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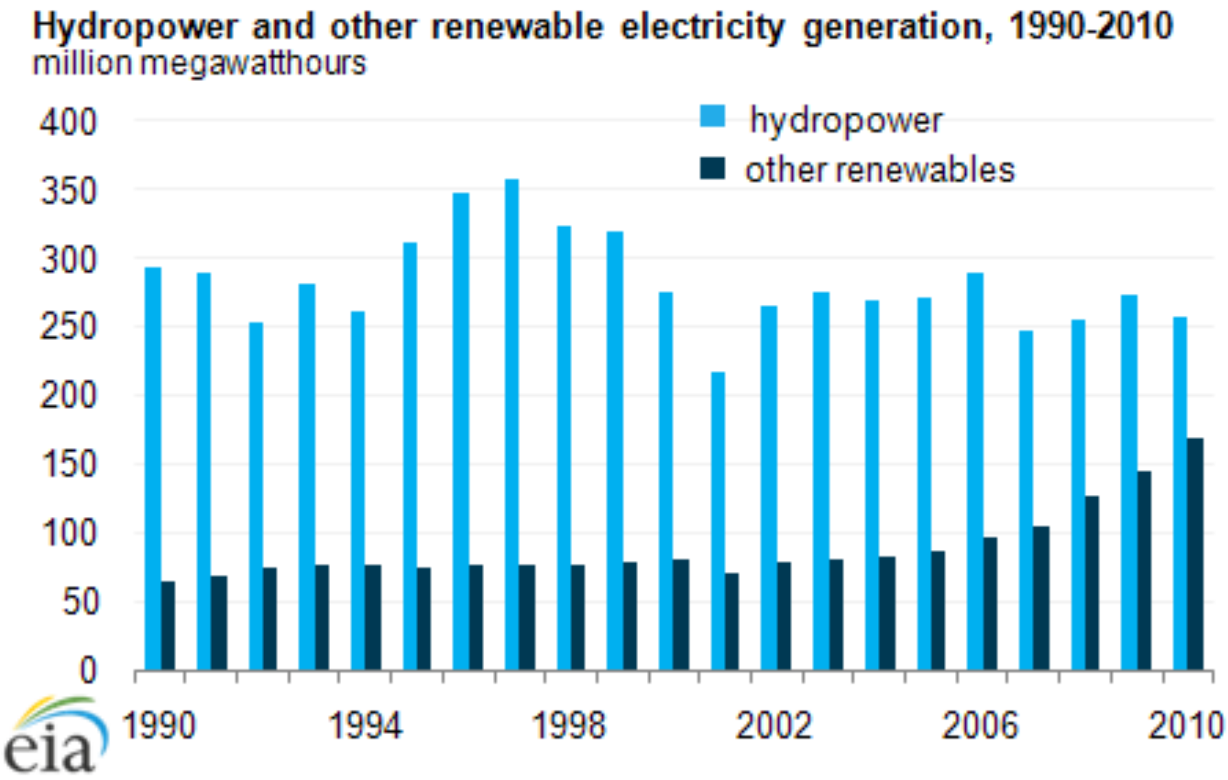
Combined CO_2-storage and geothermal energy extraction: potential and options

7. März, 2016, Deutsche Physikalische Gesellschaft (DPG) Konferenz - Regensburg

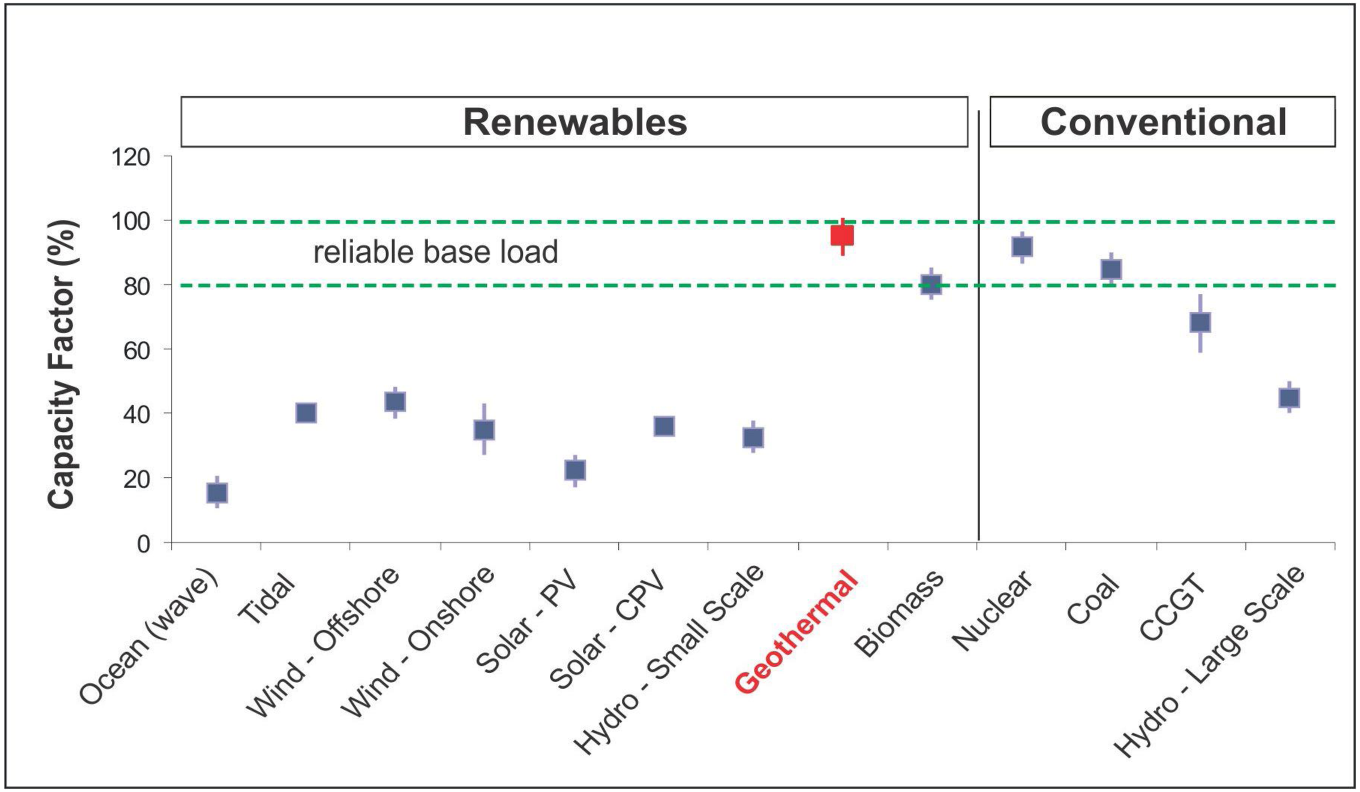
Strong Growth in Renewables



Hydropower and other renewable electricity generation, 1990-2010
million megawatthours

Courtesy: Roland Horne, Stanford

Geothermal energy is a baseload energy source

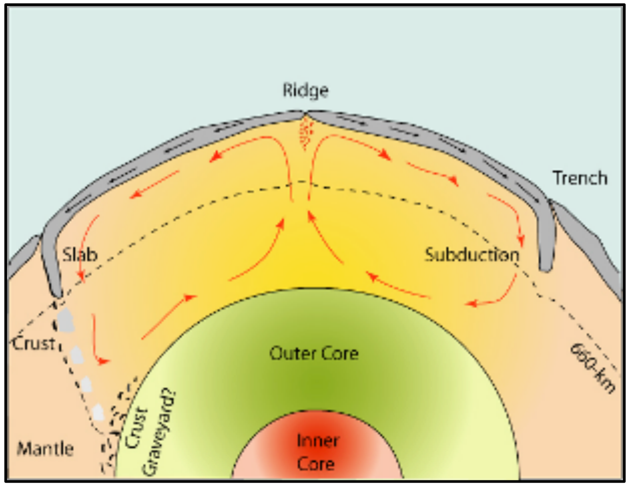


Source: Emerging Energy Research (2009)

Courtesy: Roland Horne, Stanford

Geothermal: often forgotten but we can see the effects of it

Mantle convection



Modified from S. Rost, 2008

Earthquakes

From Nasa

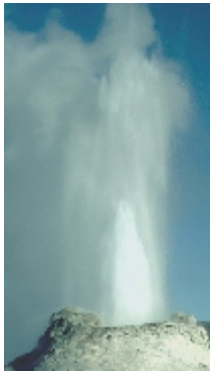
Mountain formation

Photo from Nasa

Volcanism

Photo from USGS

Geysers



Brantley (1983)

Black smokers

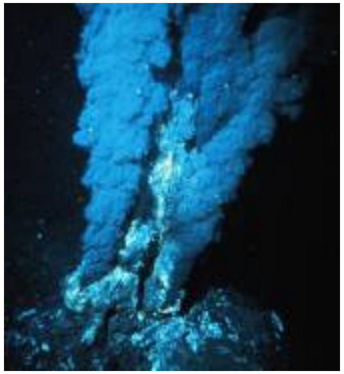
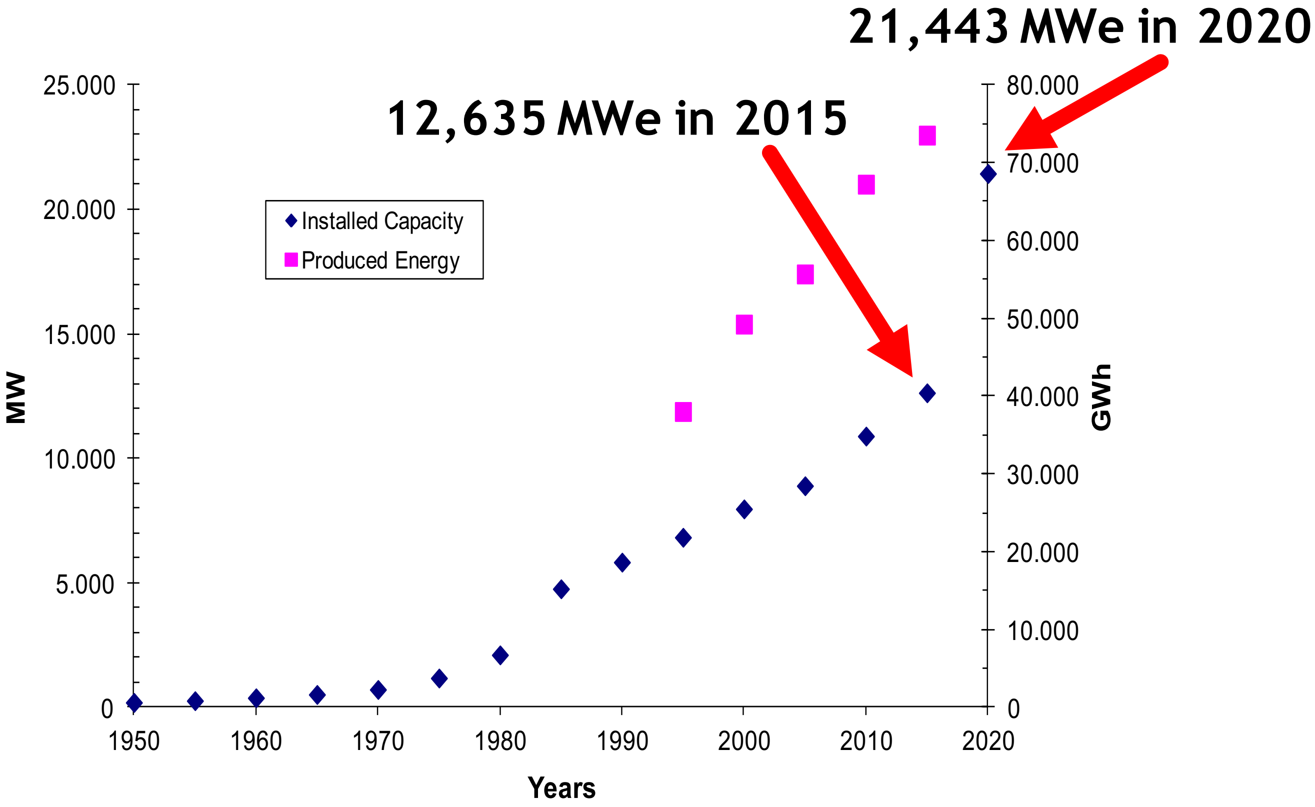


Photo from NOAA

➡ Large energy source

World Geothermal Electricity (2015)



