CO_2-Storage-Based Geothermal Electricity Generation Potential of Sedimentary Basins in the United States*

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Abstract

To manage global climate change and maintain global mean surface temperatures within 2°C of the pre-industrial value, the Intergovernmental Panel on Climate Change has concluded that the cumulative amount of CO_2 emitted to the atmosphere must be below 3600 $GtCO_2$. But more than half of this budget has already been emitted, and meeting this aggressive goal requires a substantial reduction in CO_2 emissions—between a 40% and 70% reduction by 2050 and even negative emissions (up to a 120% reduction) by the year 2100. For these reductions to be achievable there must be extensive investment in zero and low-carbon energy technologies, such as wind, solar, nuclear, and fossil fuel, the latter with CO_2 capture and (geologic) storage (CCS). Estimates suggest that if CO_2 emission mitigation efforts are delayed until 2030, the market share for these energy technologies will need to increase to approximately 90% by 2100 and costs will increase 40%. As such, there is an urgent need to deploy these energy sources. CO_2 Plume Geothermal (CPG) combines CCS with geothermal resources to produce baseload and/or dispatchable renewable electricity with no CO_2 emissions. With CPG, underground-stored CO_2 is circulated to the surface, extracting heat from the naturally porous and permeable sedimentary basin. These geologic resources are more ubiquitous than the faulted systems presently used with natural geofluid (brine) geothermal electricity generation. Thus, CPG could be a vital part of climate change mitigation if it is spatially and economically viable. In this work, we combine our existing levelized cost of electricity (LCOE) models with geospatial data on sedimentary basins in the United States to conduct a resource assessment of the national potential for CPG systems. The results indicate that 7200 km^2 of the U.S. has an estimated CPG LCOE less than

$50/MWh and 160,000 km^2 has an LCOE less than $100/MWh, which are less than other dispatchable energy technologies, e.g. coal with CCS ($143/MWh) and natural gas peaking plants ($191/MWh). These LCOEs are also favorable when compared to other renewable energy technologies, like conventional geothermal ($98/MWh), wind ($47/MWh), and solar ($55/MWh), although the latter two are variable and not dispatchable. Unlike conventional geothermal energy, which is limited to the southwestern U.S., CPG could be extensively deployed in sedimentary basins in the central and eastern U.S. where average geothermal temperature gradients exist.

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AAPG | SEG Conference & Exposition

Alterra Soda Lake 15 MWe Facility – Fallon, NV

Puna, HI 38 MWe Plant

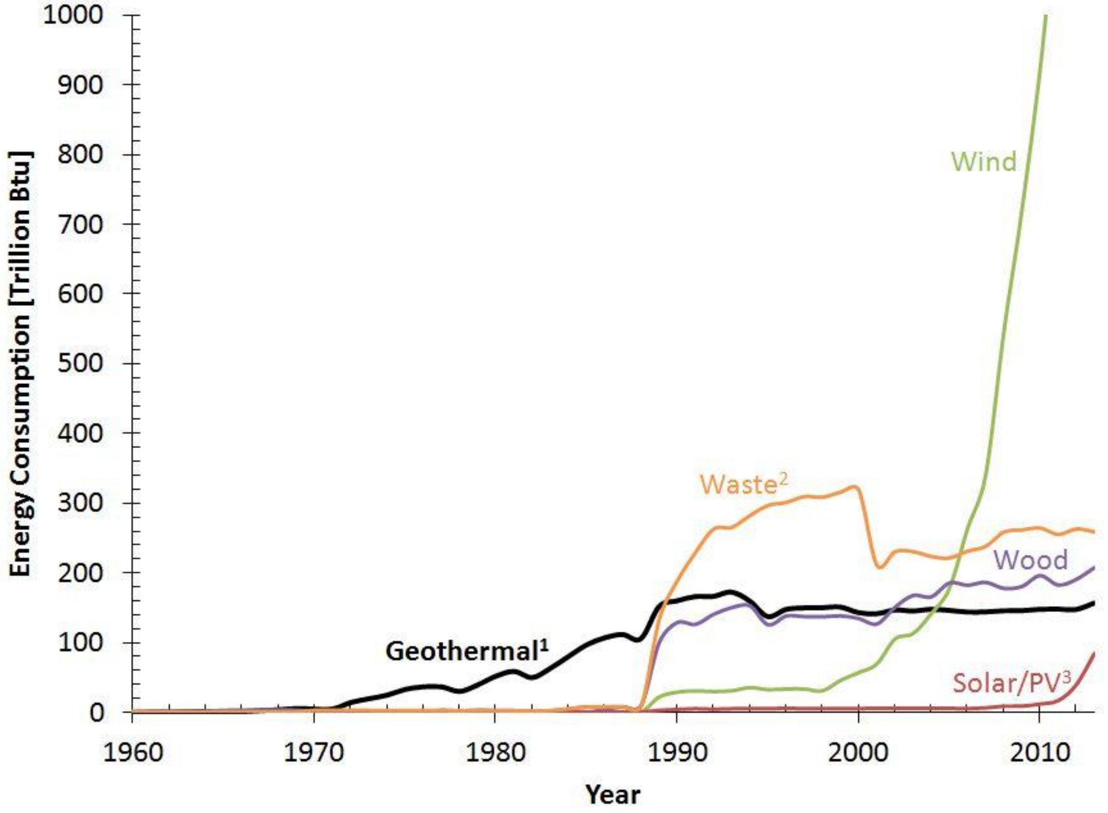
Approximate Earth Crust
Temperature Gradient = **30 °C km^{-1}**

Source: (Left) Ormat; (Right) britannica.com

Existing Geothermal

Geysers—Middletown, CA 725 MWe Plant   Source: Calpine

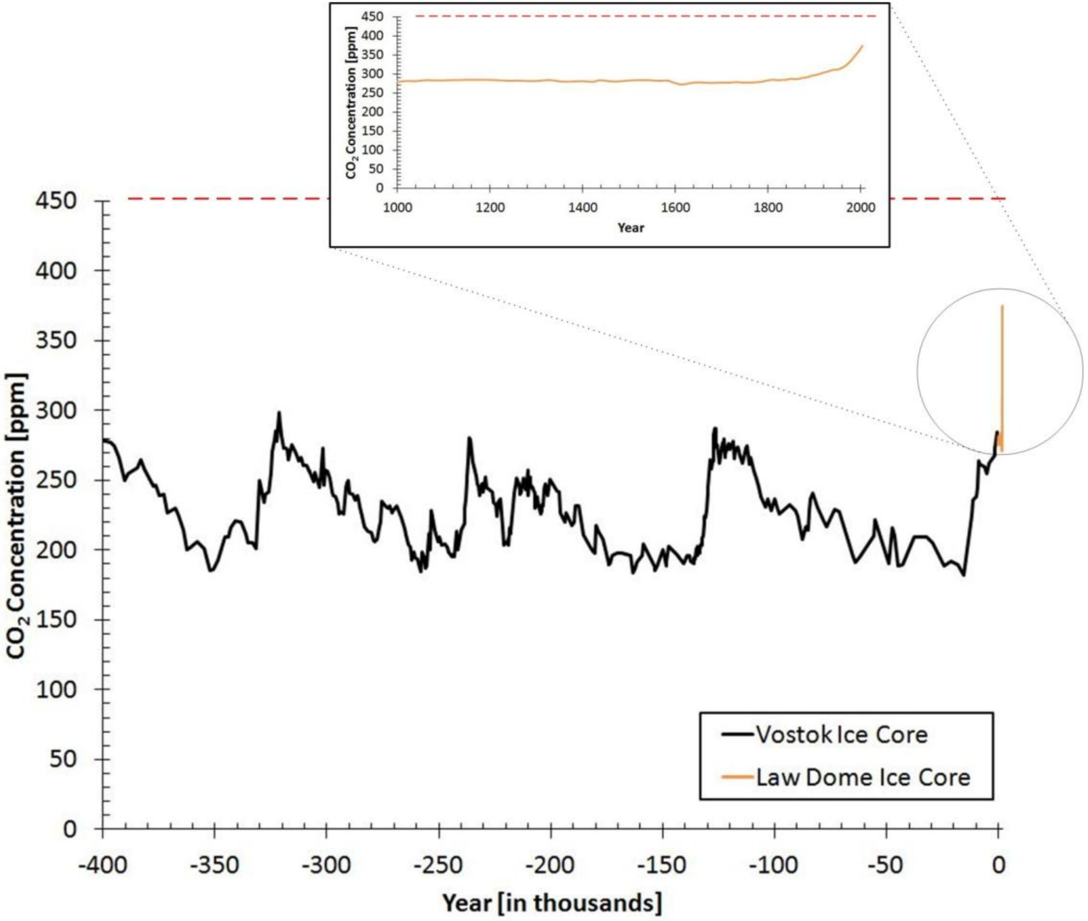
U.S. Geothermal development has stagnated



