties of CO_2

$$Q = \Delta P \cdot \frac{kA}{L} \cdot \frac{\rho}{\mu} \cdot C_{p,ave} \cdot \Delta T$$





$$C_{p,ave} = \frac{h_{out,res} - h_{in,res}}{T_{out,res} - T_{in,res}}$$

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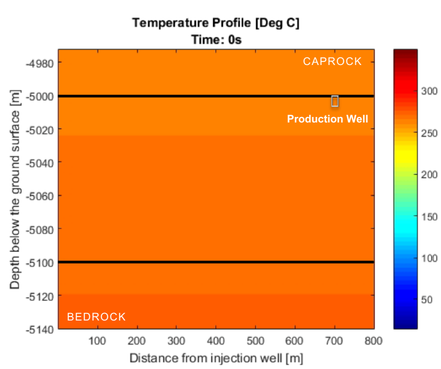
Randolph and Saar (2011); Adams et al., (2014); Garapti et al., (2014)

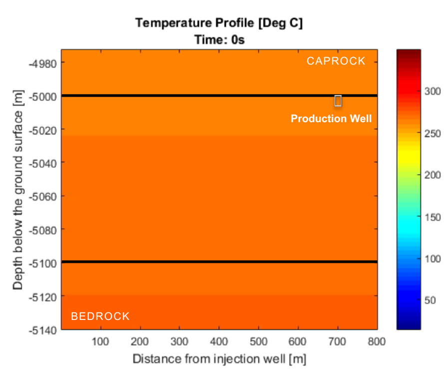
Temperature Drawdown:

100 kg/s, $\kappa = 10^{-12}$ m^2, d = 5 km, t = 100m; G = 50°C/km

Water



CO_2



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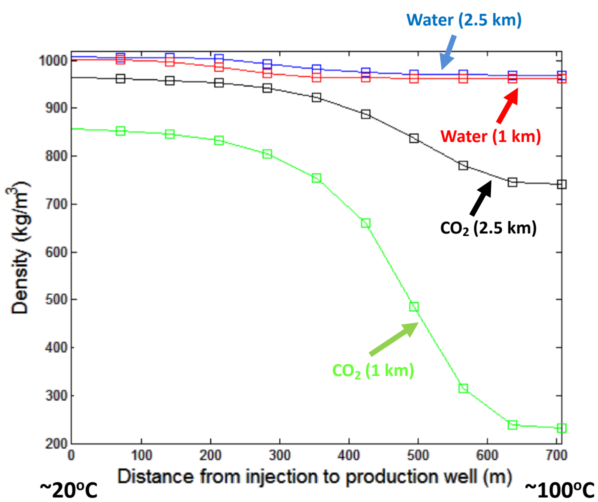
CO_2 Density is Highly Temperature and Pressure Dependent



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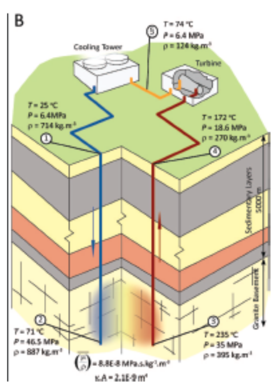
Self-Convecting Thermosiphon



density difference between injection and production wells generates flow

Atrens et al., (2009): 17 MWe from 80 MWth @ 5km depth

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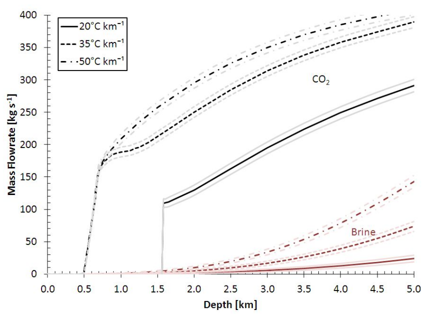
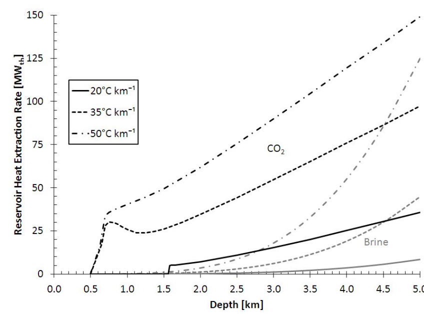
Self-Convecting Thermosiphon





Thermosiphon Induced Mass Flowrate:
CO_2 has more vigorous flow than brine

Reservoir Heat Extraction:
CO_2 extracts more heat than brine

Effective pumping power of a CO_2 system is an order of magnitude greater than that of a brine system.