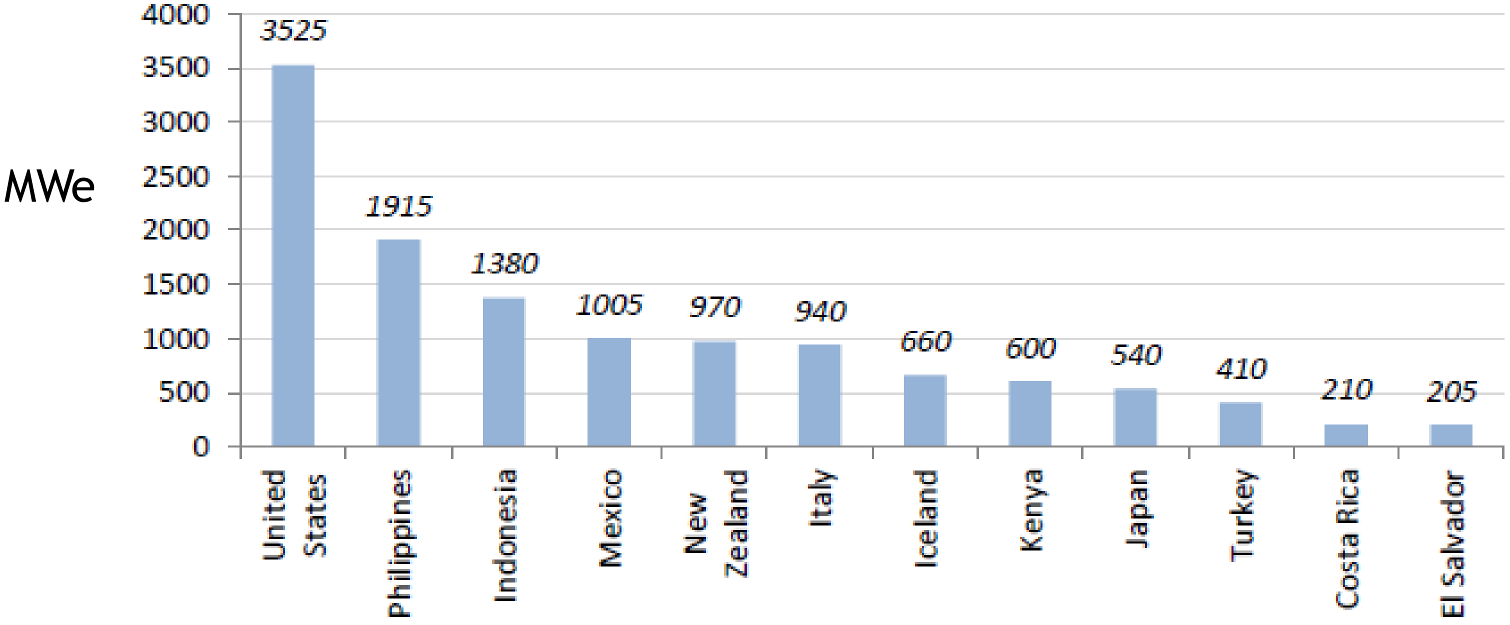
21,443 MWe in 2020

12,635 MWe in 2015

Bertani, 2015, WGC

Courtesy: Roland Horne, Stanford

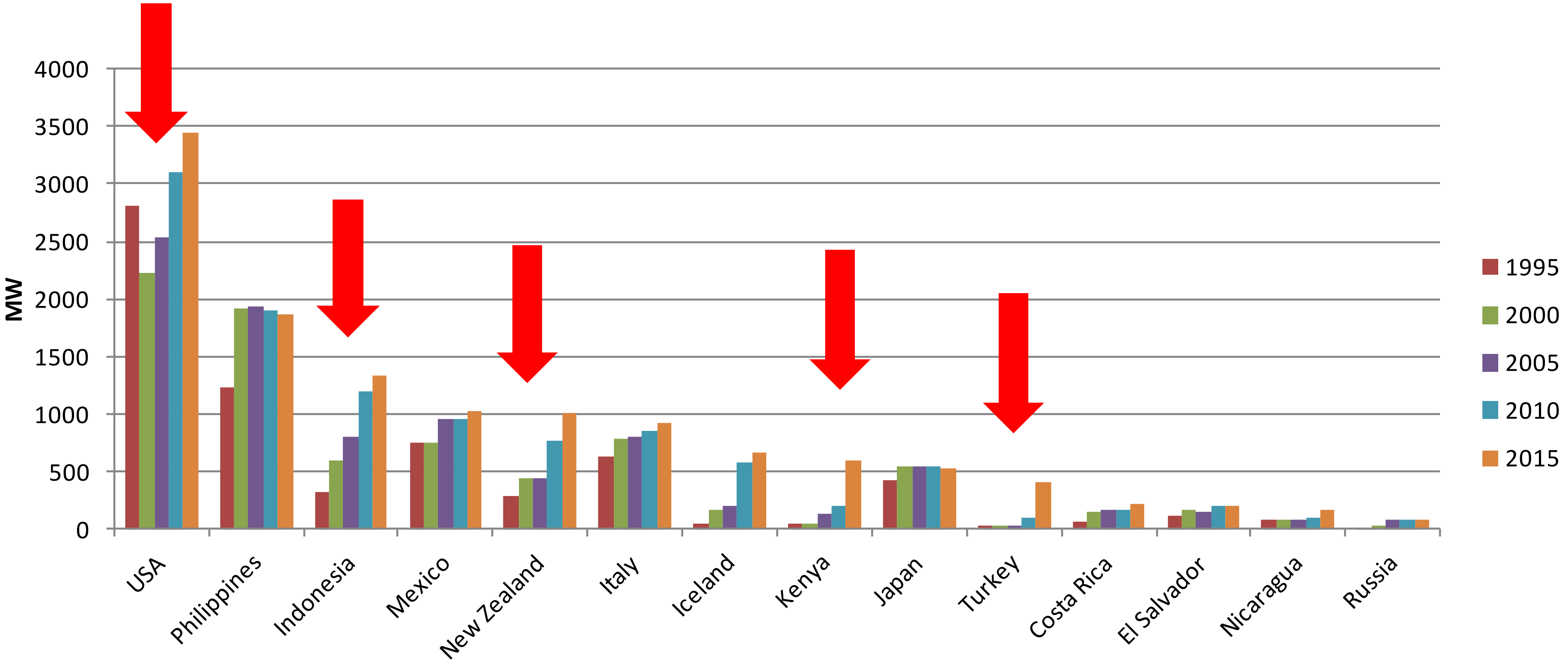
Operating Capacity (2015)



(GEA, February 2015)

Courtesy: Roland Horne, Stanford

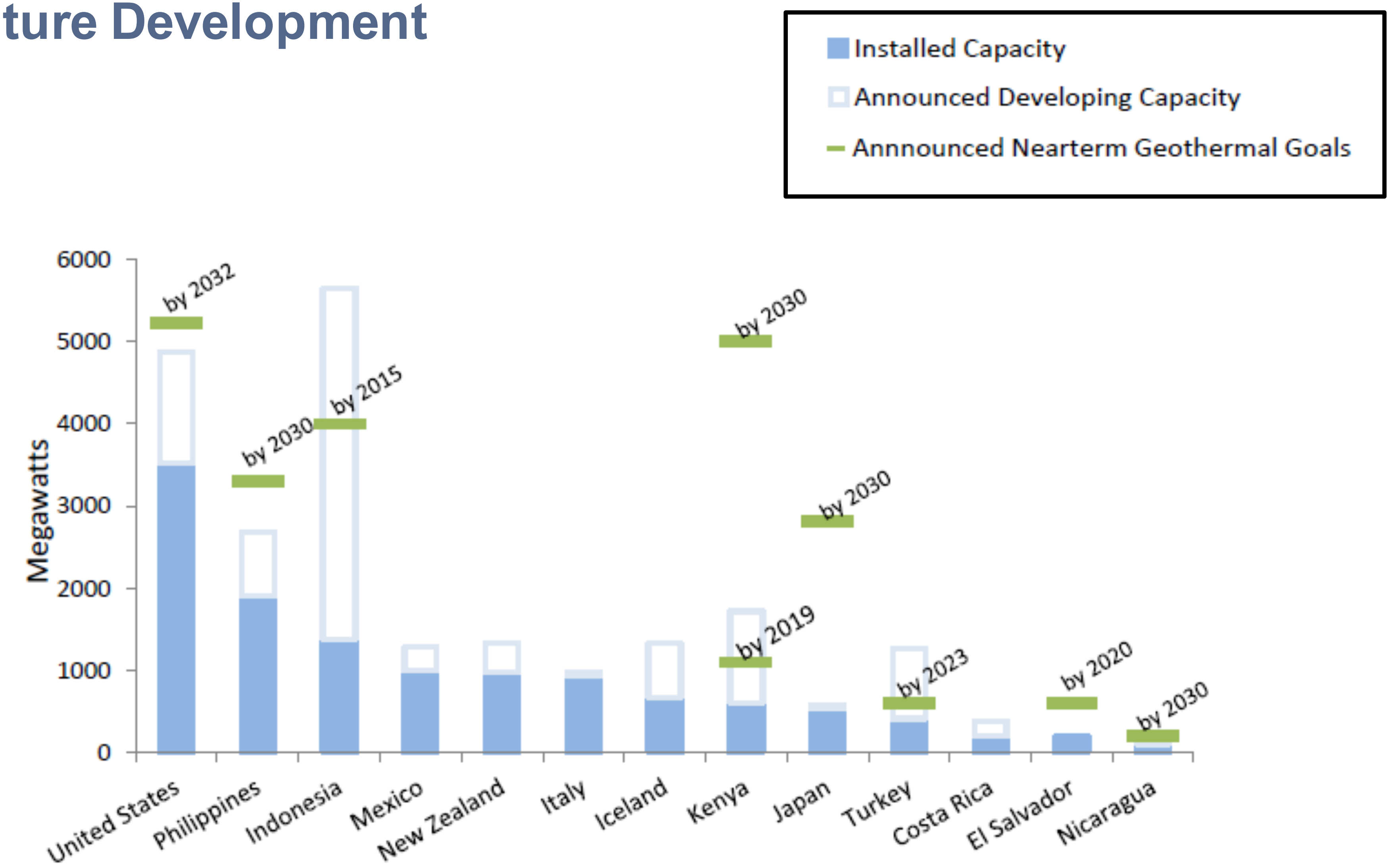
Geothermal electricity growth



Bertani, 2015, WGC

Courtesy: Roland Horne, Stanford

Future Development

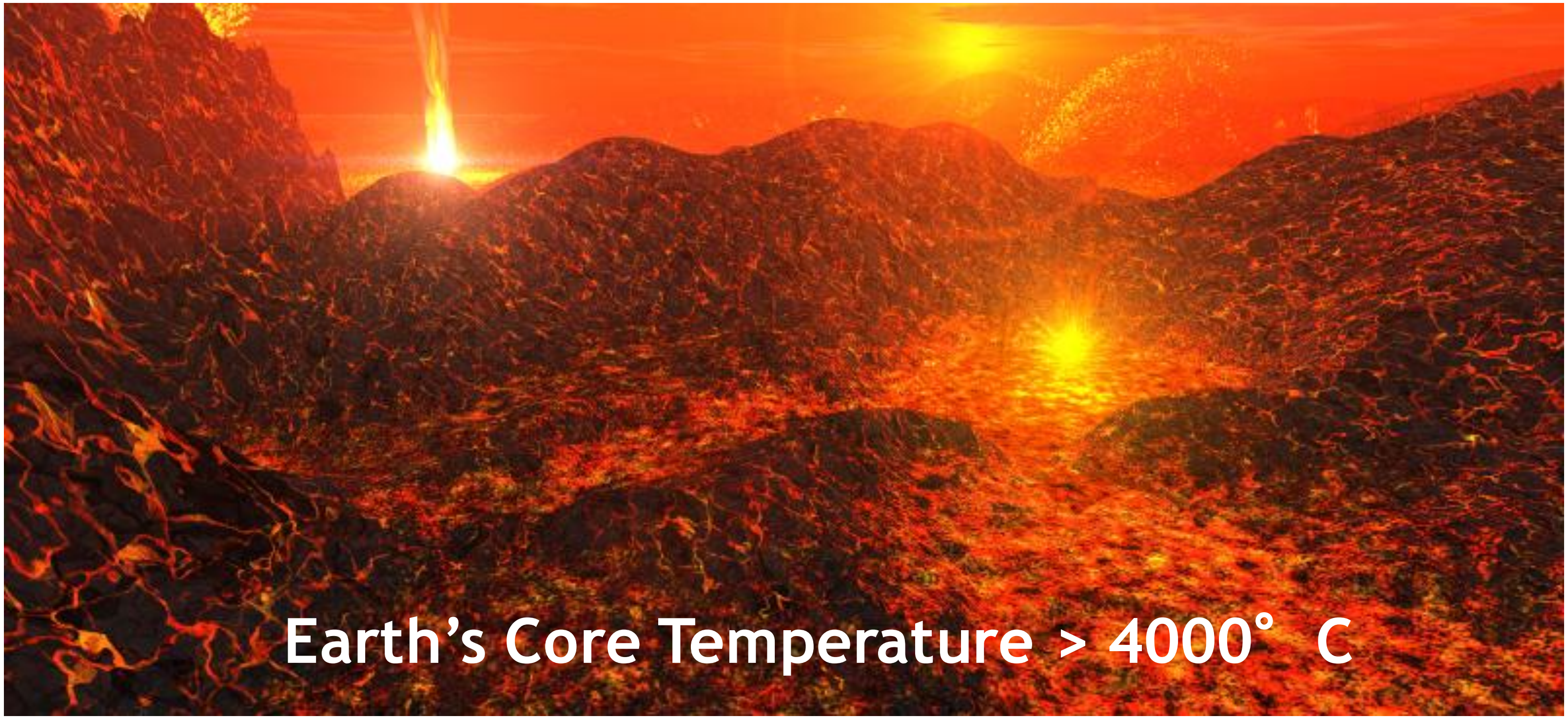


(GEA, February 2015)