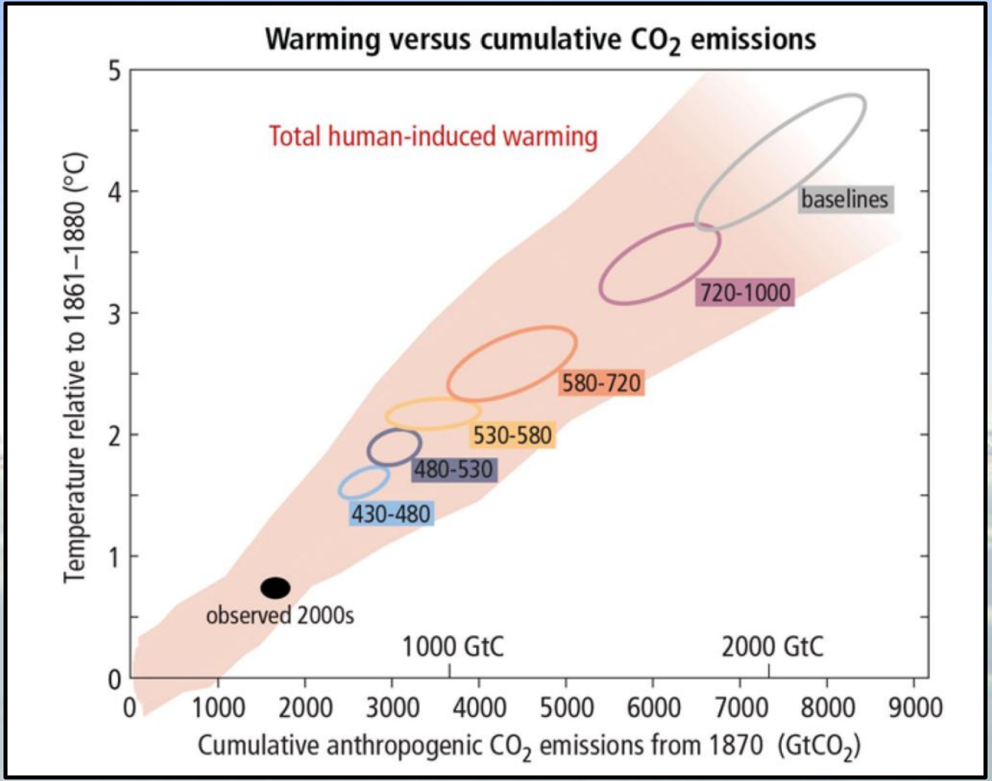
Data Source: U.S. Energy Information Administration (EIA)

Agenda

- Atmospheric CO_2 is bad (>450 ppm)
- Sequester, sequester
- Use captured CO_2 for geothermal
- CPG can work better than brine
- Potential for <50 $/MW CPG
- CO_2 availability limits its scaleout



Data Source: Carbon Dioxide Information Analysis Center (CDIAC)



IPCC: Reduction of 78% to 118% by 2100 is necessary to keep temperature increase below 2°C.

Source: (Top) IPCC 5th Assessment Synthesis Report (Bottom) kplu.org

Mitigation Measures

More efficient use of energy

Greater use of low-carbon and no-carbon energy

- Many of these technologies exist today

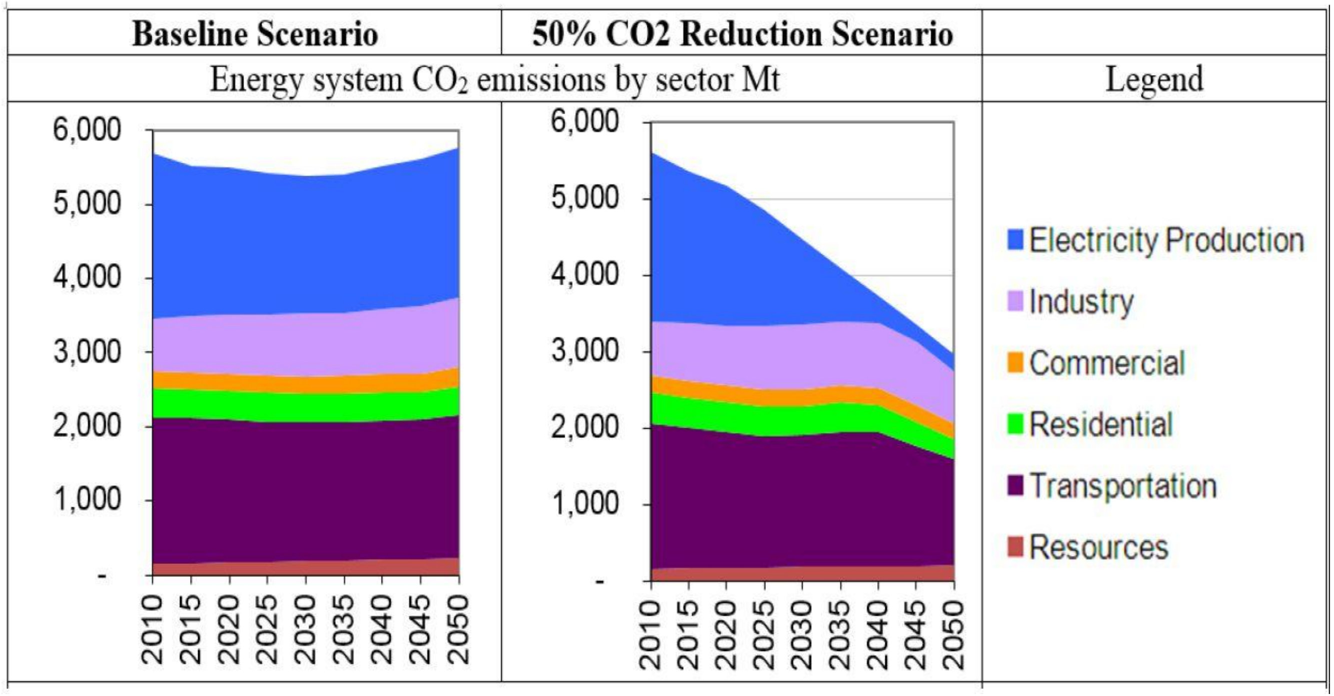
Improved carbon sinks

- Reduced deforestation and improved forest management and planting of new forests
- Bio-energy with carbon capture and storage