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Adams et al., (2014)

CO_2-Geothermal System

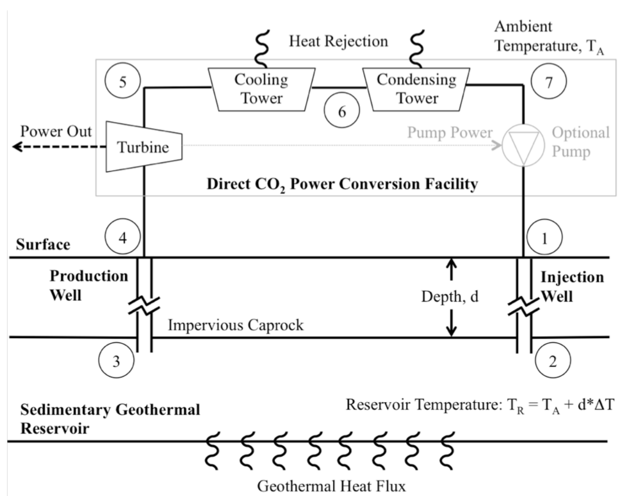
Coupled Models

Direct CO_2 Power Plant[1]

Geothermal Reservoir Model[1,2]

Simplified Wellbore[1,2]

Economic Costs[3,4]



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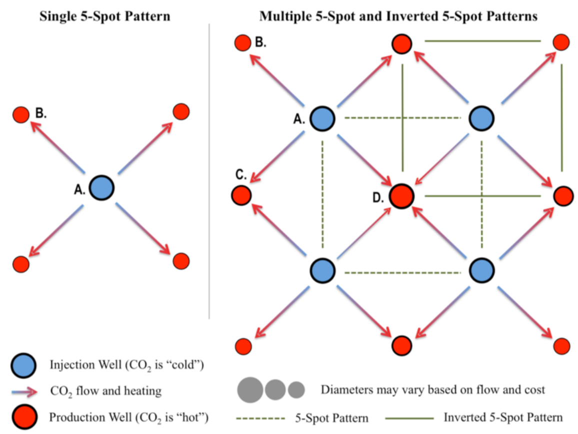
[1]Adams et al (2014); [2]Adams et al (2015); [3]EPA (2012); [4]GETEM (2012)

Well Patterns and Diameters

Inverted 5-Spot Pattern(s)
- cool CO_2 injected into center well
- hot CO_2 produced from corner wells

Well Diameters
- can vary
- optimized for cost and energy production



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System Configurations and Characteristics

Parameter	Values
Well Pattern (km^2) (Configuration Number in Parenthesis)	1-100 (1-10)
Well Diameter (m)	0.14, 0.27, 0.33, 0.41
Surface Temperature (°C)	15
Reservoir Thickness (m)	305
Geothermal Gradient (°C/km)	20, 35, 50
Ambient Temperature (°C)	15
Porosity	10%
Permeability (m^2)	$1x10^{-15}$, $5x10^{-15}$, $1x10^{-14}$, $5x10^{-14}$, $1x10^{-13}$, $1x10^{-12}$, $1x10^{-11}$
Depth (km)	1.5, 2.5, 3.5, 5.0
Approach Temperature (°C)	7, 12, 14, 17, 21, 28