Courtesy: Roland Horne, Stanford

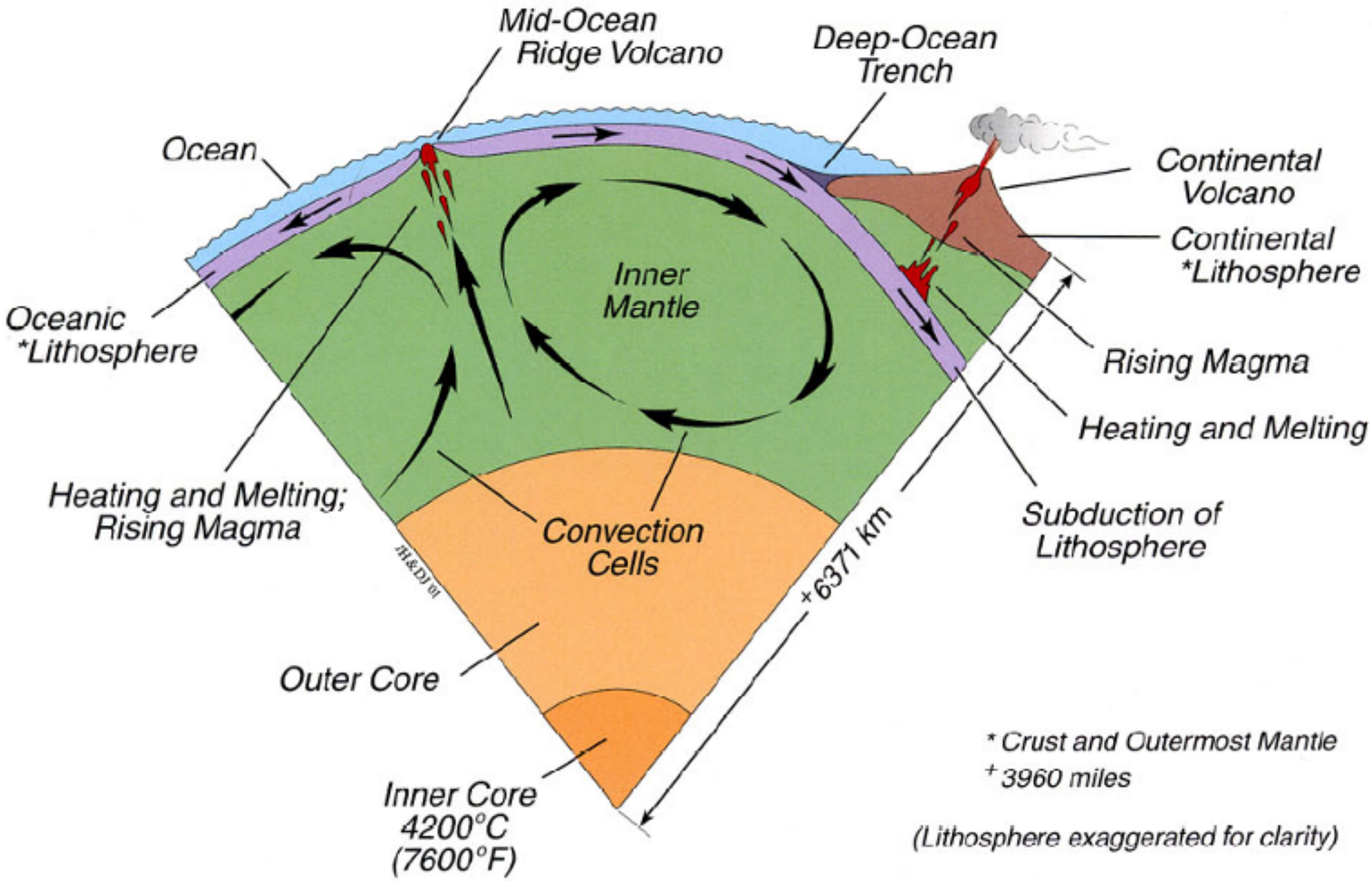
Sources of Earth’s heat

- Gravitational compression (formation of Earth)
- Radioactive decay of unstable elements in the crust
- Latent heat of crystallization (Ni, Fe in the outer core)
- Accretion (impacts of extraterrestrial objects)



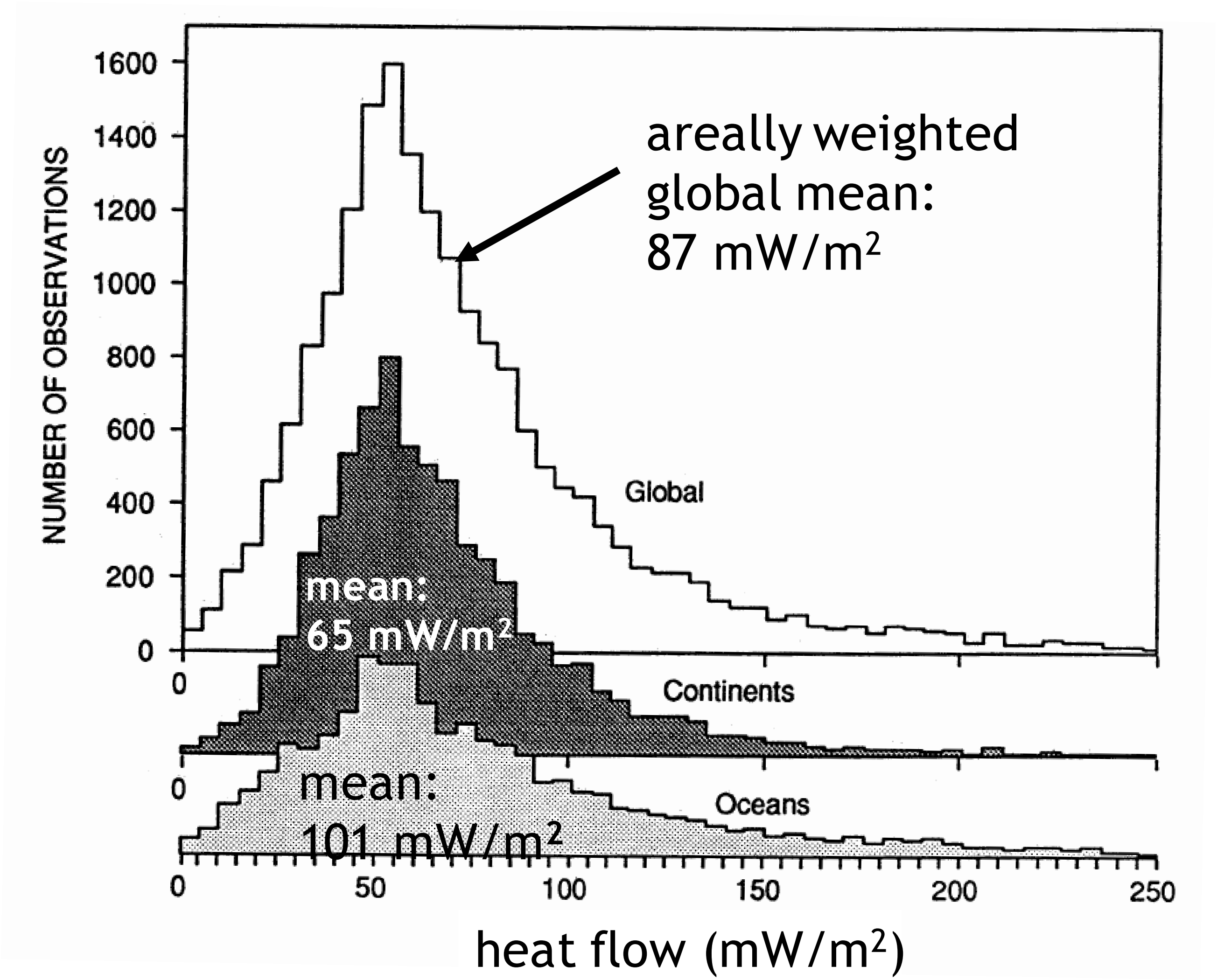
Earth’s Core Temperature > 4000° C

Earth's Interior Dynamics



Geothermal Research Council (GRC)

Global Heat Flow



areally weighted global mean: 87 mW/m^2

mean: 65 mW/m^2

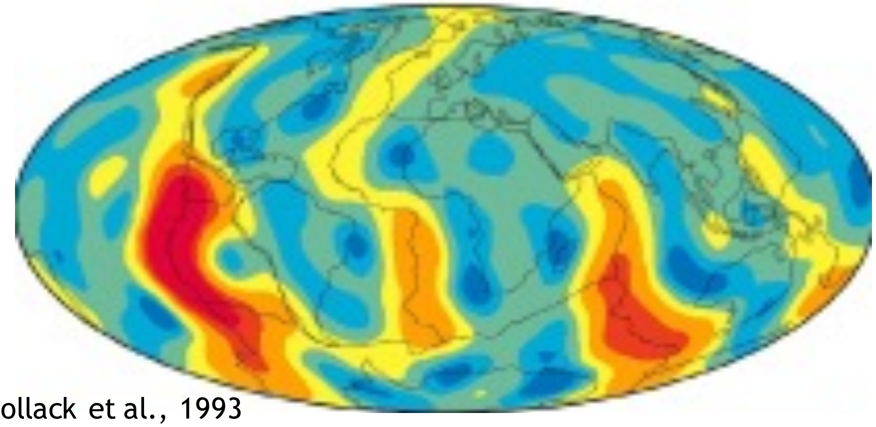
mean: 101 mW/m^2

heat flow (mW/m^2)

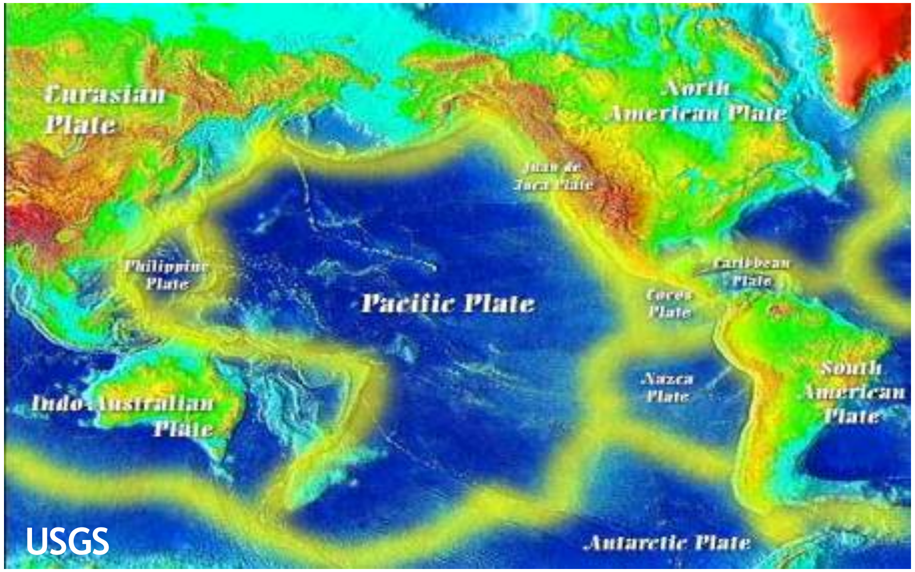
Pollack et al., Rev. Geophys., 1993

Focusing of Diffusive Heat Flow

1) Due to localized tectonic and/or magmatic activity.