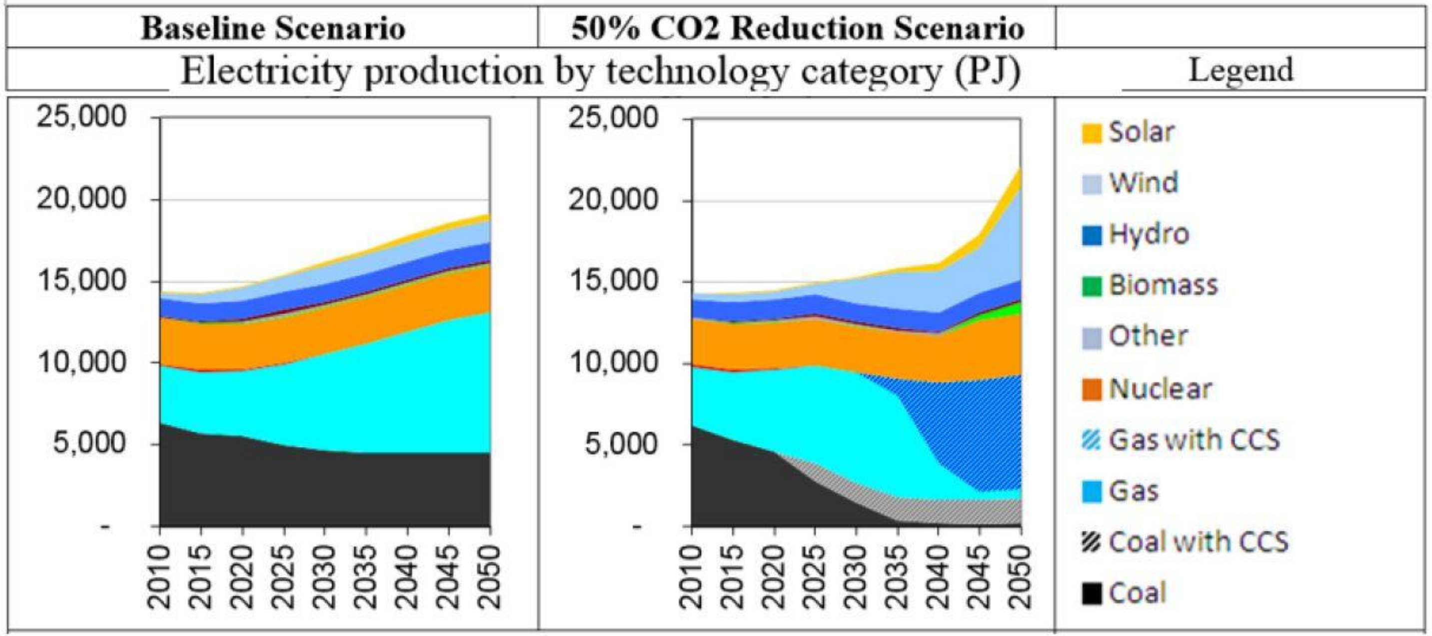
Lifestyle and behavioural changes

AR5 WGIII SPM

INTERGOVERNMENTAL PANEL ON climate change

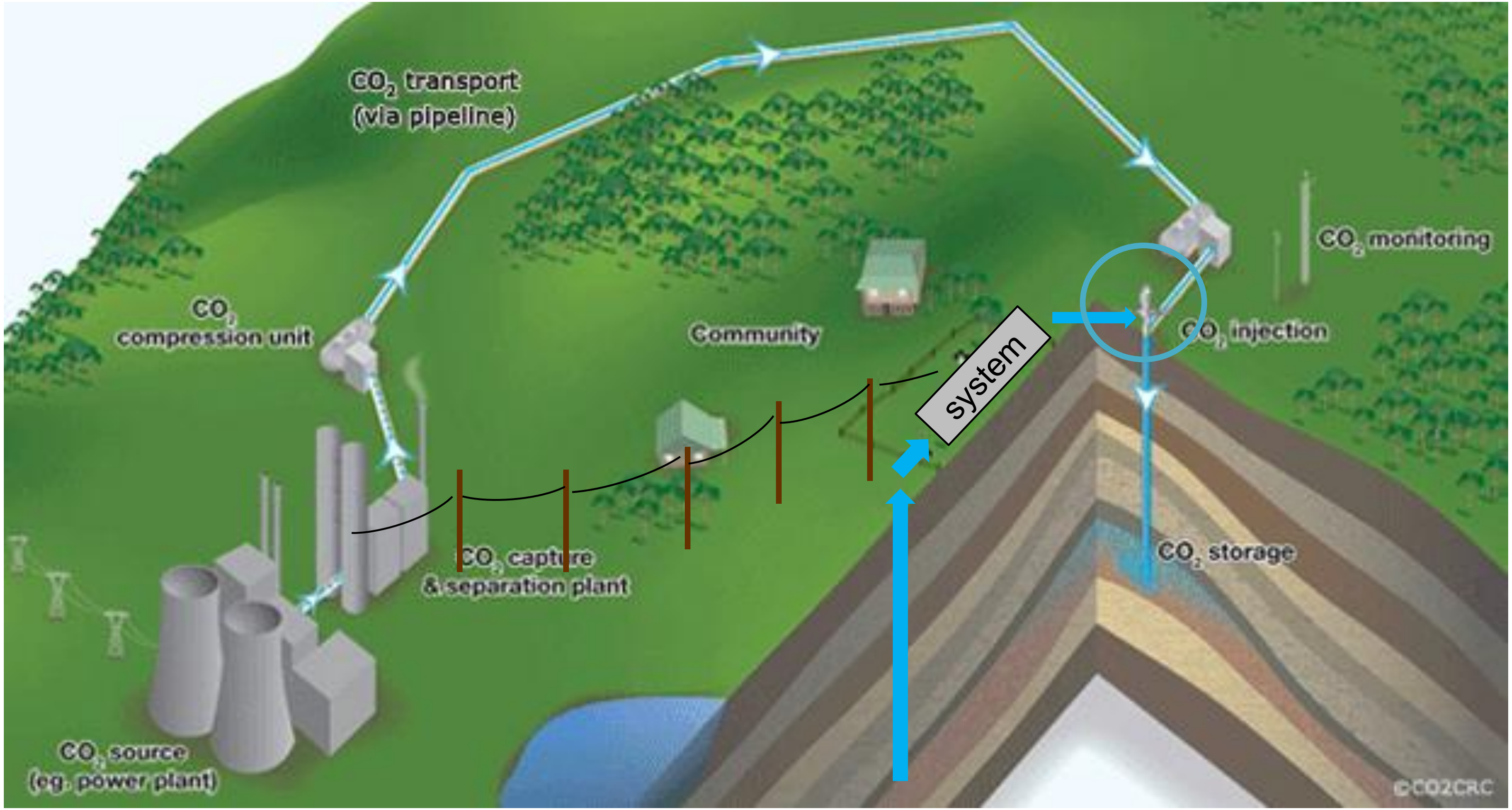


Source: Princiotta & Loughlin (2014)

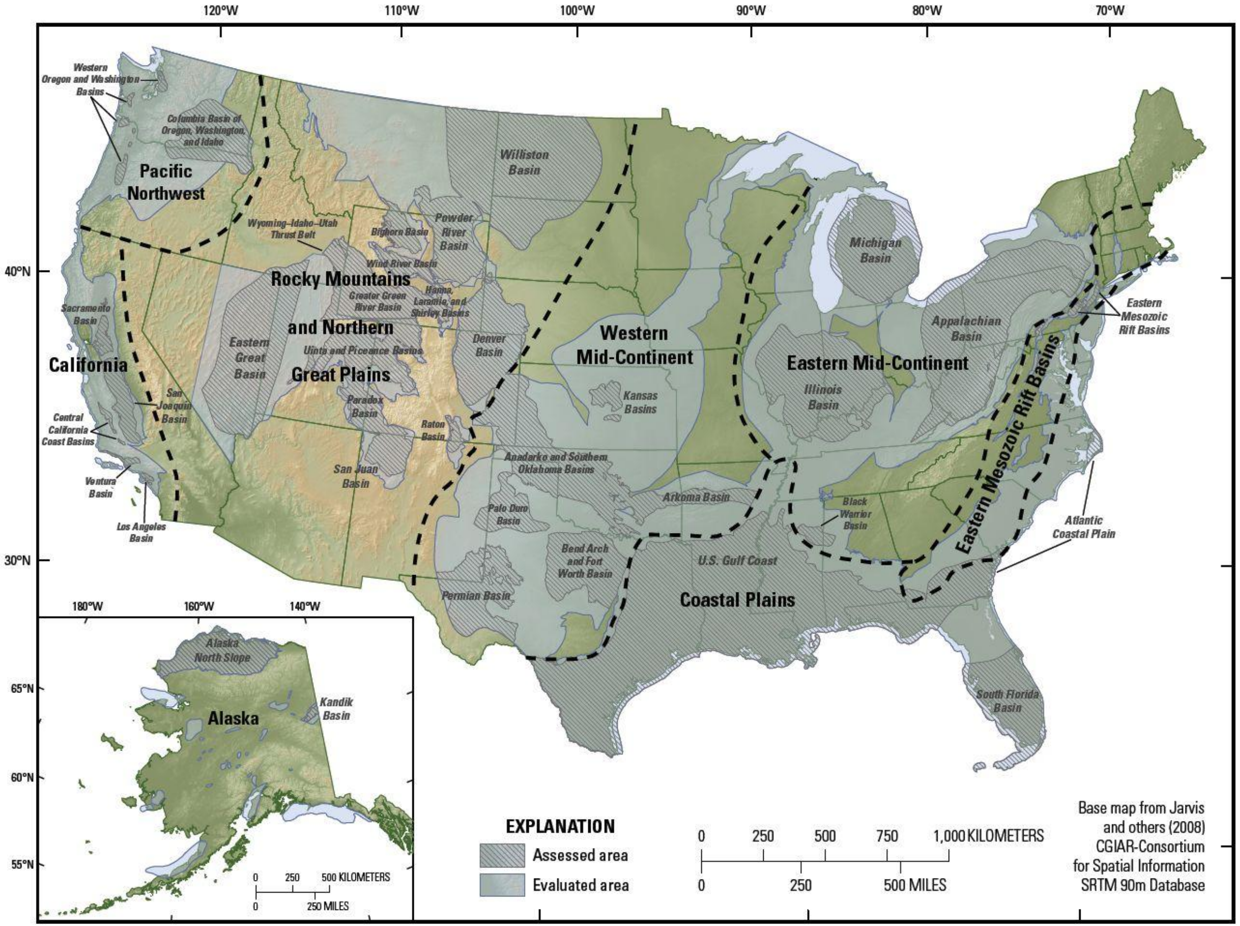


Source: Princiotta & Loughlin (2014)

CPG is built on CCS



Source: GlobalCcsInstitute.com



3000 Gt CO_2
US: 5.5 Gt/yr

Permeability and porosity vary. Source: USGS National Assessment of CO_2 Resources (2013)

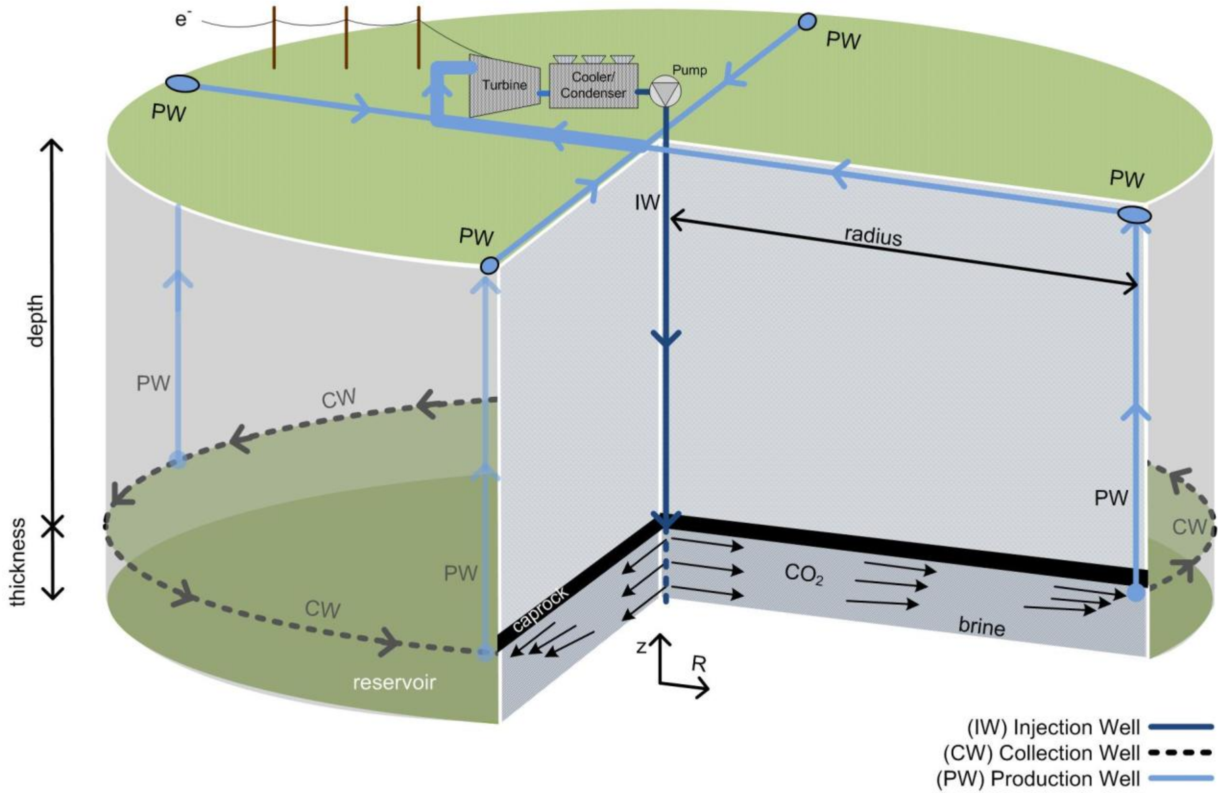
CPG Basics

Circulate CO_2!