Greenfield or Brownfield Development
Thermosiphon or Pumped System

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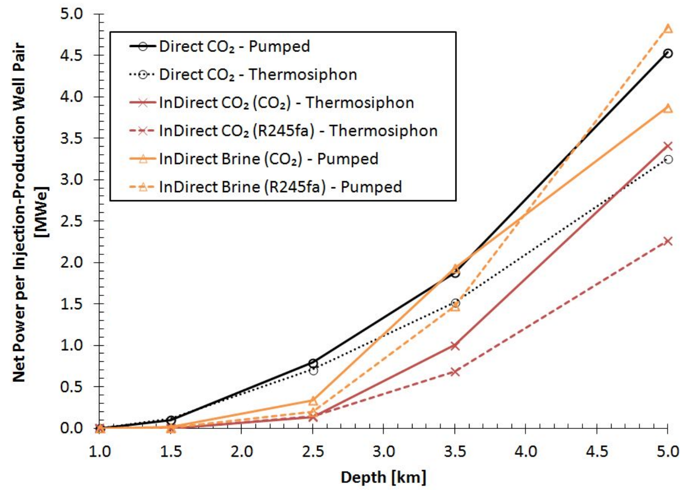
Power Generation

CO_2 generates more power than water (brine) at shallow depths

Base Case
5×10^{-14} m^2 Permeability
35 °C km^{-1} Thermal Gradient
0.41m Injection Well
0.27m Production Well



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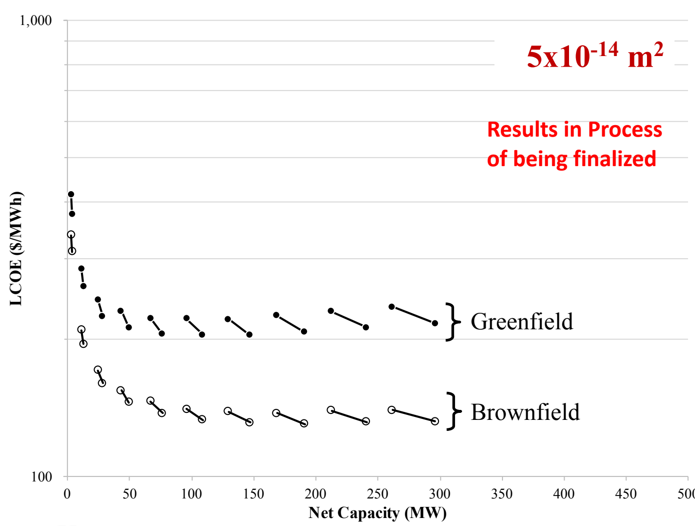
Adams et al., 2015

Levelized Cost of Electricity:

2.5 km, 35°C/km



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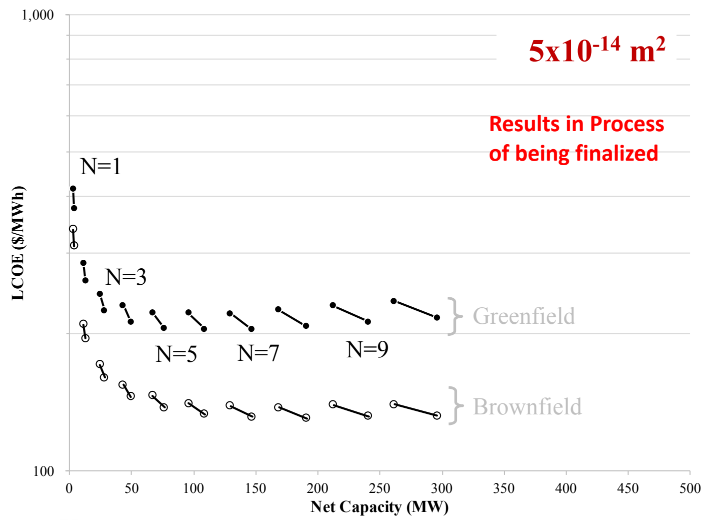

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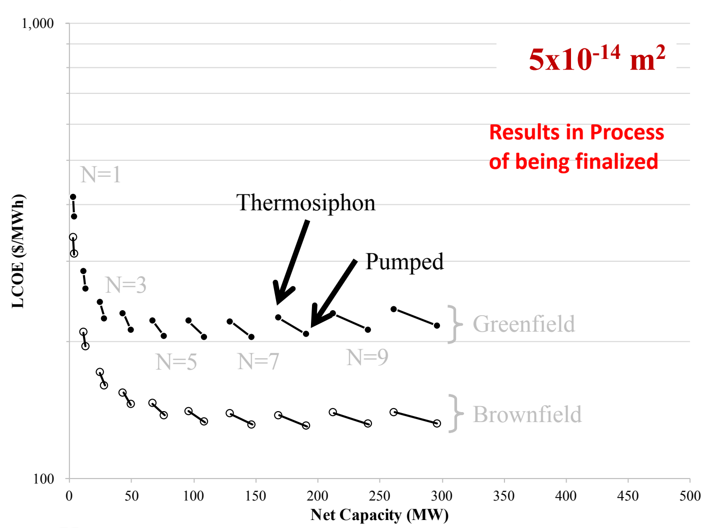