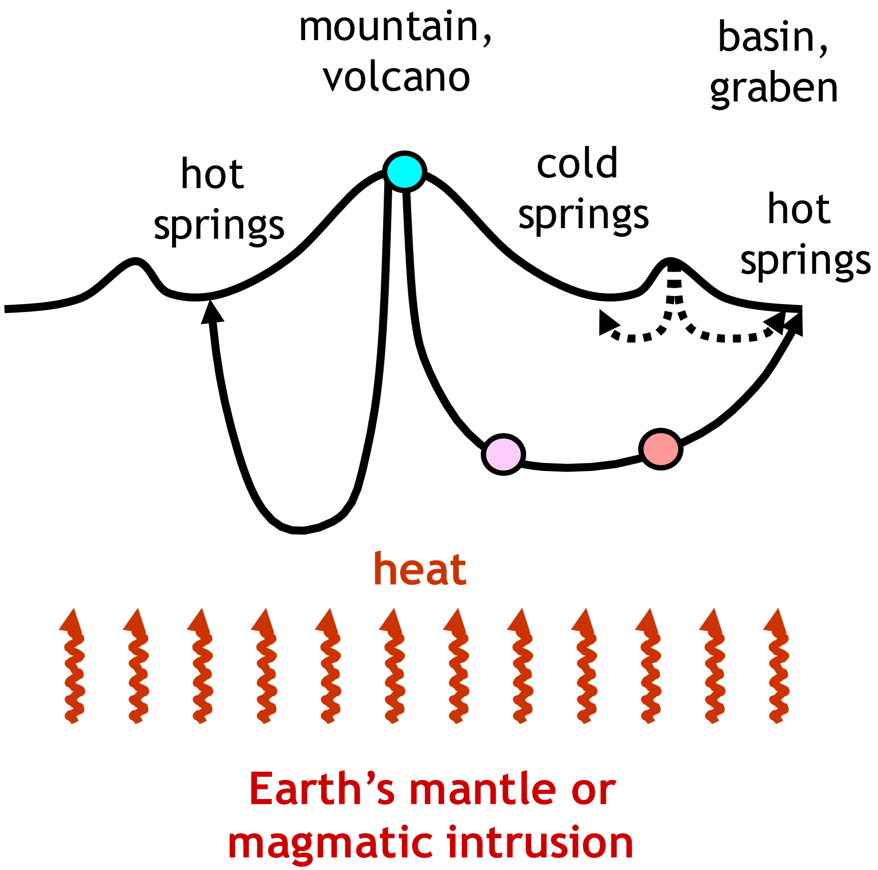


Pollack et al., 1993



USGS

2) Due to groundwater flow “collecting” diffusive heat and discharging it at hot springs.



mountain, volcano

basin, graben

hot springs

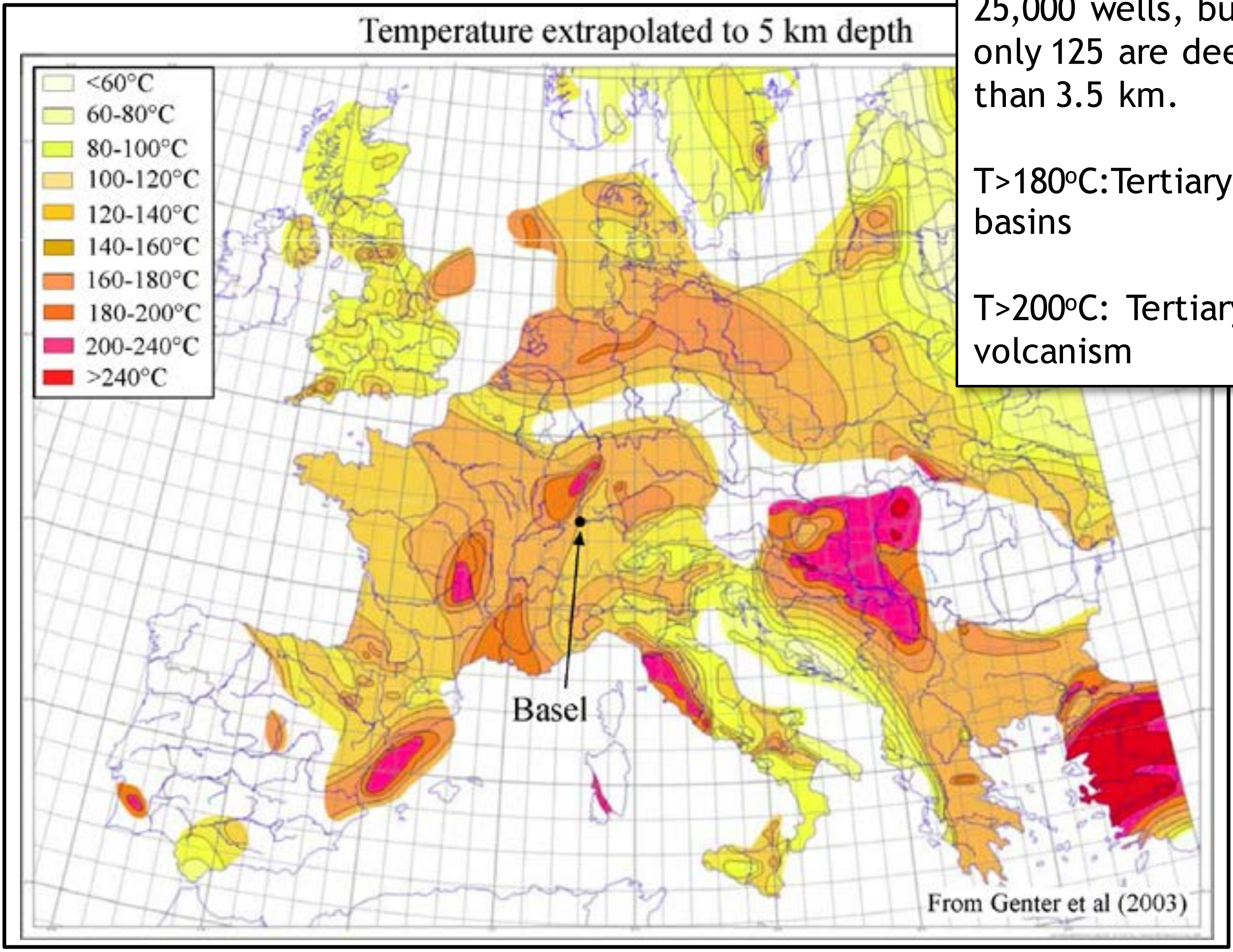
cold springs

hot springs

heat

Earth’s mantle or magmatic intrusion

Estimated T at 5 km depth



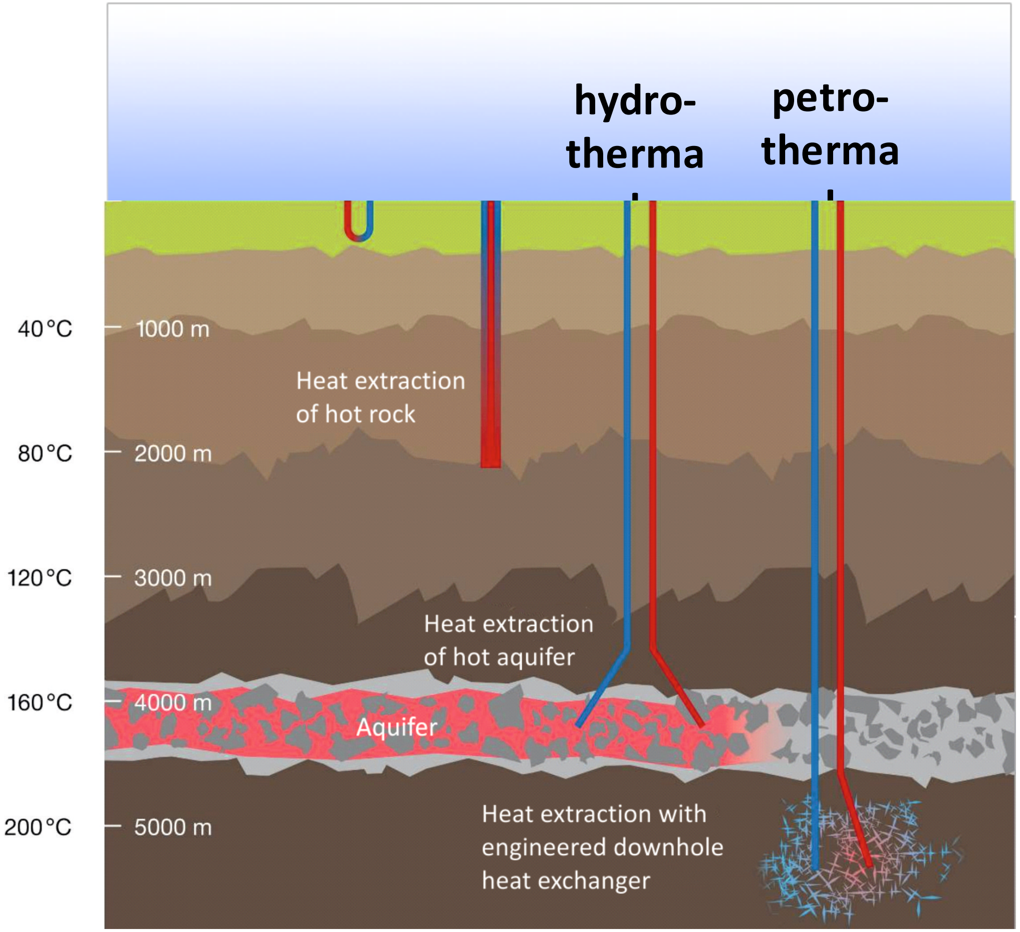
From Genter et al (2003)

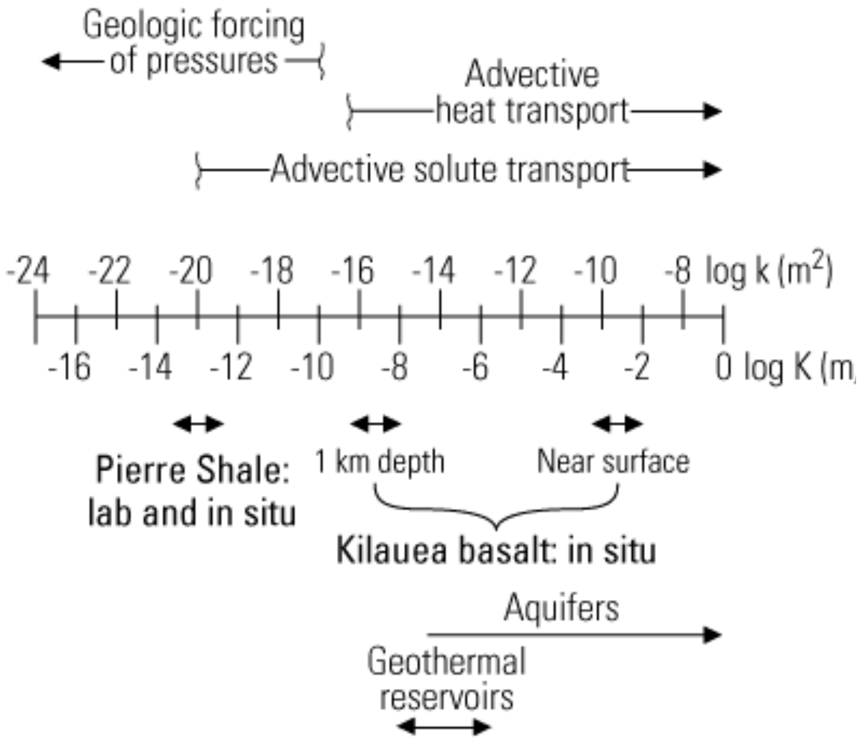
Based on data from 25,000 wells, but only 125 are deeper than 3.5 km.