CO_2 is a better geothermal fluid because:

- Low Viscosity
- Similar Heat Capacity
- Compressible
- No or Few Pumps
- Low Silica Solubility

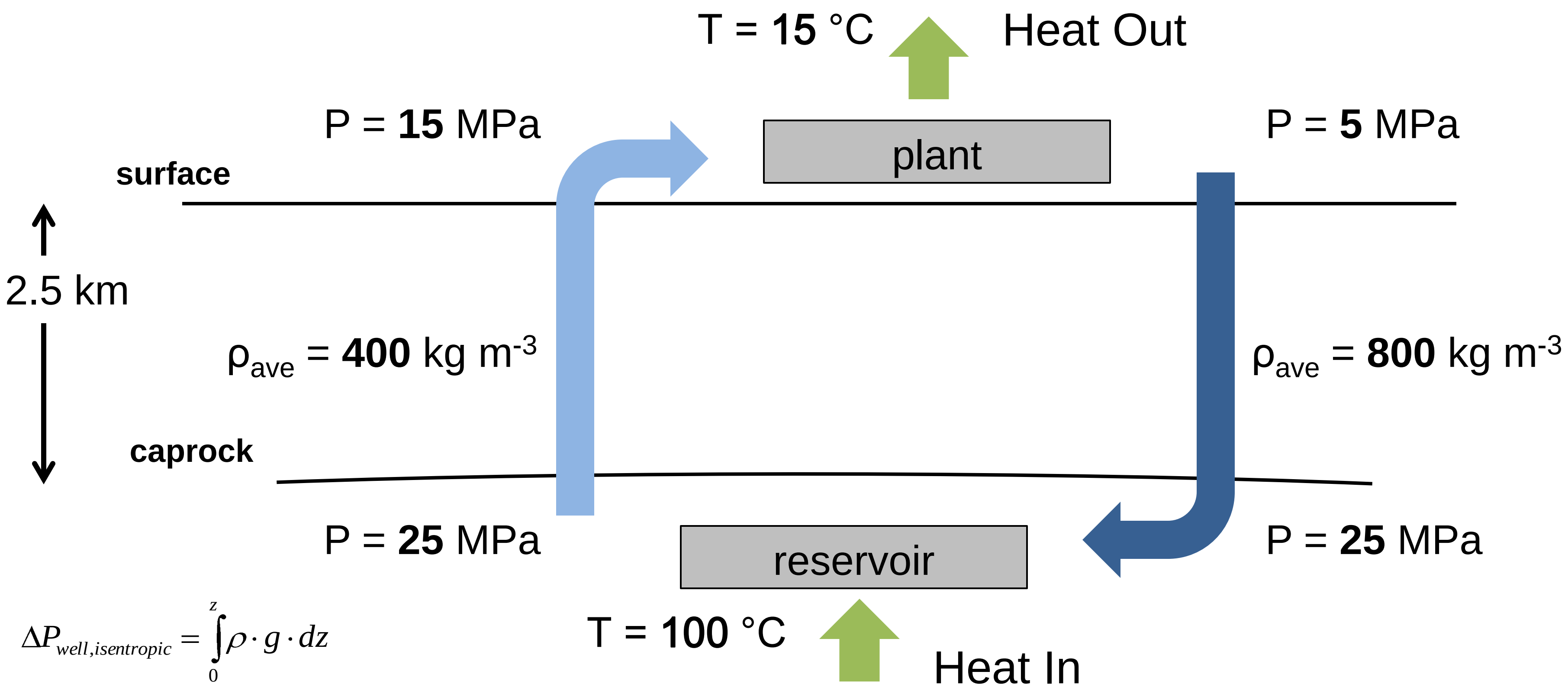
What is CO_2 Plume Geothermal (CPG)?



- CO_2-based
- Deep
- Sedimentary
- Scalable

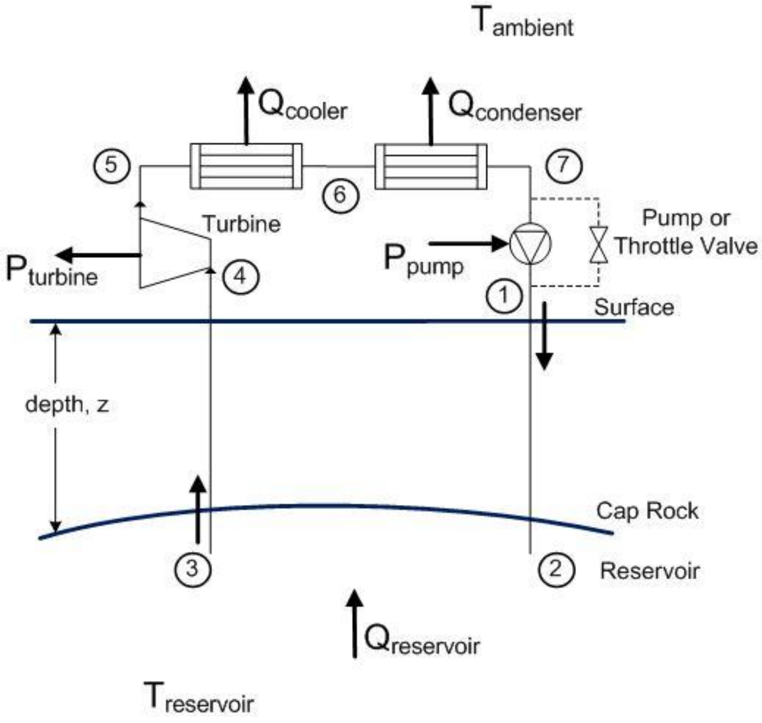
Source: Adams et al. (In Preparation)

How a Thermosiphon Works



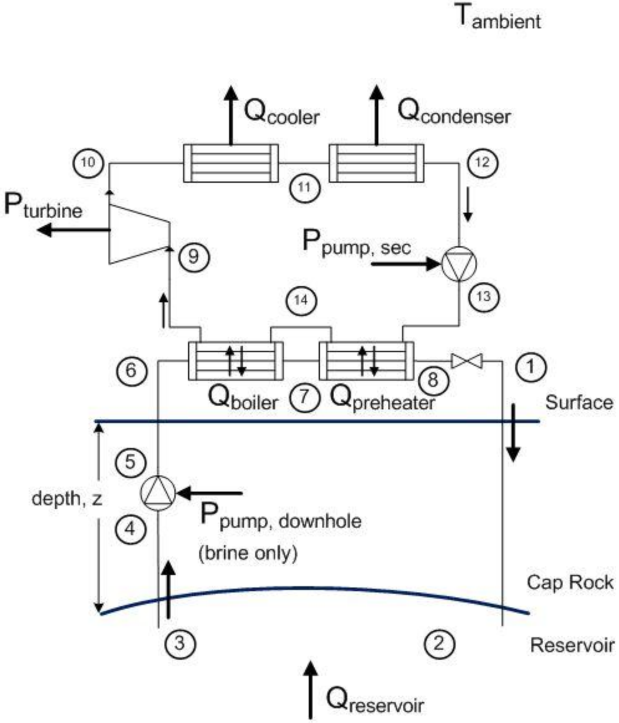
$$\Delta P_{well,isentropic} = \int_0^z \rho \cdot g \cdot dz$$

Injection and production wellhead pressure difference generated by thermosiphon



Direct

Primary Fluid: CO_2
Options: Thermosiphon –or – Supplemental Pumping



Indirect

Primary Fluid: CO_2 or brine
Secondary Fluid: CO_2 or R245fa

Source: Adams et al. (2015)

Direct CO_2 - Pumped

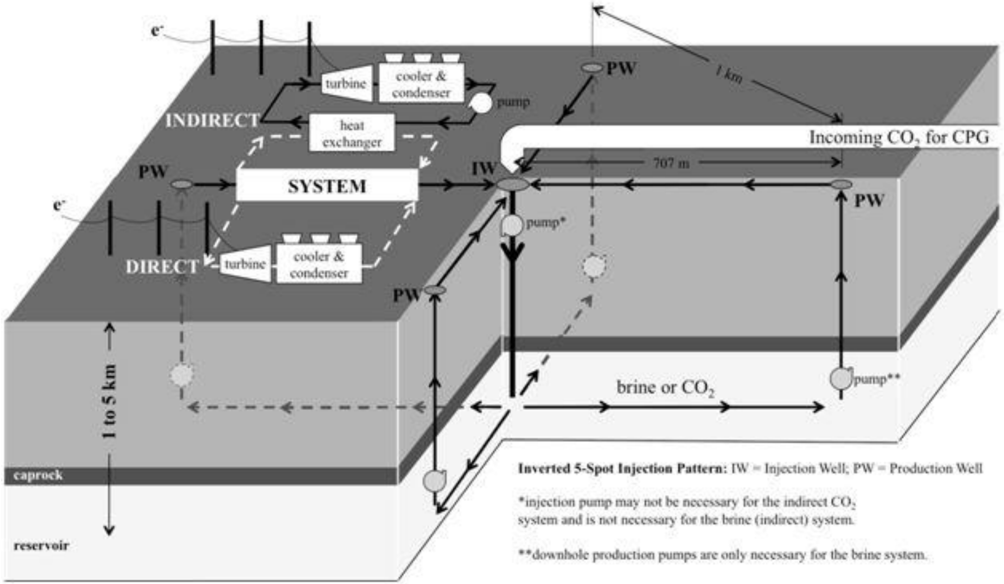
Power Output per Production-Injection Pair [MWe]

Temp Gradient [°C km⁻¹]	Depth [km]	0.27m Inj & Prod Diameter					0.33m Inj & Prod Diameter					0.41m Inj & Prod Diameter				
		$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2	$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2	$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2
20	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1
	3.5	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.2	0.2	0.0	0.0	0.2	0.3	0.4
	5.0	0.0	0.1	0.3	0.3	0.4	0.0	0.2	0.4	0.5	0.6	0.0	0.2	0.6	0.8	1.1
35	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1.5	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.2	0.2	0.0	0.0	0.2	0.3	0.3
	2.5	0.0	0.2	0.5	0.6	0.6	0.0	0.2	0.7	0.9	1.1	0.0	0.3	0.9	1.3	1.8
	3.5	0.1	0.6	1.0	1.1	1.2	0.1	0.7	1.6	1.8	2.1	0.1	0.7	2.3	2.9	3.6
	5.0	0.2	1.5	2.3	2.5	2.6	0.2	1.9	3.7	4.0	4.4	0.2	2.2	5.6	6.5	7.7
50	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.1
	1.5	0.0	0.2	0.6	0.7	0.7	0.0	0.3	0.8	1.0	1.2	0.0	0.3	1.1	1.5	2.1
	2.5	0.1	0.8	1.6	1.7	1.9	0.1	1.0	2.4	2.7	3.1	0.1	1.0	3.4	4.3	5.4
	3.5	0.3	1.9	3.0	3.2	3.4	0.3	2.3	4.7	5.2	5.7	0.3	2.6	7.0	8.4	10.0
	5.0	0.8	4.4	6.0	6.2	6.5	0.8	5.9	9.6	10.2	10.9	0.8	7.2	15.3	17.1	19.1