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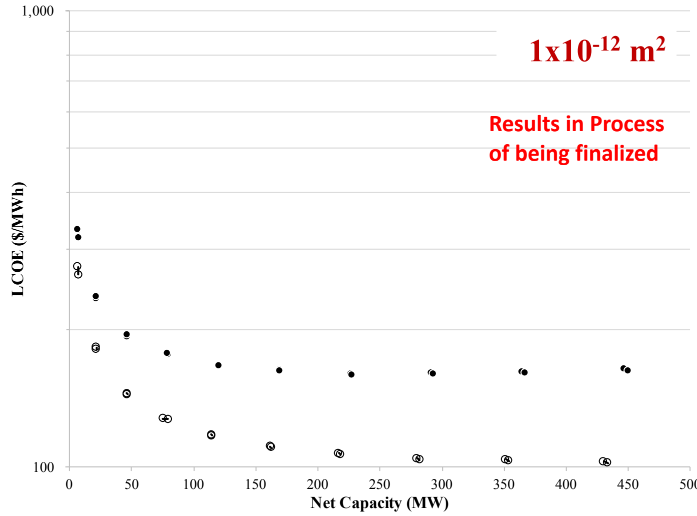
Levelized Cost of Electricity:
2.5 km, 35°C/km



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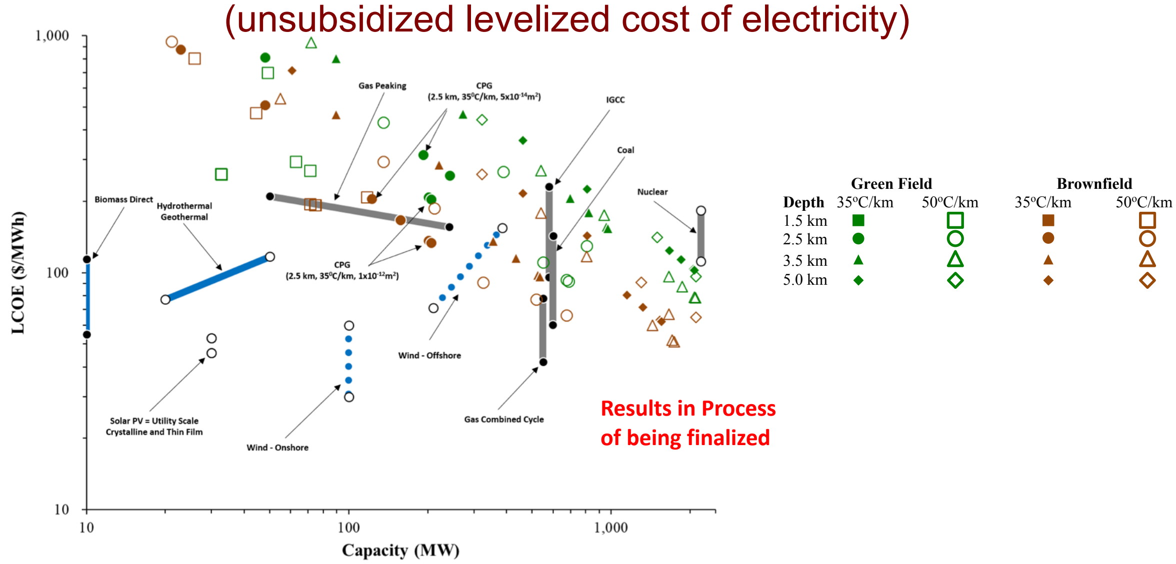
(Can be) Competitive on Cost and Capacity
(unsubsidized levelized cost of electricity)