T>180^{o}C: Tertiary rift basins

T>200^{o}C: Tertiary volcanism

Finding sufficient permeability, k, is difficult





Ingebritsen et al., 2006

OUTLINE

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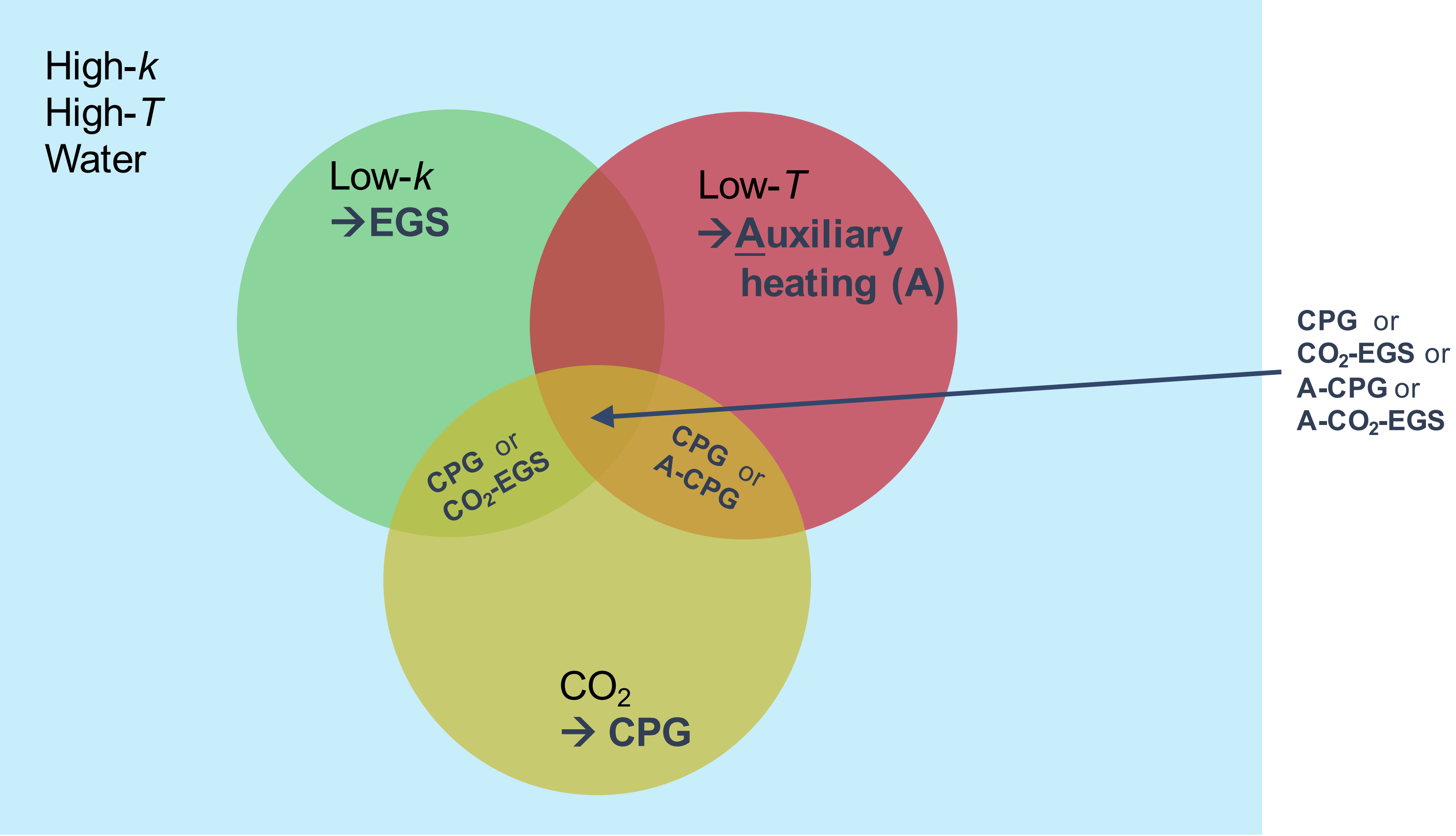
4) Summary

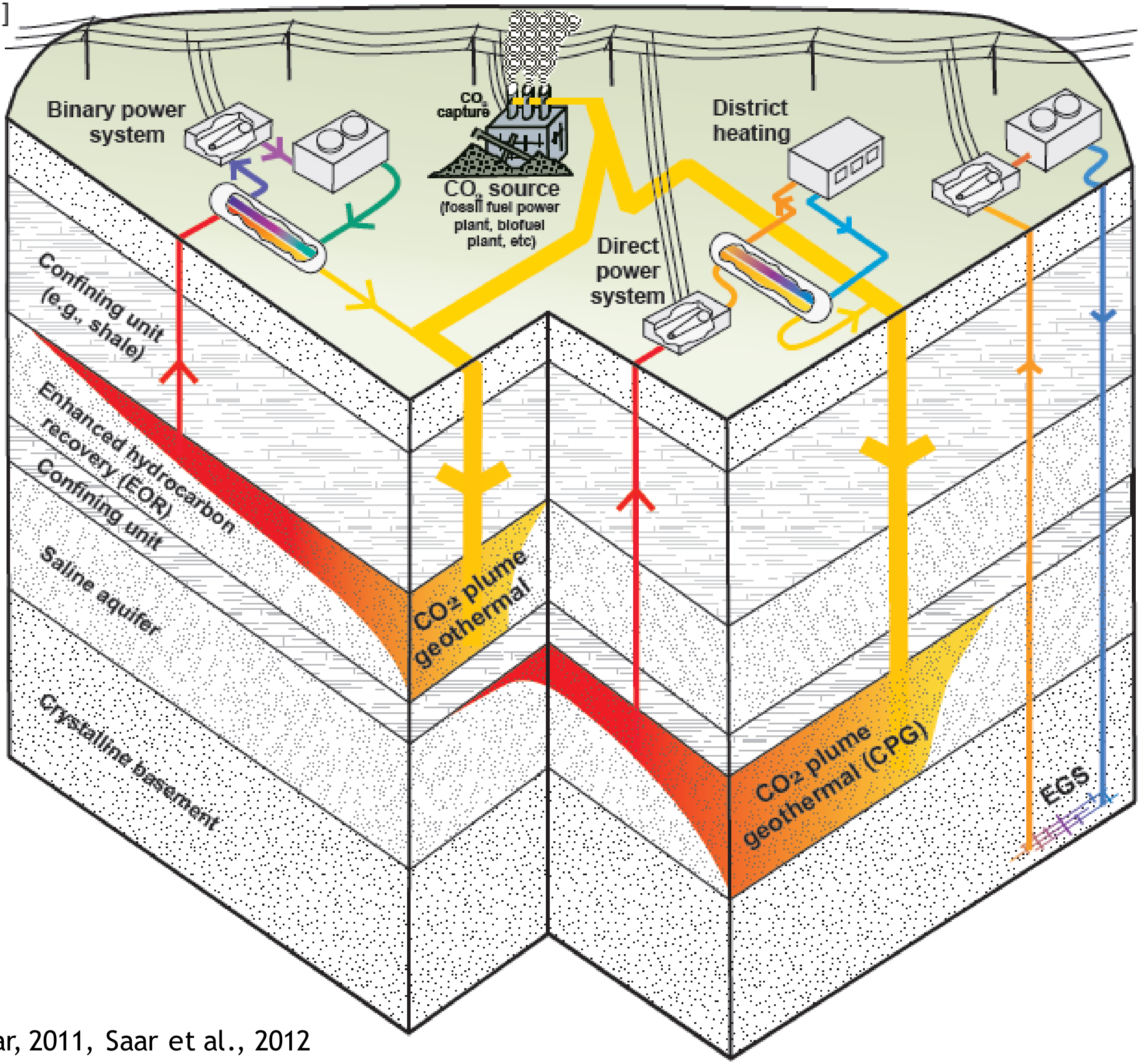
To generate electricity geothermally, we need:

High-*k*, high-*T*, and lots of fluid (water/CO_2)



CO_2-Plume Geothermal (CPG)

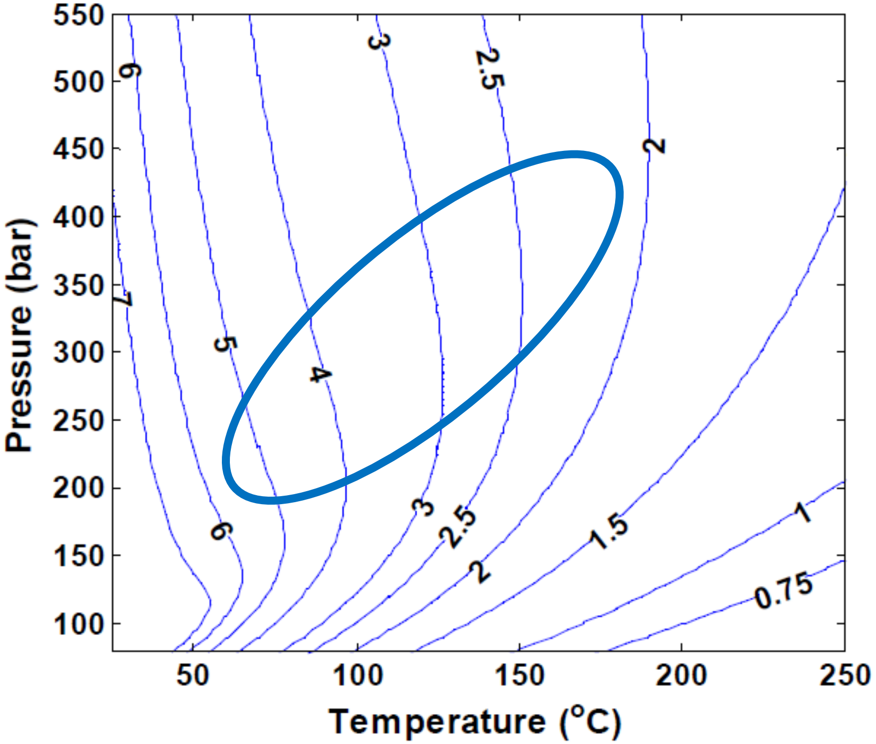
[1]



Randolph and Saar, 2011, Saar et al., 2012

What makes CO_2 a more efficient working fluid than water?

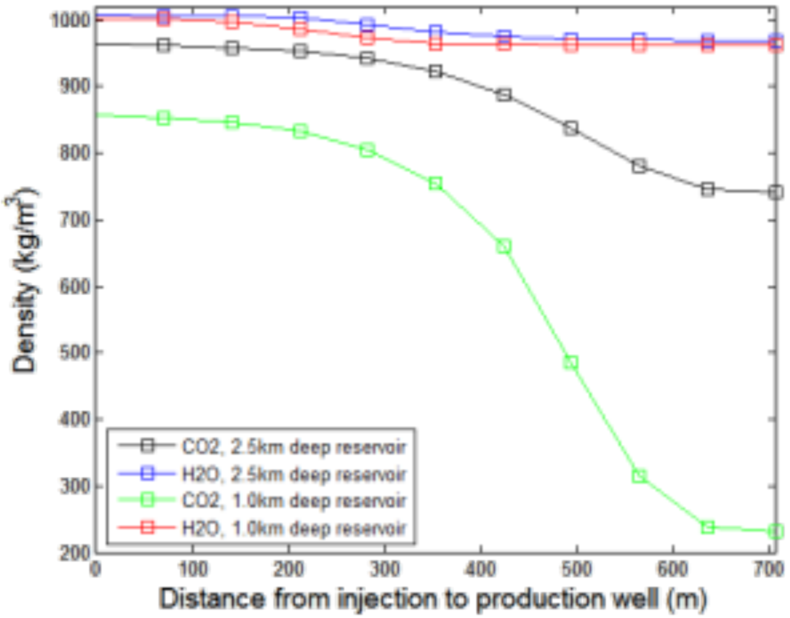
Ratio of CO_2 to H_20 mobility



Fluid density profiles

~20°C

~100°C



Water
(2.5km)

Water
(1 km)

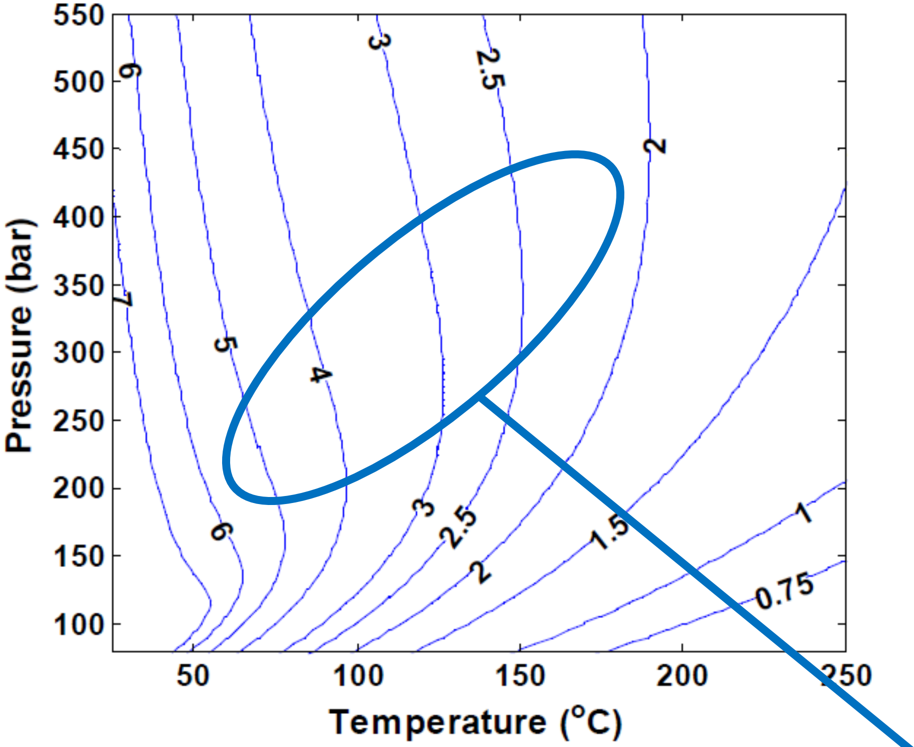
CO_2
(2.5 km)