Indirect Brine (R245fa) - Pumped

Power Output per Production-Injection Pair [MWe]

Temp Gradient [°C km⁻¹]	Depth [km]	0.27m Inj & Prod Diameter					0.33m Inj & Prod Diameter					0.41m Inj & Prod Diameter				
		$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2	$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2	$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2
20	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3.5	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.1	0.4
	5.0	0.0	0.1	0.4	0.5	0.8	0.0	0.1	0.4	0.7	1.3	0.0	0.1	0.4	0.8	2.1
35	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1
	2.5	0.0	0.0	0.2	0.3	0.6	0.0	0.0	0.2	0.4	0.9	0.0	0.0	0.2	0.4	1.5
	3.5	0.0	0.3	1.1	1.5	2.1	0.0	0.3	1.4	2.1	3.5	0.0	0.3	1.5	2.6	5.9
	5.0	0.1	1.1	3.2	3.8	4.5	0.1	1.2	4.2	5.6	7.6	0.1	1.2	5.1	7.9	13.0
50	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
	1.5	0.0	0.0	0.1	0.1	0.4	0.0	0.0	0.1	0.1	0.6	0.0	0.0	0.1	0.1	0.8
	2.5	0.0	0.4	1.4	1.9	2.7	0.0	0.4	1.6	2.5	4.4	0.0	0.4	1.7	3.1	7.4
	3.5	0.1	1.1	3.5	4.4	5.4	0.1	1.2	4.5	6.3	8.9	0.1	1.2	5.3	8.6	15.3
	5.0	0.1	1.5	3.5	4.1	4.6	0.1	1.5	4.9	6.2	7.7	0.1	1.6	6.3	9.1	13.3



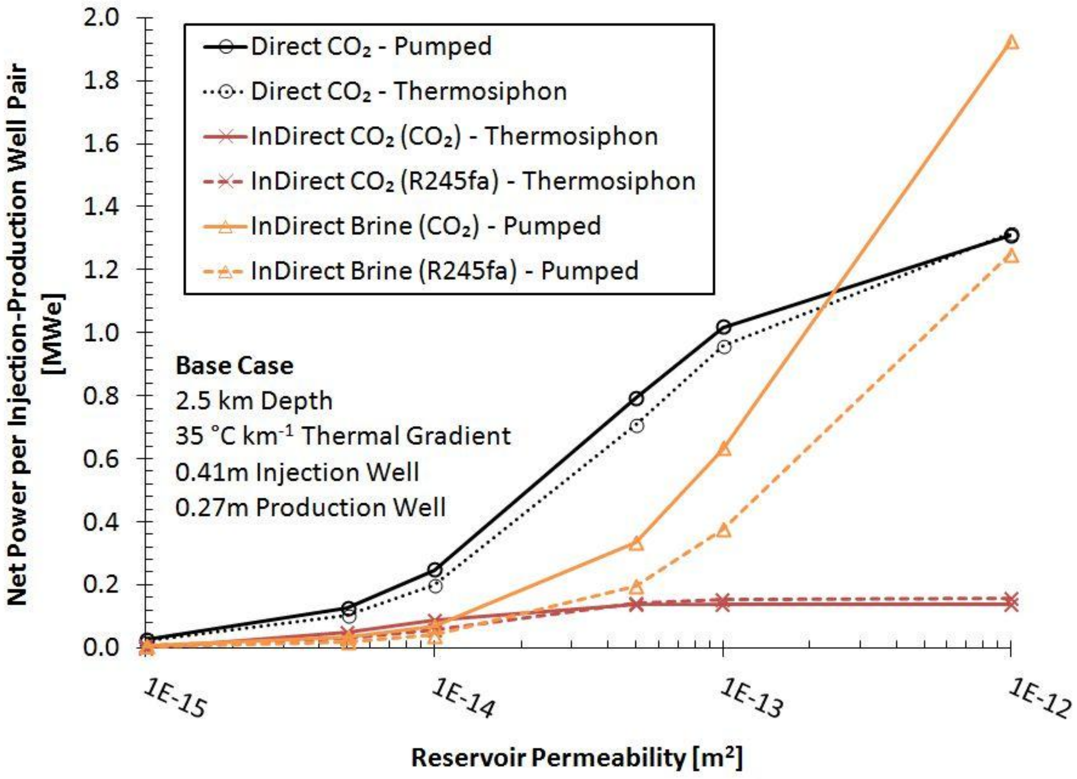
Source: Adams et al. (2015)

A Direct CPG system provides more power than Indirect brine at low to moderate permeabilities and depths.

Temp Gradient [°C km^{-1}]	Depth [km]	0.27m Inj & Prod Diameter					0.33m Inj & Prod Diameter					0.41m Inj & Prod Diameter				
		$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2	$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2	$1x10^{-15}$ m^2	$1x10^{-14}$ m^2	$5x10^{-14}$ m^2	$1x10^{-13}$ m^2	$1x10^{-12}$ m^2
	1.0															
	1.5															
20	2.5														0.1	0.1
	3.5			0.1					0.1	0.1				0.1	0.2	
	5.0			-0.1	-0.2	-0.4		0.1		-0.2	-0.6		0.1	0.1		-1.0
	1.0															
	1.5			0.1	0.1	0.1			0.1	0.2	0.1			0.2	0.3	0.2
35	2.5		0.2	0.3	0.3			0.2	0.5	0.5	0.1		0.2	0.7	0.9	0.3
	3.5	0.1	0.3	-0.1	-0.4	-0.9	0.1	0.3	0.2	-0.3	-1.4		0.4	0.8	0.2	-2.3
	5.0	0.1	0.4	-0.8	-1.3	-1.9	0.1	0.8	-0.6	-1.6	-3.2	0.1	1.0	0.5	-1.3	-5.4
	1.0								0.1	0.1				0.1	0.1	0.1
	1.5		0.2	0.5	0.5	0.4		0.2	0.7	0.9	0.7		0.2	1.0	1.3	1.3
50	2.5	0.1	0.5	0.2	-0.2	-0.8	0.1	0.6	0.8	0.2	-1.3	0.1	0.7	1.7	1.2	-1.9
	3.5	0.2	0.8	-0.5	-1.1	-2.0	0.2	1.2	0.2	-1.1	-3.2	0.2	1.5	1.7	-0.2	-5.3
	5.0	0.7	3.0	2.5	2.2	1.9	0.7	4.3	4.7	4.0	3.2	0.7	5.6	9.0	7.9	5.8

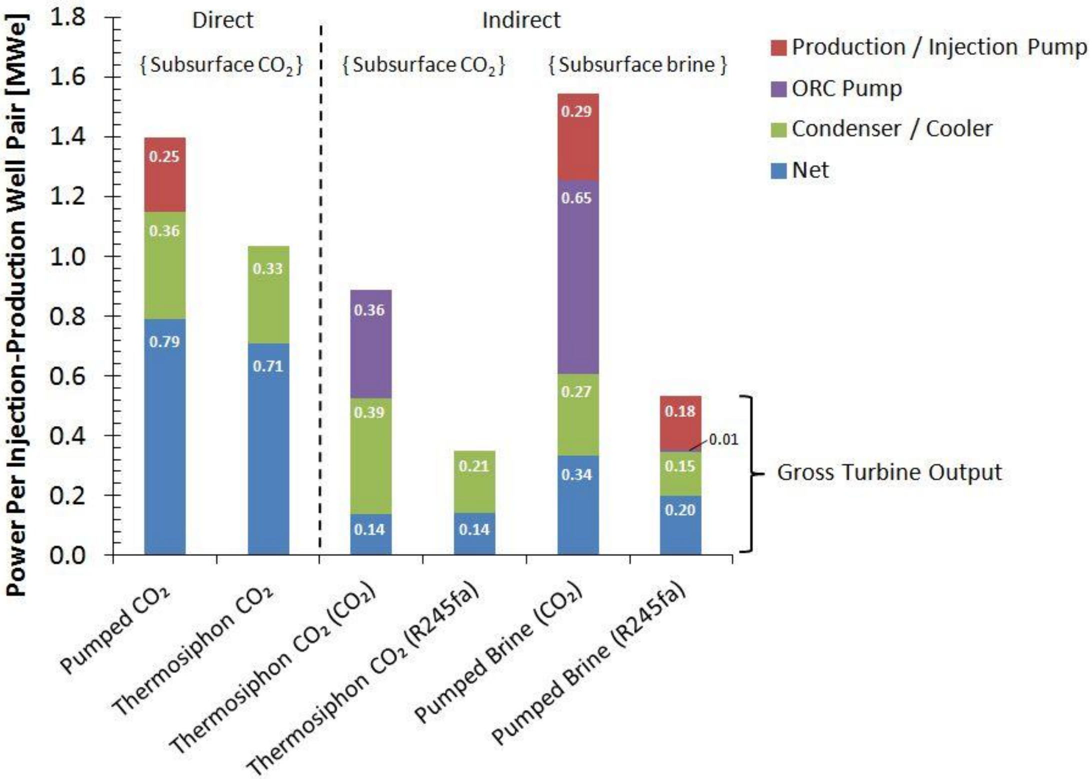
Source: Adams et al. (2015)

CPG systems produce more power at low to moderate permeability.