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LCOE: Dependence on Parameters

Well Pattern Expansion: LCOE initially decreases and then starts to increase

Pumped vs Thermosiphon: pumped systems have higher capacities and lower LCOEs than thermosiphon systems unless very high permeability

Development: brownfield cheaper than greenfield

Permeability: drives decrease in LCOE, up to ~10^{-12} m^2

Depth: LCOE decreases as depth increases, but decrease tapers; not feasible at 1.5 km

Gradient: LCOE decreases as gradient increases, not feasible at 20°C/km

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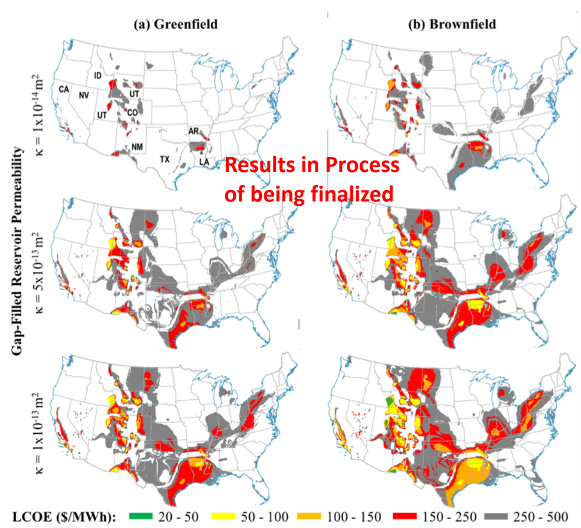
Possible Geospatial Potential

Unsubsidized

Cost-competitive in many areas

WY, LA, AR, CA, TX Gulf Coast



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Take Aways

CO_2 Systems Suited for Relatively shallow depths.

- CO_2 systems preferred over brine up to ~5km, particularly advantageous between 0.5 and 3.0km

LCOE:

- highly sensitive to permeability
- less sensitive to depth and gradient (but 20°C/km and 1.5 km are not viable)

Design and Development

- Most often preferred well pattern is 49 km^2
- brownfield cheaper than greenfield
- pumped system typically cheaper than thermosiphon system

Comparison to Other Energy Technologies

- can be cost competitive
- can be capacity competitive
- can be geographically competitive

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CO_2 vs. Water for Enhanced Geothermal Systems

Check for updates

Special Collection: Advances of Exploration and Utilization Technology of Geothermal Resources in China

ENERGY EXPLORATION & EXPLOITATION

Energy Exploration & Exploitation
2019, Vol. 37(2) 736–755
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DOI: 10.1177/0144598718795492
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Comparison of enhanced geothermal system with water and CO_2 as working fluid: A case study in Zhacanggou, Northeastern Tibet, China

Yanguang Liu, Guiling Wang, Gaofan Yue, Wei Zhang, Xi Zhu and Qinglian Zhang

Abstract
In the study, we analyzed the hot dry rock geothermal field of the Guide Basin in Qinghai Province, China. We used T2Well software—a coupled wellbore–reservoir simulator—to build a "wellbore–reservoir" coupled model with a "three-spot" well pattern (one injection and two production wells). We simulated several fixed flow rate cases in which water or CO_2 is injected. The objectives of our present work are (1) to investigate the fluid flow and thermal processes of water circulating at well bottoms, wellbores, and wellheads; (2) to identify the changing parameters at all physical fields; (3) to understand the influence of injection rates on heat extraction; and (4) to measure the maximum heat extraction capacity of the Guide area. Water extracts more heat than CO_2 at the same flow rate. However, water consumes more pressure in reservoir, and its pressure decreases more quickly as the flow rate increases. In contrast, CO_2 is in a sense a better working fluid. CO_2 consumes less pressure when it flows and can circulate automatically due to the siphon phenomenon. In this way, a lower injection pressure is required in a higher CO_2 flow rate case. The density of CO_2 is sensitive to both temperature and pressure and vice versa. Inside a wellbore, such interactions are extremely complicated. When the fluid rate is slow, a system could operate for 30 years and remain stable, and there is only a small decrease in temperature. However, with higher flow rate scenarios—namely 50, 75, and 100 kg/s—the reservoir will exhibit greater heat loss. The reservoir's production temperature and extraction efficiency will drop dramatically. Therefore, for the Guide area, if a

Institute of Hydrogeology and Environmental Geology Chinese Academy of Geological Sciences

Corresponding author:
Yanguang Liu, 268 Zhonghua North Street, Shijiazhuang, Hebei 050061, China.
Email: gaoyuanzhixing@163.com

"Water extracts more heat than CO_2 at the same flow rate… However, water consumes more pressure in reservoir, and its pressure decreases more quickly as the flow rate increases.