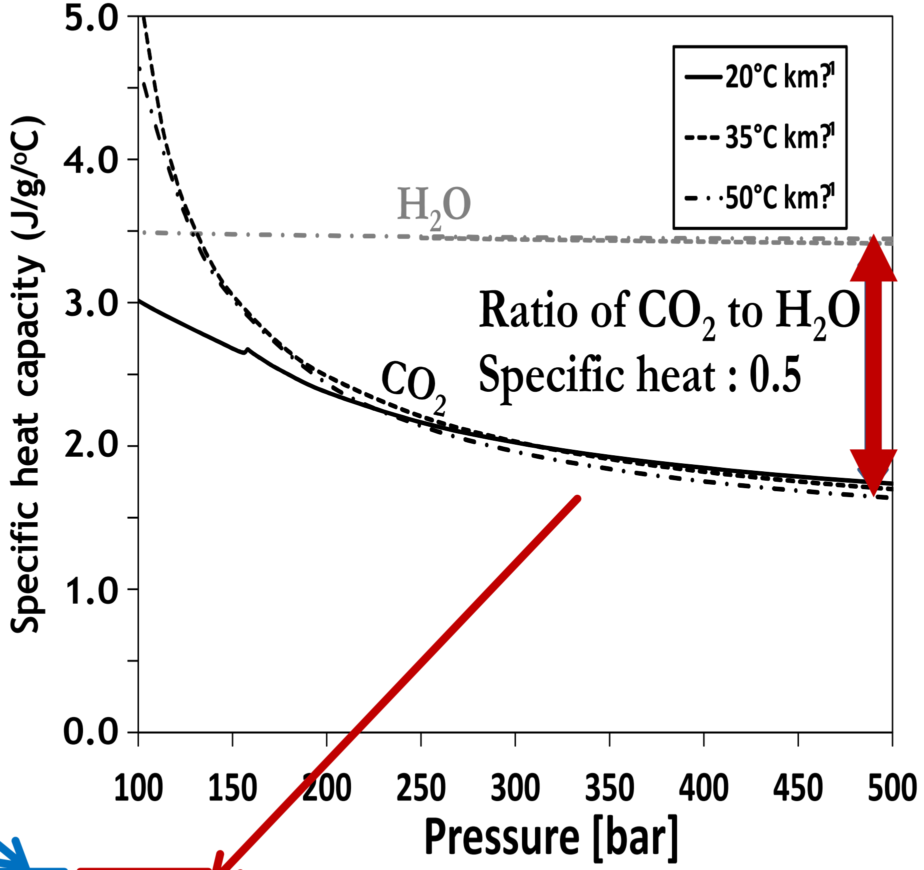
CO_2
(1 km)

see also: Adams et al., Energy, 2014

What makes CO_2 a more efficient working fluid than water?

Ratio of CO_2 to H_20 mobility

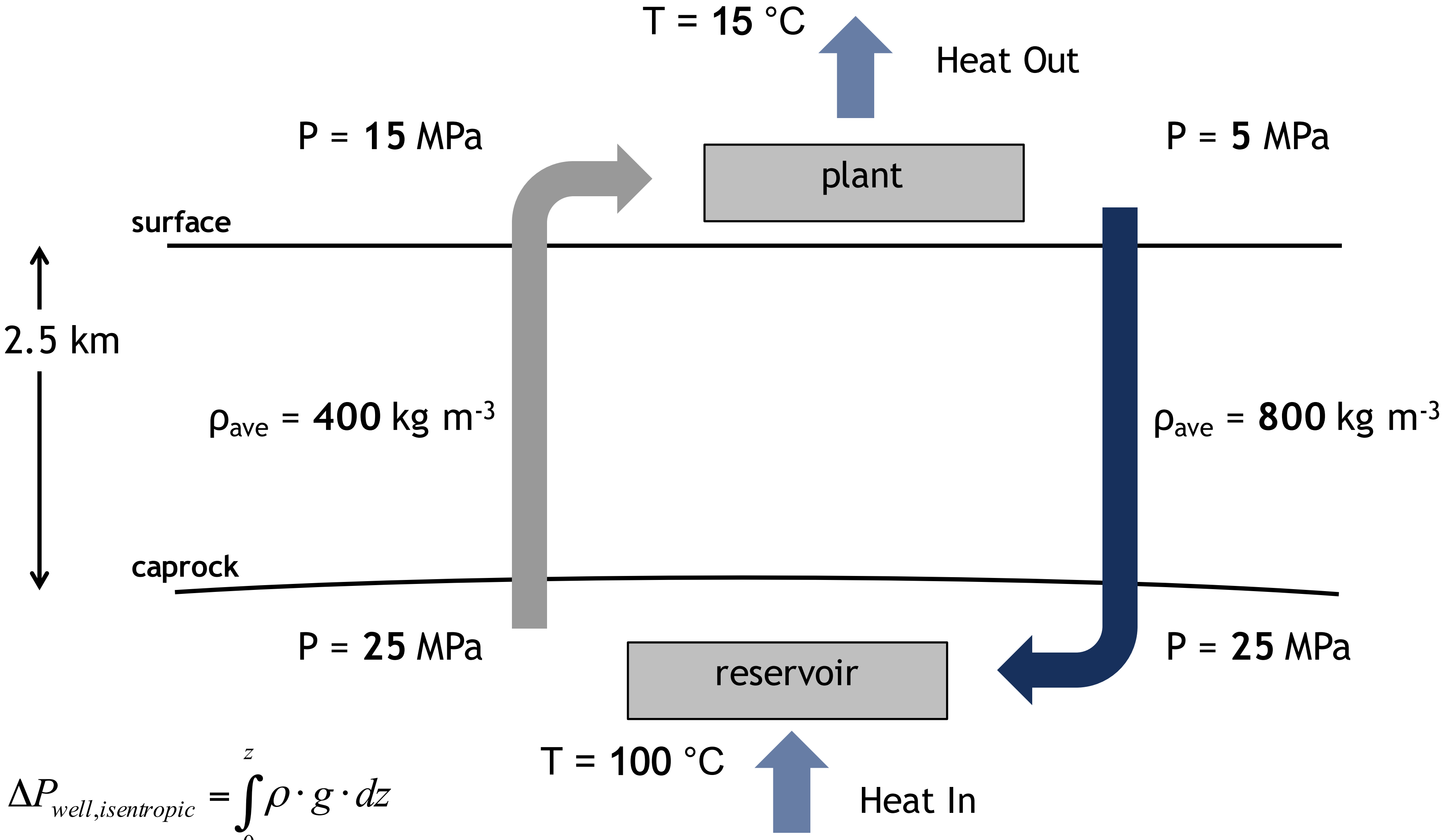




$$Q = \Delta P \left(\frac{kA}{L}\right)\boxed{\left[\frac{\rho}{\mu}\right]}\boxed{C_{p,ave}}\Delta T$$

see also: Adams et al., Energy, 2014

How a $_{sc}CO_2$ thermosiphon works



T = **15** °C

Heat Out

P = **15** MPa

plant

P = **5** MPa

surface

2.5 km

ρ_{ave} = **400** kg m^{-3}

ρ_{ave} = **800** kg m^{-3}

caprock

P = **25** MPa

reservoir

P = **25** MPa

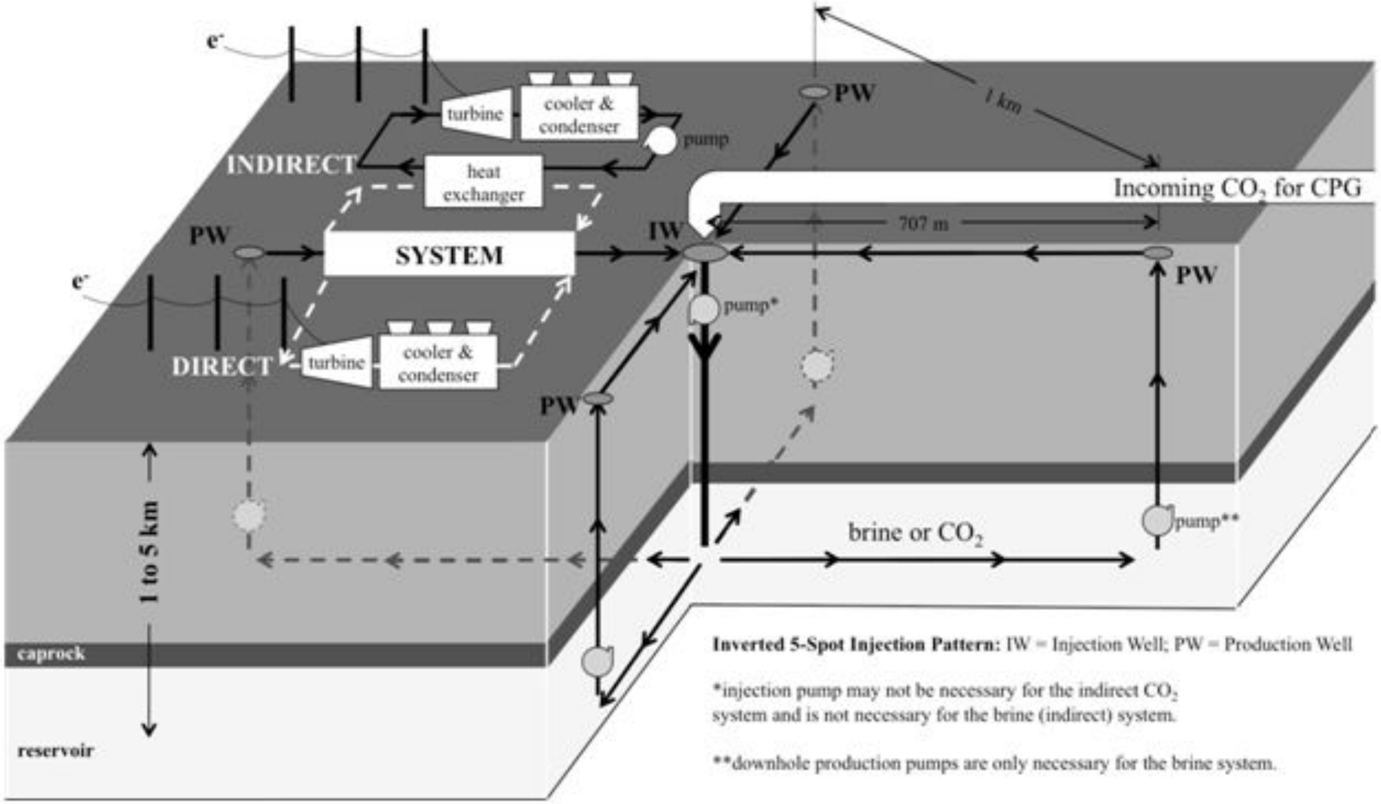
T = **100** °C

Heat In

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

Injection and production wellhead pressure difference generated by thermosiphon

Direct and indirect 5-spot CPG well configurations



Inverted 5-Spot Injection Pattern: IW = Injection Well; PW = Production Well

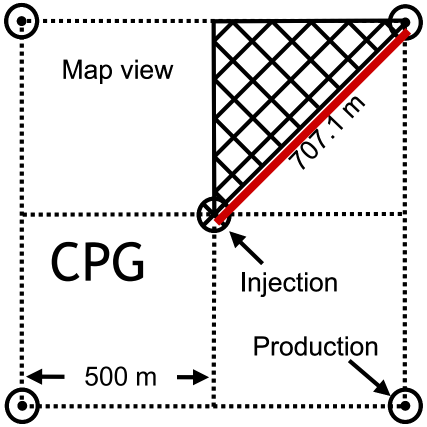
*injection pump may not be necessary for the indirect CO_2 system and is not necessary for the brine (indirect) system.

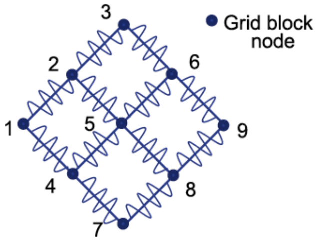
**downhole production pumps are only necessary for the brine system.