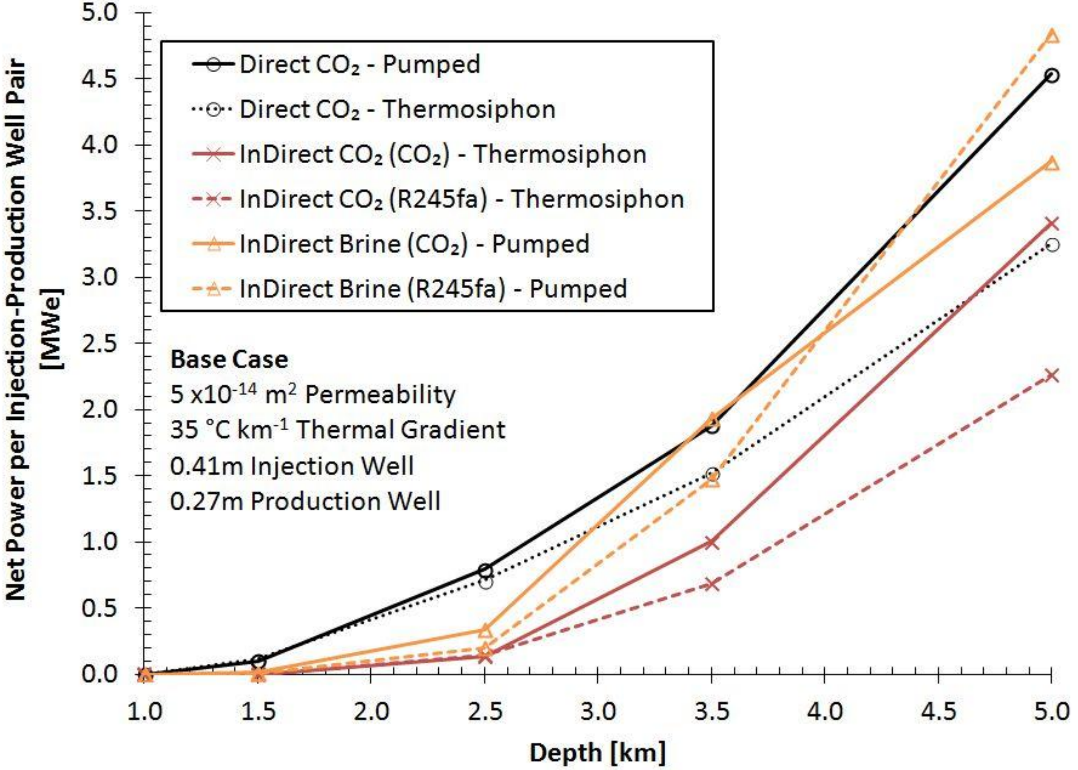
Source: Adams et al. (2015)

Direct systems tend to be most efficient at 2.5 km, 50 mD.



Source: Adams et al. (2015)

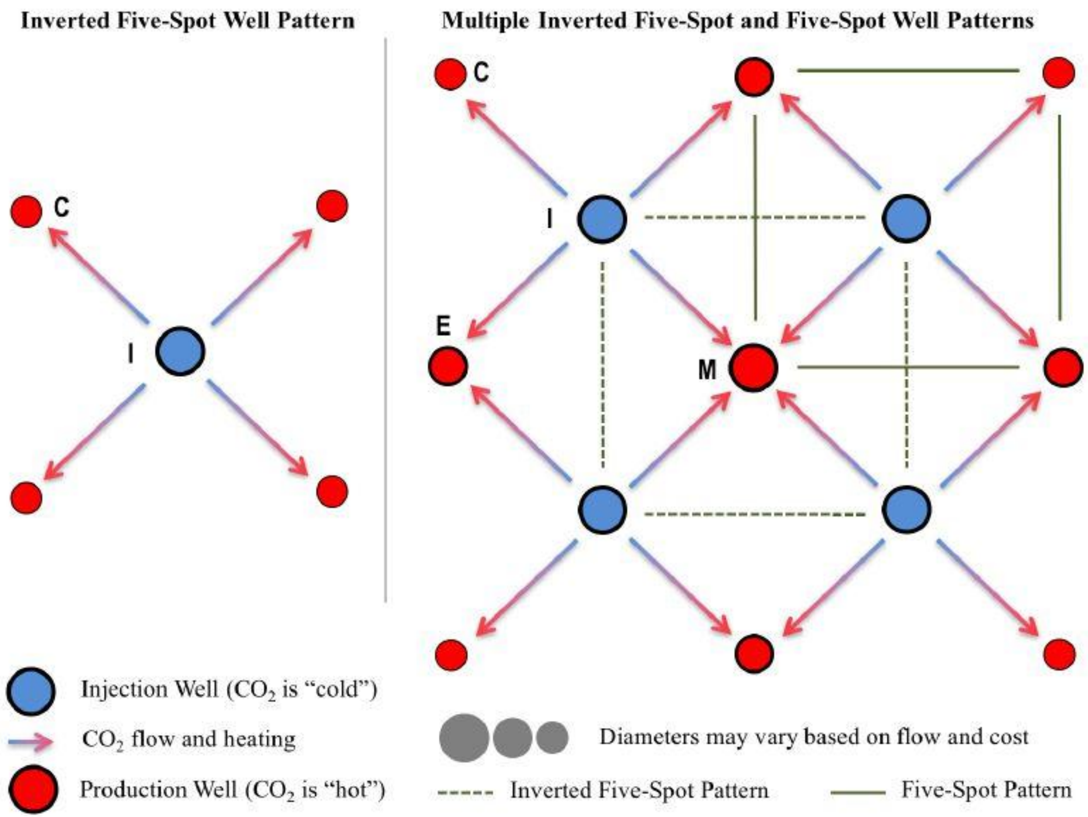
CPG has greater power at shallower depths



Source: Adams et al. (2015)