In contrast, **CO_2 is in a sense a better working fluid. CO_2 consumes less pressure when it flows and can circulate automatically due to the siphon phenomenon**…

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With higher flow rate scenarios—namely 50, 75, and 100 kg/s—the reservoir will exhibit greater heat loss. The reservoir's production temperature and extraction efficiency will drop dramatically.

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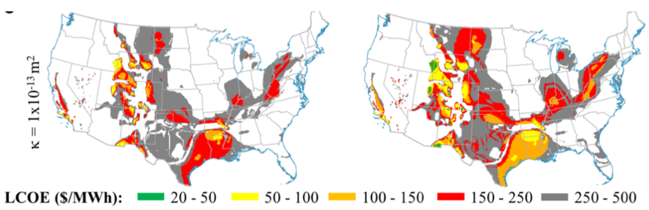
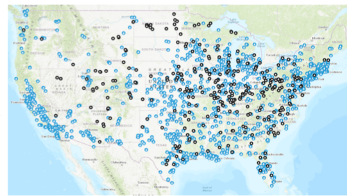
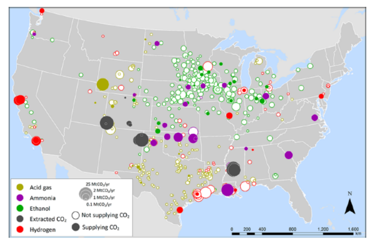
Geospatial Infrastructure Deployment: Source-Sink Matching



Geospatial Potential



Coal and Natural Gas Power Plants



Industrial Sources of CO_2

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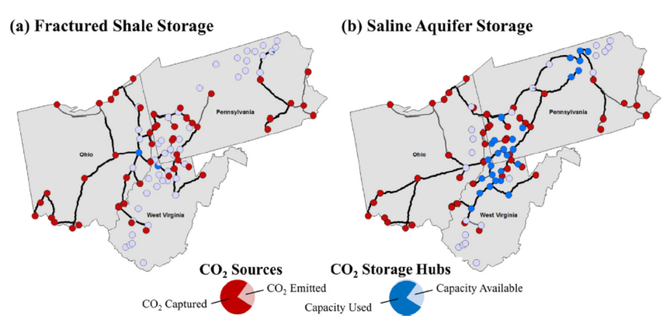
Viable Geospatial Deployment: *SimCCS*

Engineering-Economic, Geospatial Optimization Model

- Where and how much CO_2 to capture
- Where and how much CO_2 to store
- Pipelines: Route, Size, and Flow



Bielicki et al, (2018); Middleton and Bielicki (2009)

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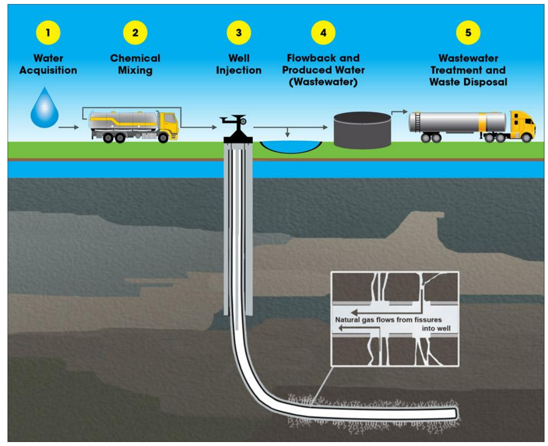
Bedrock for Shale

Where did the "shale" (re)evolution come from?