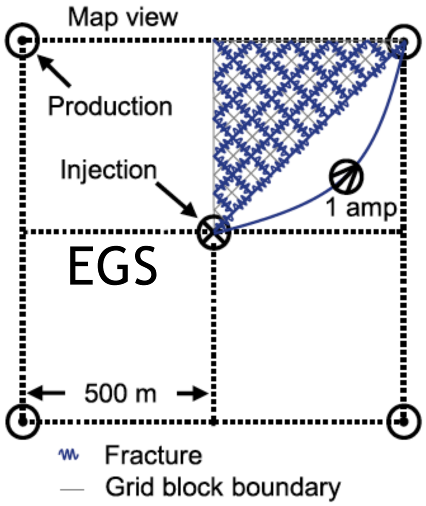
Adams et al. (2015)

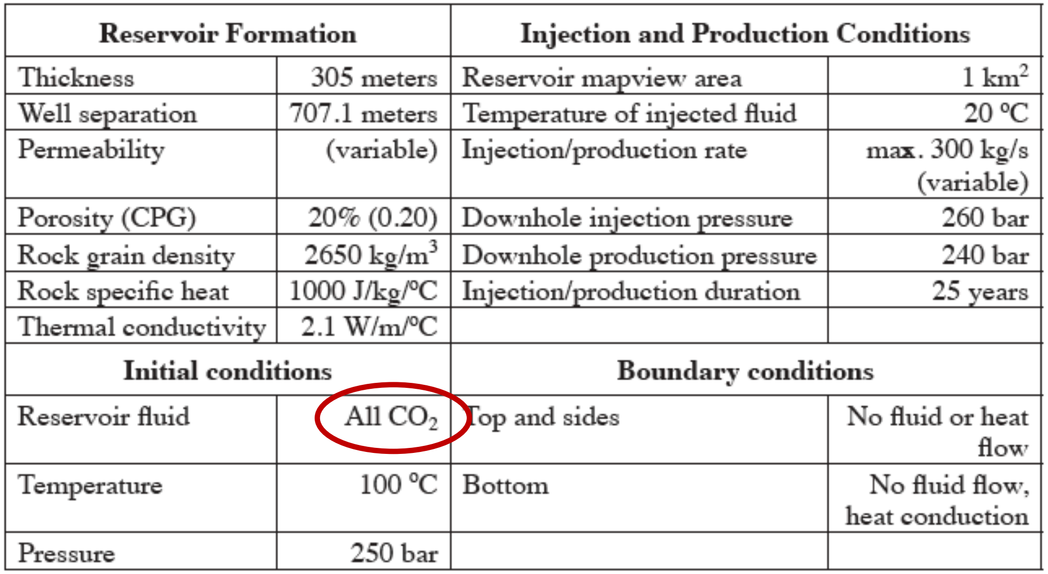
Numerical modeling: Classic 5-spot well system

- TOUGH2 Integrated finite difference code (Pruess, 1999, 2000, 2004, 2006, 2008)
- CO_2, H_2O, NaCl:
  - Geothermal energy
  - CO_2 sequestration



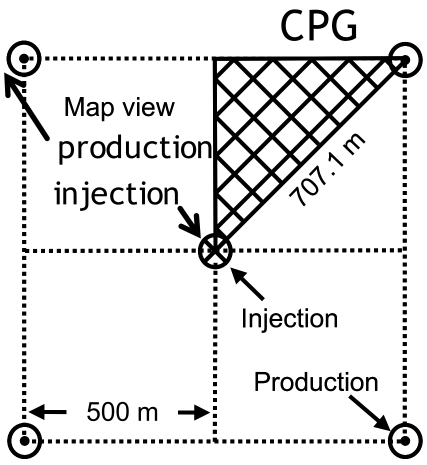


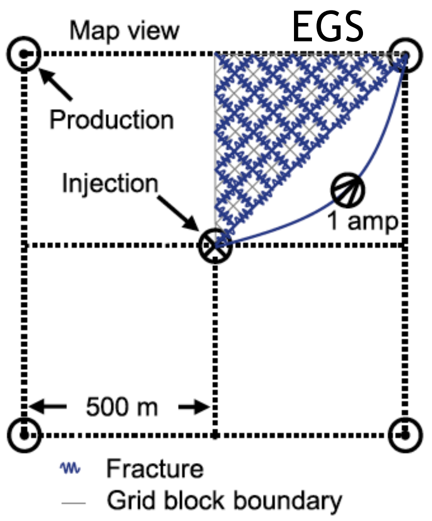


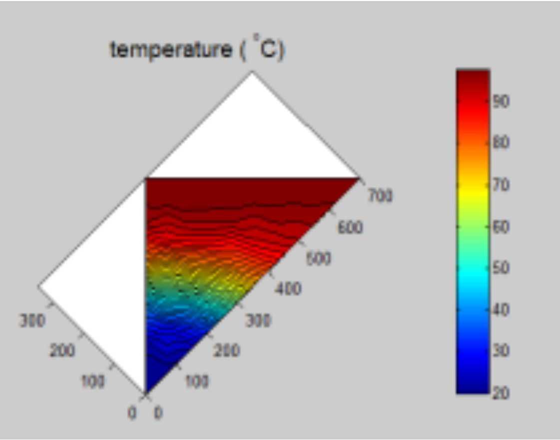


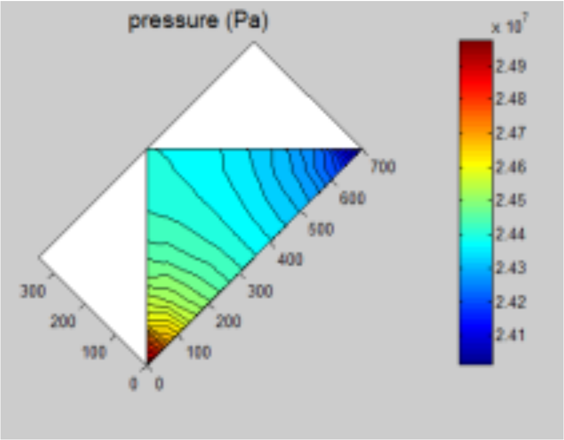
Reservoir Formation		Injection and Production Conditions	
Thickness	305 meters	Reservoir mapview area	1 km^2
Well separation	707.1 meters	Temperature of injected fluid	20 °C
Permeability	(variable)	Injection/production rate	max. 300 kg/s (variable)
Porosity (CPG)	20% (0.20)	Downhole injection pressure	260 bar
Rock grain density	2650 kg/m^3	Downhole production pressure	240 bar
Rock specific heat	1000 J/kg/°C	Injection/production duration	25 years
Thermal conductivity	2.1 W/m/°C		
Initial conditions		**Boundary conditions**	
Reservoir fluid	All CO_2	Top and sides	No fluid or heat flow
Temperature	100 °C	Bottom	No fluid flow, heat conduction
Pressure	250 bar		

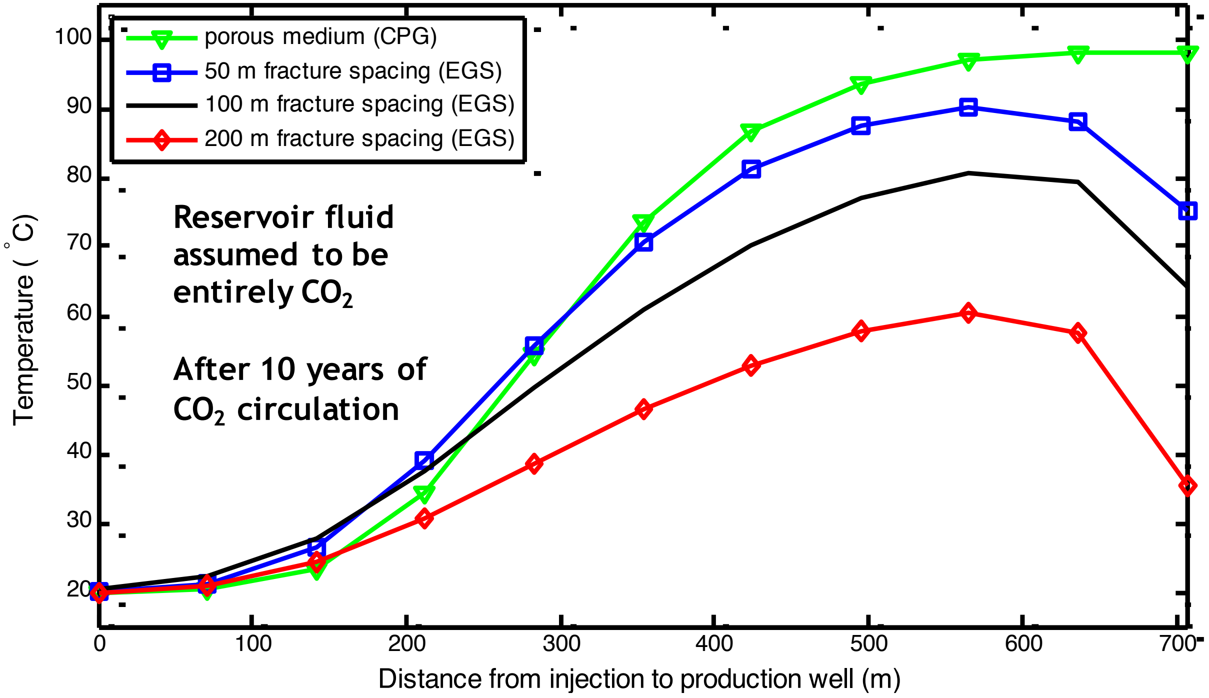
Reservoir temperature depletion: Modeling











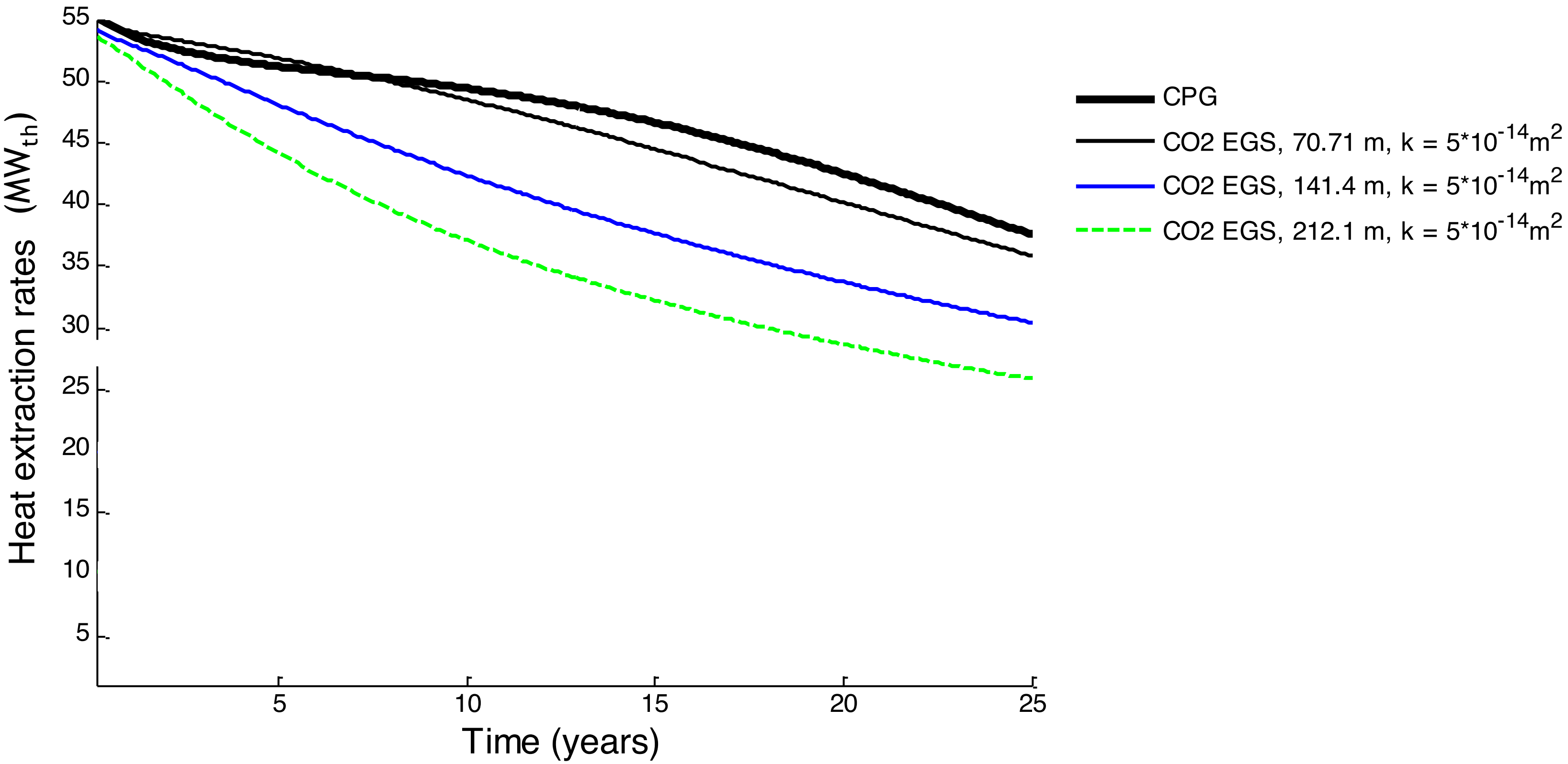
Reservoir fluid assumed to be entirely CO_2