CPG Economics

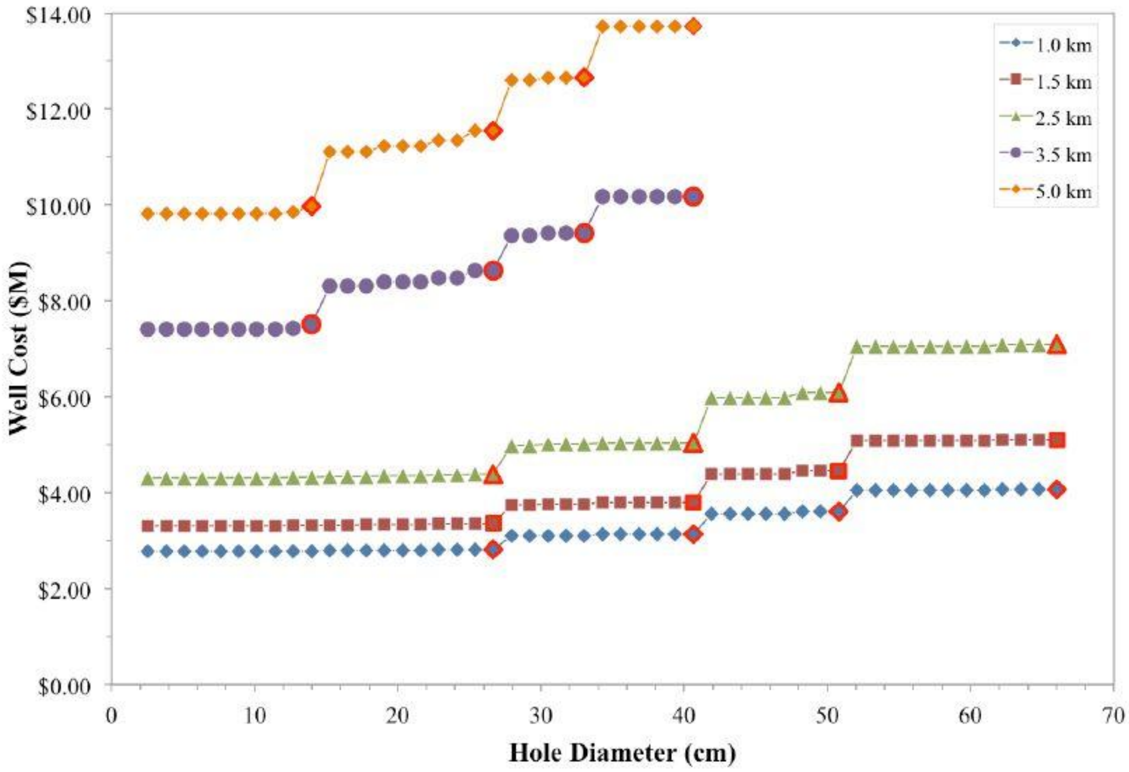
System is Scalable



For 5-spot:
10 Mton CO_2 => 4 MWe

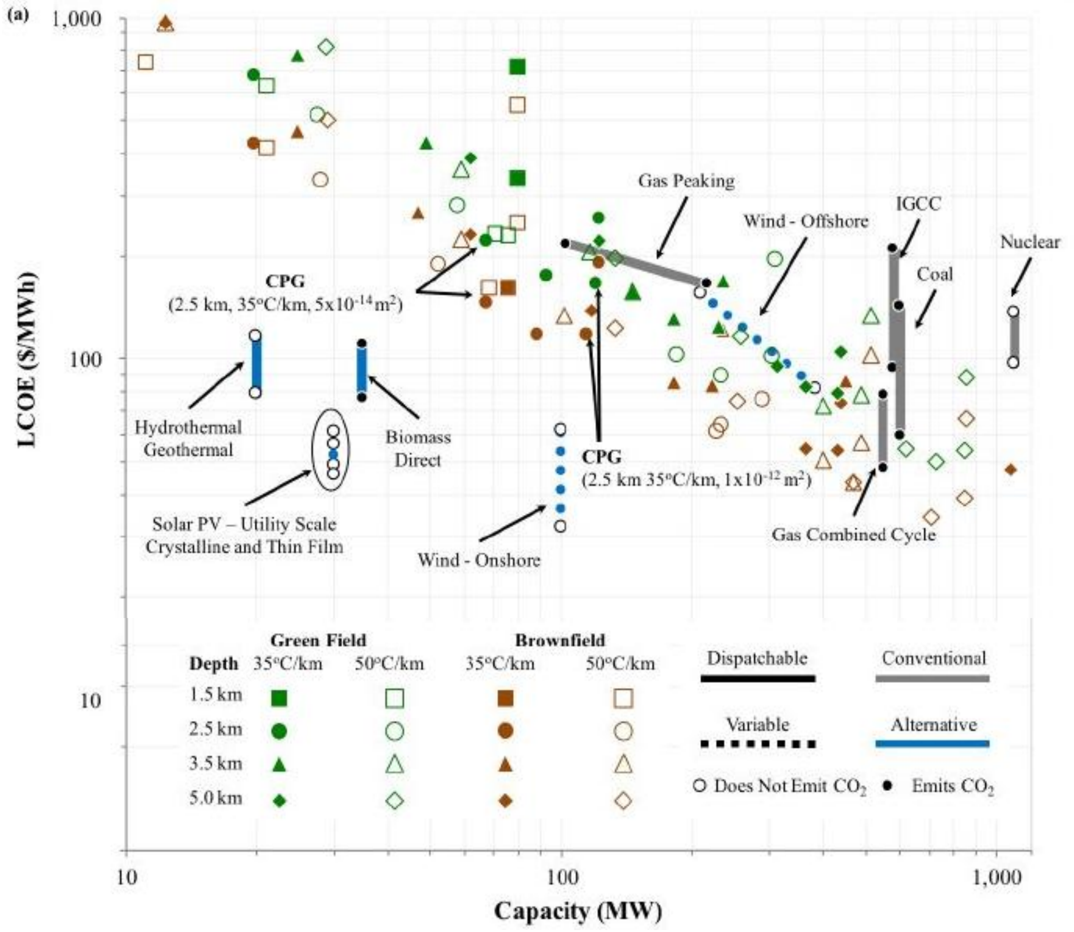
Source: Bielicki et al. (submitted)

Cost values from GETEM



$$m = f(d^{2.5})$$

Source: Bielicki et al. (submitted)



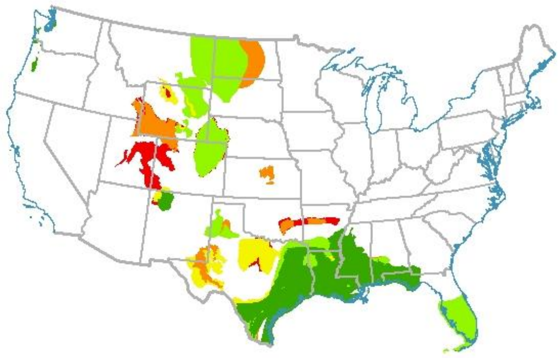
Source: Bielicki et al. (submitted) mapped on Lazard (2015)

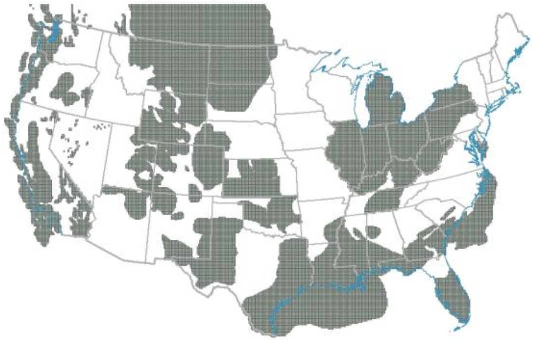
Multiple Data Sources Needed

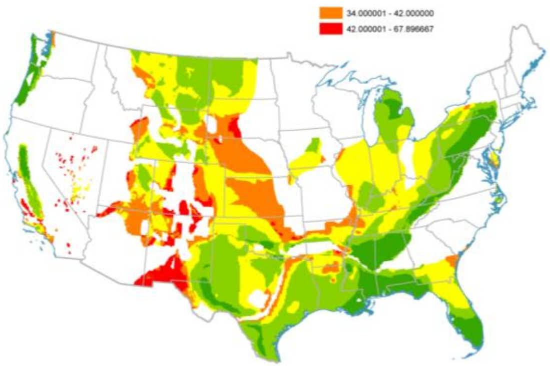
USGS

NATCARB

Princeton





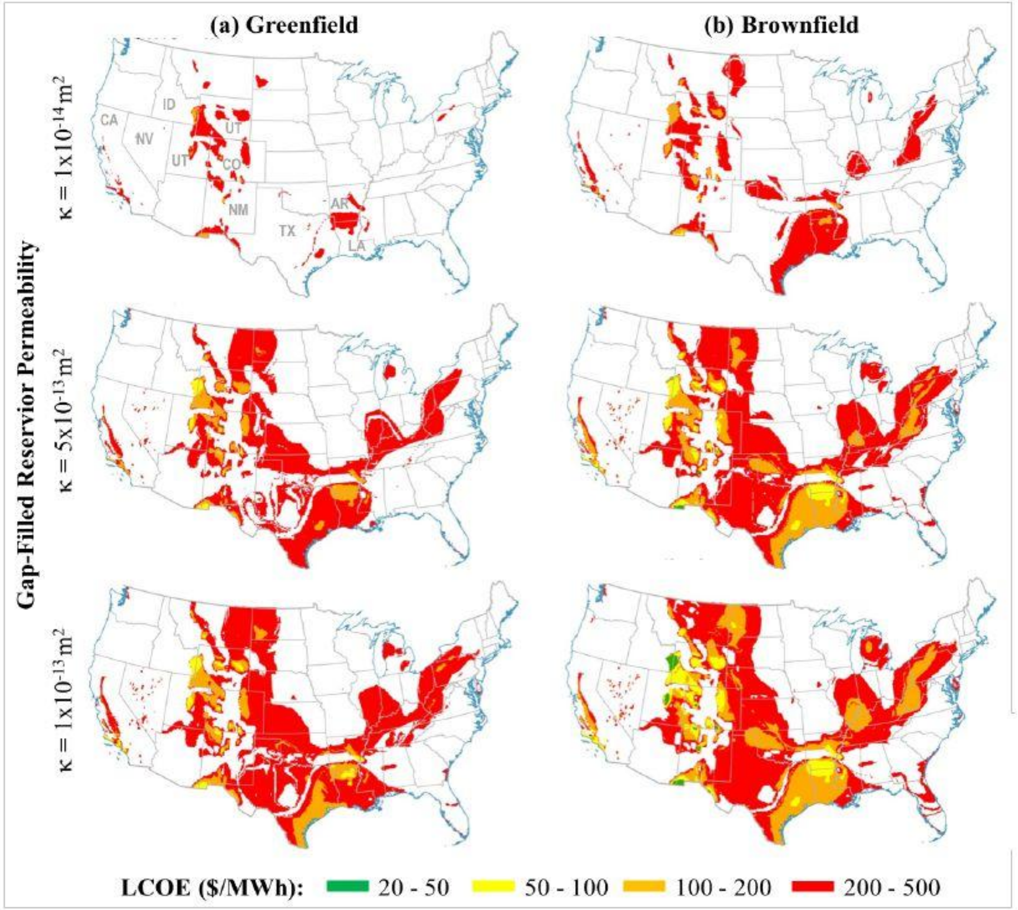


- Permeability
- CO_2 Volume

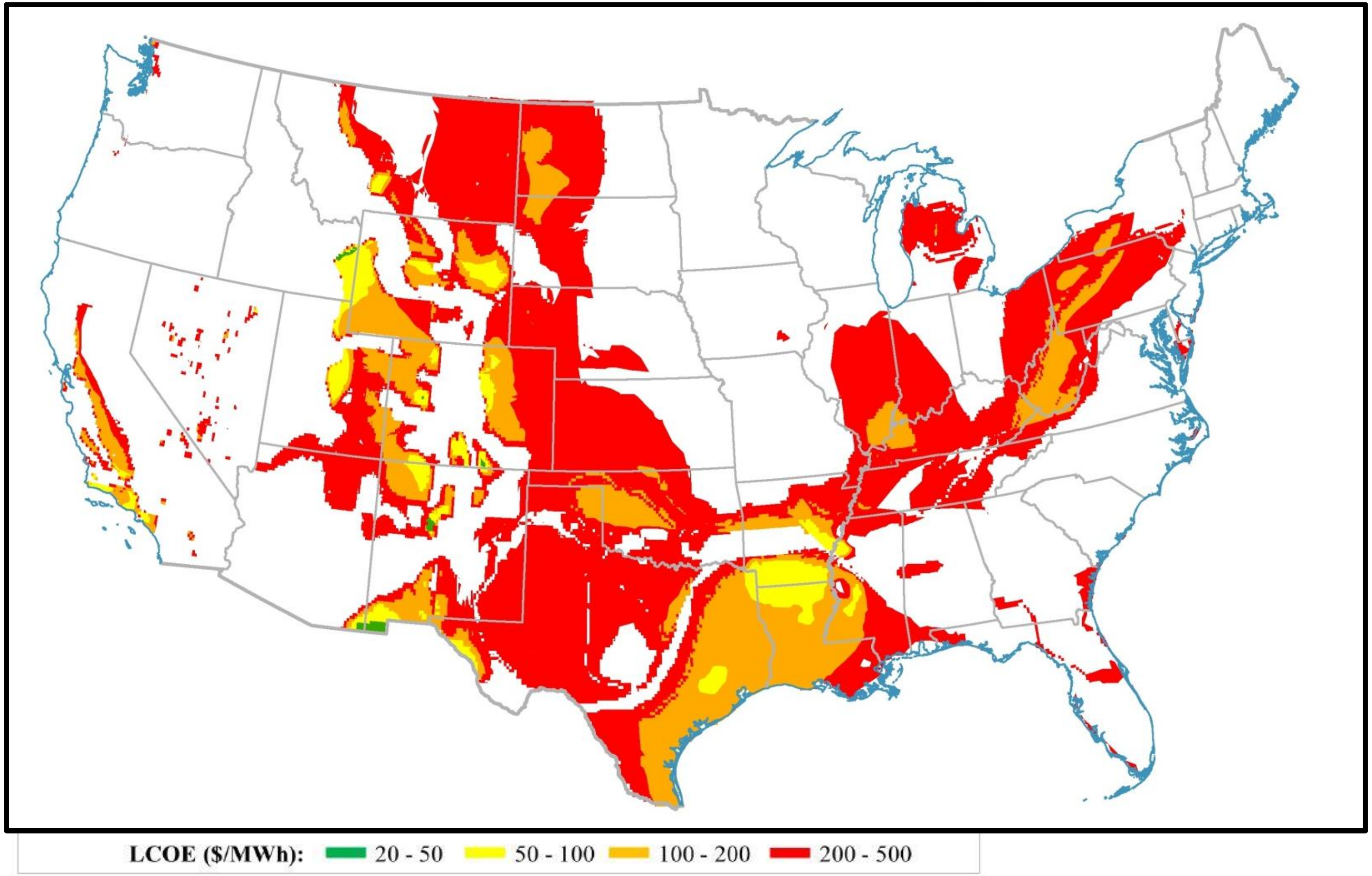
- Occasionally Permeability
- Occasionally CO_2 Volume