- Technology
- Markets
- Policy
- First-movers



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2005 Energy Policy Act

Exempted hydraulic fracturing from regulation under the Safe Drinking Water Act

119 STAT. 694 PUBLIC LAW 109–58—AUG. 8, 2005

Subtitle C—Production

SEC. 321. OUTER CONTINENTAL SHELF PROVISIONS.

(a) STORAGE ON THE OUTER CONTINENTAL SHELF.—Section 5(a)(5) of the Outer Continental Shelf Lands Act (43 U.S.C. 1334(a)(5)) is amended by inserting "from any source" after "oil and gas".

(b) NATURAL GAS DEFINED.—Section 3(13) of the Deepwater Port Act of 1974 (33 U.S.C. 1502(13)) is amended by adding at the end before the semicolon the following: ", natural gas liquids, liquefied petroleum gas, and condensate recovered from natural gas".

SEC. 322. HYDRAULIC FRACTURING.

Paragraph (1) of section 1421(d) of the Safe Drinking Water Act (42 U.S.C. 300h(d)) is amended to read as follows:

"(1) UNDERGROUND INJECTION.—The term 'underground injection'—

"(A) means the subsurface emplacement of fluids by well injection; and

"(B) excludes—

"(i) the underground injection of natural gas for purposes of storage; and

"(ii) the underground injection of fluids or propping agents (other than diesel fuels) pursuant to hydraulic fracturing operations related to oil, gas, or geothermal production activities.".

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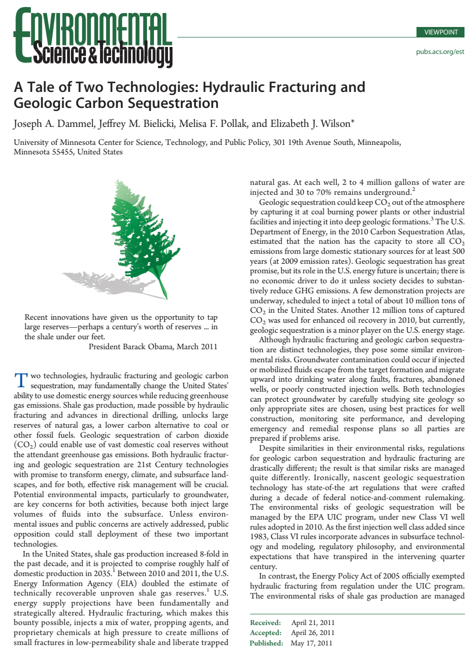
Law / Regulation

Geologic CO_2 injection regulated under a modern regulatory system

Hydraulic Fracturing regulated under less modern regulatory system

Geothermal regulatory system?

Reconcile the hybrid characteristics?



Environmental Science & Technology
VIEWPOINT
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A Tale of Two Technologies: Hydraulic Fracturing and Geologic Carbon Sequestration

Joseph A. Dammel, Jeffrey M. Bielicki, Melisa F. Pollak, and Elizabeth J. Wilson*

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Recent innovations have given us the opportunity to tap large reserves—perhaps a century's worth of reserves ... in the shale under our feet.

President Barack Obama, March 2011

Two technologies, hydraulic fracturing and geologic carbon sequestration, may fundamentally change the United States' ability to use domestic energy sources while reducing greenhouse gas emissions. Shale gas production, made possible by hydraulic fracturing and advances in directional drilling, unlocks large reserves of natural gas, a lower carbon alternative to coal or other fossil fuels. Geologic sequestration of carbon dioxide (CO_2) could enable use of vast domestic coal reserves without the attendant greenhouse gas emissions. Both hydraulic fracturing and geologic sequestration are 21st Century technologies with promise to transform energy, climate, and subsurface landscapes, and for both, effective risk management will be crucial. Potential environmental impacts, particularly to groundwater, are key concerns for both activities, because both inject large volumes of fluids into the subsurface. Unless environmental issues and public concerns are actively addressed, public opposition could stall deployment of these two important technologies.

In the United States, shale gas production increased 8-fold in the past decade, and it is projected to comprise roughly half of domestic production in 2035.[1] Between 2010 and 2011, the U.S. Energy Information Agency (EIA) doubled the estimate of technically recoverable unproven shale gas reserves.[1] U.S. energy supply projections have been fundamentally and strategically altered. Hydraulic fracturing, which makes this bounty possible, injects a mix of water, propping agents, and proprietary chemicals at high pressure to create millions of small fractures in low-permeability shale and liberate trapped natural gas. At each well, 2 to 4 million gallons of water are injected and 30 to 70% remains underground.[2]

Geologic sequestration could keep CO_2 out of the atmosphere by capturing it at coal burning power plants or other industrial facilities and injecting it into deep geologic formations.[3] The U.S. Department of Energy, in the 2010 Carbon Sequestration Atlas, estimated that the nation has the capacity to store all CO_2 emissions from large domestic stationary sources for at least 500 years (at 2009 emission rates). Geologic sequestration has great promise, but its role in the U.S. energy future is uncertain; there is no economic driver to do it unless society decides to substantively reduce GHG emissions. A few demonstration projects are underway, scheduled to inject a total of about 10 million tons of CO_2 in the United States. Another 12 million tons of captured CO_2 was used for enhanced oil recovery in 2010, but currently, geologic sequestration is a minor player on the U.S. energy stage.

Although hydraulic fracturing and geologic carbon sequestration are distinct technologies, they pose some similar environmental risks. Groundwater contamination could occur if injected or mobilized fluids escape from the target formation and migrate upward into drinking water along faults, fractures, abandoned wells, or poorly constructed injection wells. Both technologies can protect groundwater by carefully studying site geology so only appropriate sites are chosen, using best practices for well construction, monitoring site performance, and developing emergency and remedial response plans so all parties are prepared if problems arise.

Despite similarities in their environmental risks, regulations for geologic carbon sequestration and hydraulic fracturing are drastically different; the result is that similar risks are managed quite differently. Ironically, nascent geologic sequestration technology has state-of-the art regulations that were crafted during a decade of federal notice-and-comment rulemaking. The environmental risks of geologic sequestration will be managed by the EPA UIC program, under new Class VI well rules adopted in 2010. As the first injection well class added since 1983, Class VI rules incorporate advances in subsurface technology and modeling, regulatory philosophy, and environmental expectations that have transpired in the intervening quarter century.

In contrast, the Energy Policy Act of 2005 officially exempted hydraulic fracturing from regulation under the UIC program. The environmental risks of shale gas production are managed

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Dammel et al (2011)

Techno-Economic Assessment of Energy Technologies

Levelized Cost of Electricity ($/MWh)

- Annualized capital and operating costs

Capital Costs ($/MW)

- Construction

System Integration and Effects

- Value-added
- Infrastructure reductions

Policy and Market Enablers and Constraints

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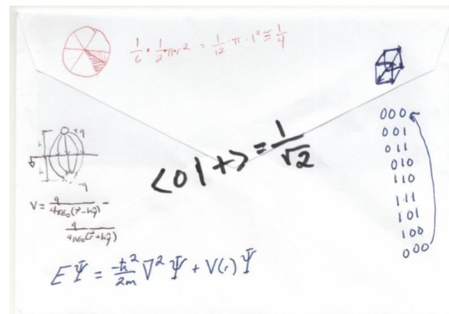
45 Q Tax Credit for Subsurface Emplacement of Industrial CO_2

Up to \$50/tCO_2 for geologic storage

Up to \$35/tCO_2 for using stored CO_2

Is CO_2-based geothermal-generated electricity worth \$15/tCO_2?



Back of the Envelope:

- Electricity revenue: \$70/MWh; Capacity factor: 85%
- Need ~29 MW/MtCO_2 (Not accounting for costs)

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Socio-Economic Assessment of Energy Technologies

Social Well-Being
- Employment
- Income / income inequality
- Rural development

Energy security
- Energy security premium
- Price volatility

Trade
- Terms
- Volume

Profitability
- Return on Investment
- Net Present Value

Social Acceptability
- Public opinion
- Sense of place / community
- Transparency / communication

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Relevant Questions for a Specific Technology

How well does it compete on its own?

How well does it fit within the relevant system?

How well does it work with / enable other energy technologies?

What are the policy, regulatory, and legal enablers and constraints?

What are the socioeconomic implications and opportunities?

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