-Temp Only
- Depth

From Elliot et al. (2012)



Source: Bielicki et al. (submitted)



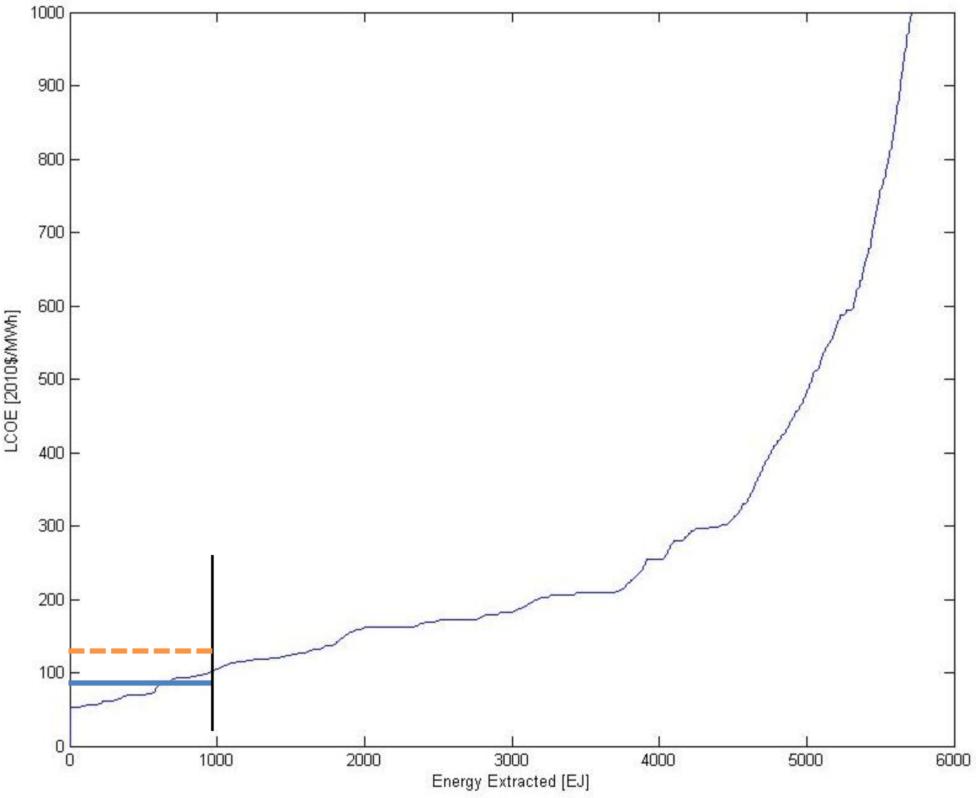
Source: Bielicki et al. (submitted)

Finding impact to future energy market

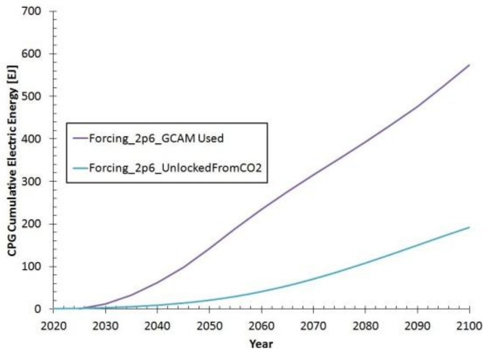
- Global Change Assessment Model (GCAM) used to predict adoption of CPG
  - Population
  - Energy Consumption
  - Energy Supply Curves for all Technologies

GCAM is free for download from Pacific Northwest National Lab and University of Maryland

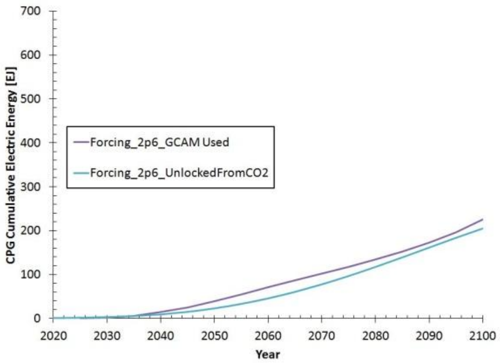
CPG Energy Supply Curves



$80/MW-hr

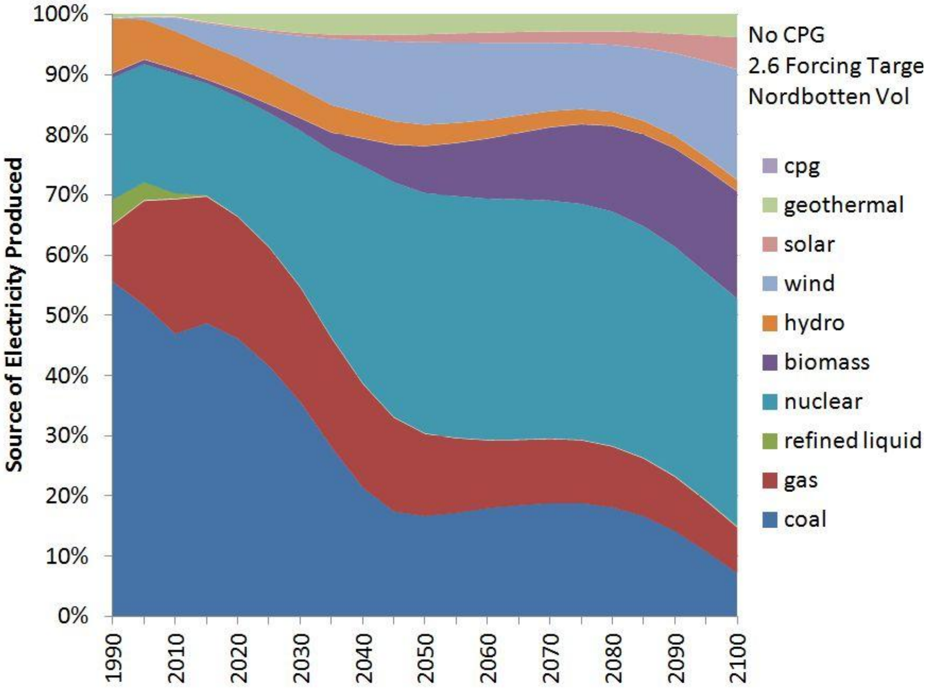


$120/MW-hr

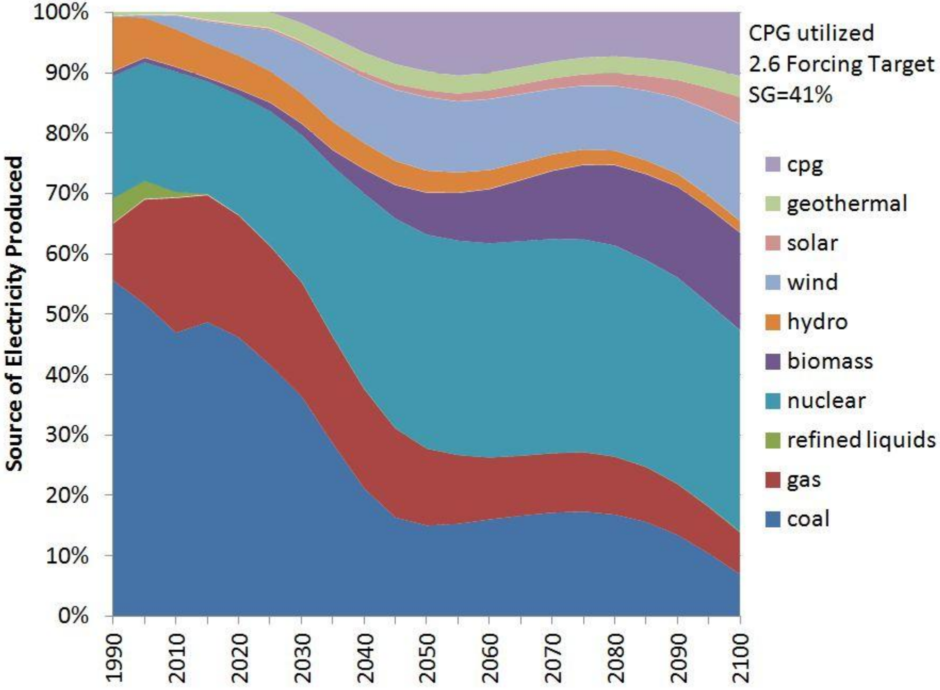


CPG would be widely utilized

No CPG



CPG At $120/MW-hr



RCP 2.6 ~ 450 ppm max conc.

Conclusions

- CPG can be used in sedimentary basins
- CPG circulates CO_2 to generate power
- CPG can generate more power than traditional brine
- CPG has competitive LCOEs
- CPG is economically viable at $120/MW-hr
- CPG is limited by sequestered CO_2 volume