After 10 years of CO_2 circulation

Randolph and Saar, GRC Transactions, 2010

Heat energy (MW_{th}) extraction over time

for both CO_2 and brine (sedimentary basin and EGS)



Randolph and Saar, GRL 2011

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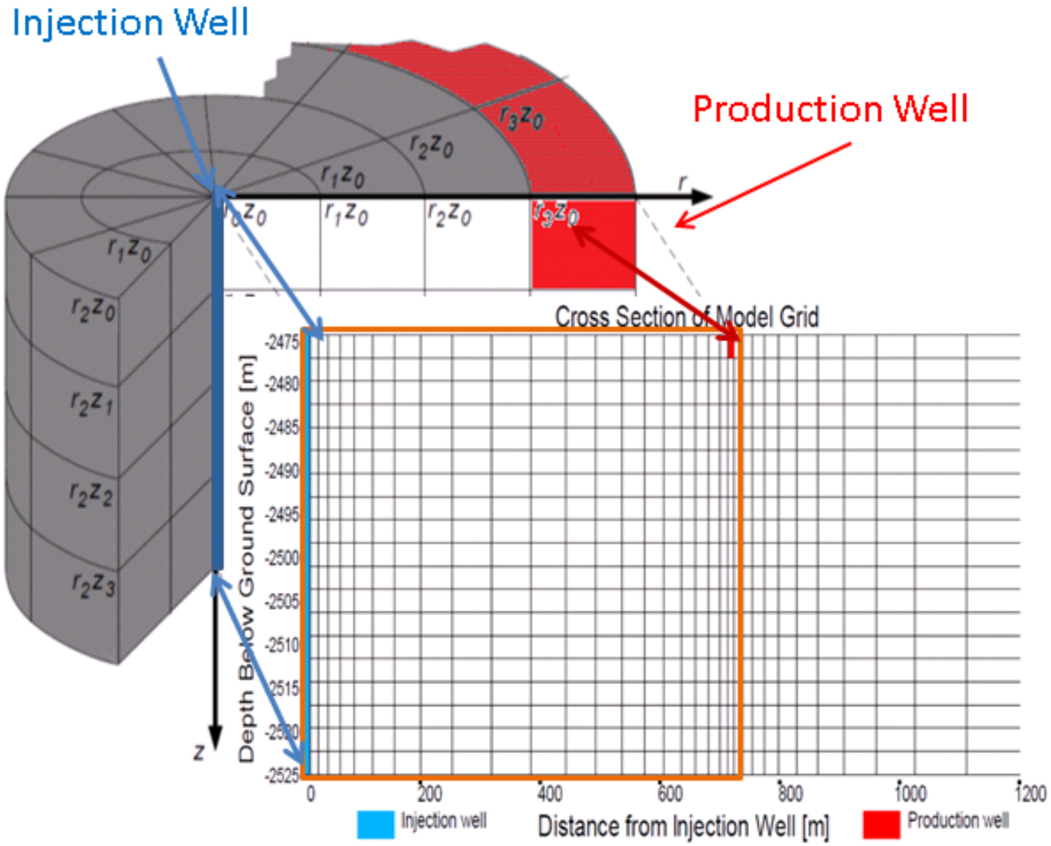
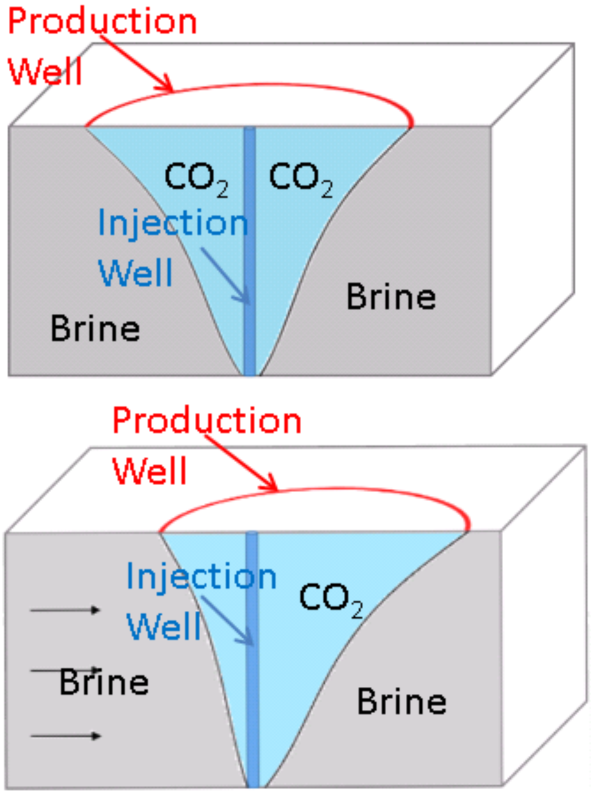
4) Summary

Radial model, brine displacement, CO_2-limited heat only

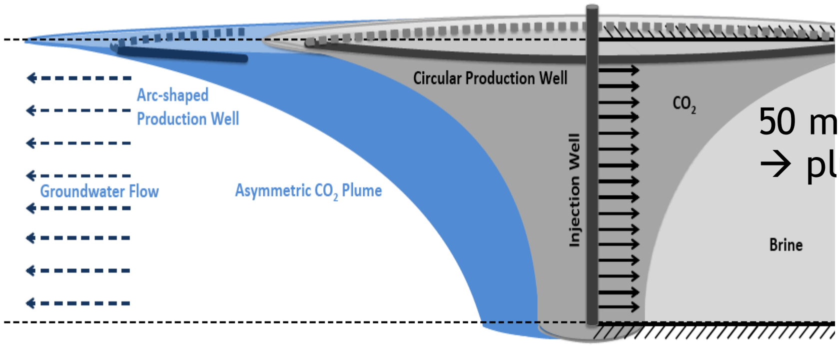




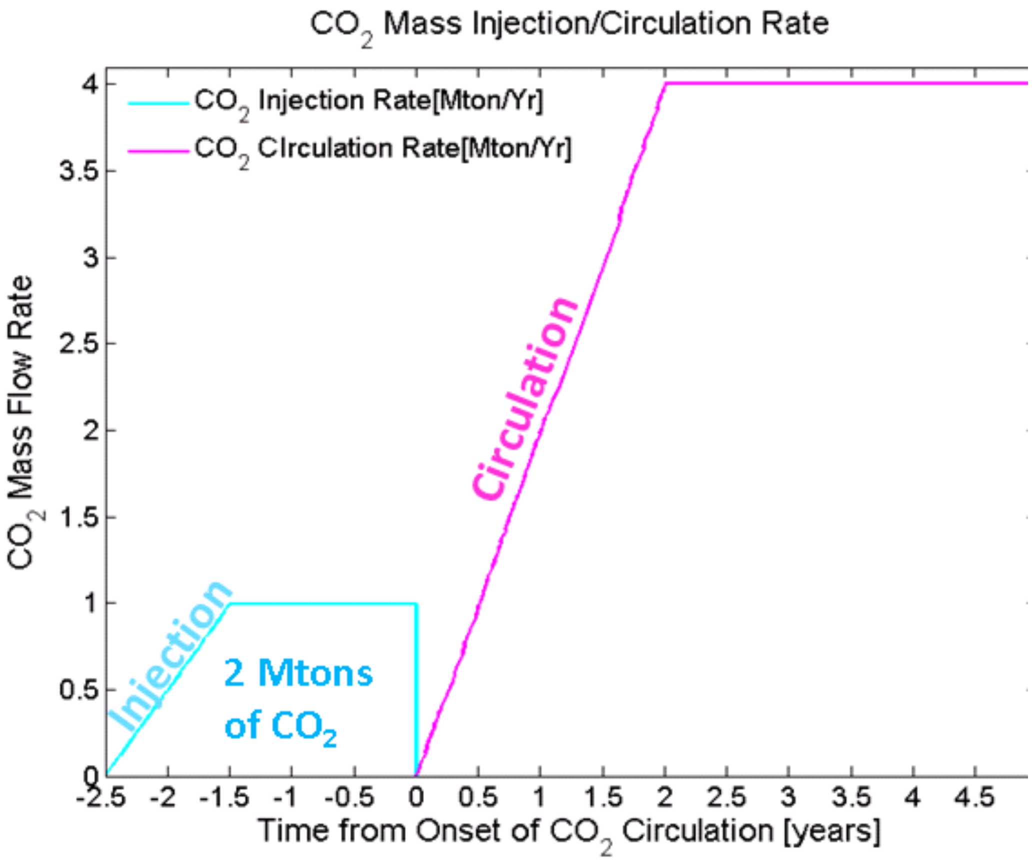
Model

Reservoir Parameter/Condition	Value
Thickness [m]	50
Average depth, D [m]	2500
Porosity	0.10
Horizontal permeability, k_x [m^2]	5×10^{-14}
Vertical permeability, k_z [m^2]	2.5×10^{-14}
Geothermal gradient[^{o}C/km]	34
Temperature, T [^{o}C]	100
Thermal conductivity [W/m/^{o}C]	2.10
Rock specific heat [J/kg/^{o}C]	1000
Rock grain density [kg/m^3]	2650
Radius [m]	100,000

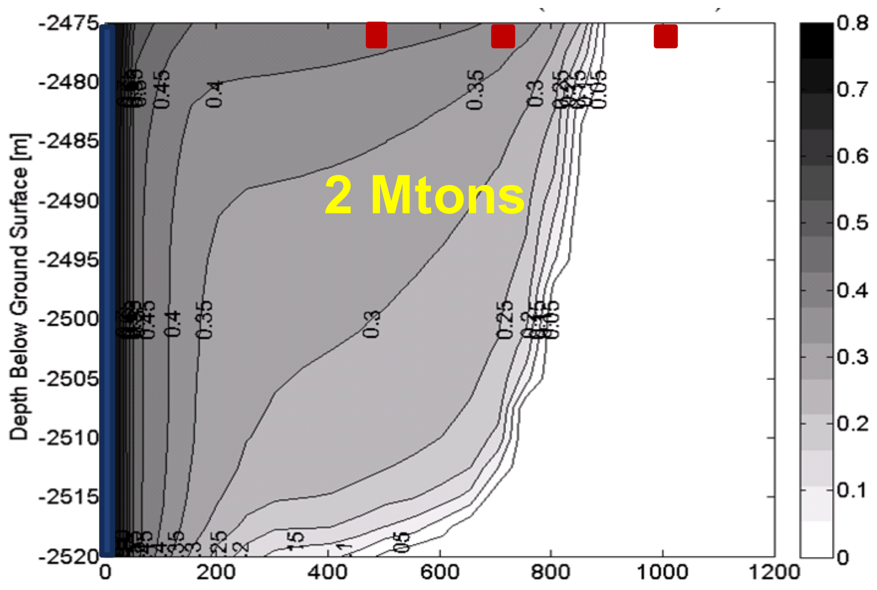
Boundary condition	Value
Top/bottom	No fluid flow, semi-analytic heat exchange
Lateral	No fluid or heat flow
Temperature of Injected fluid [^{o}C]	46

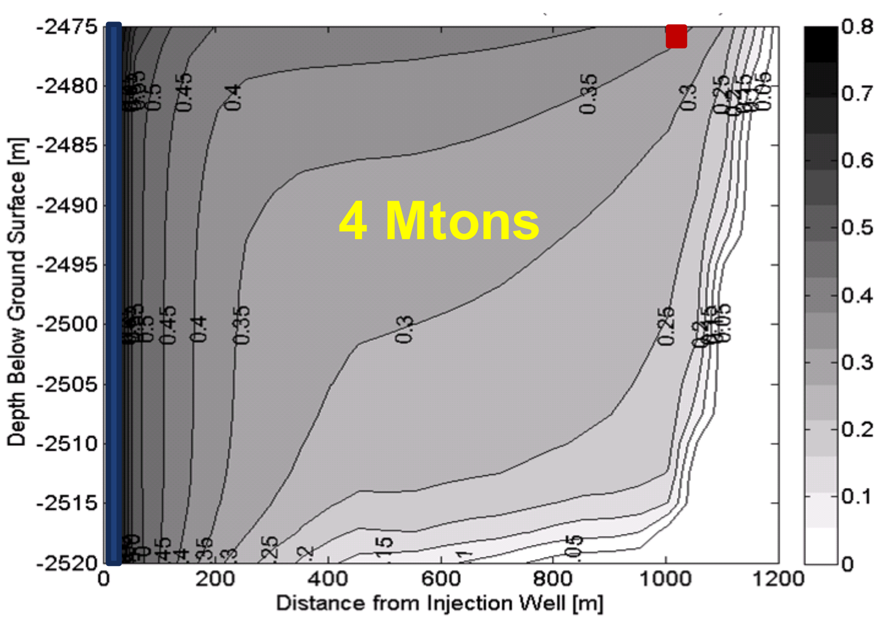


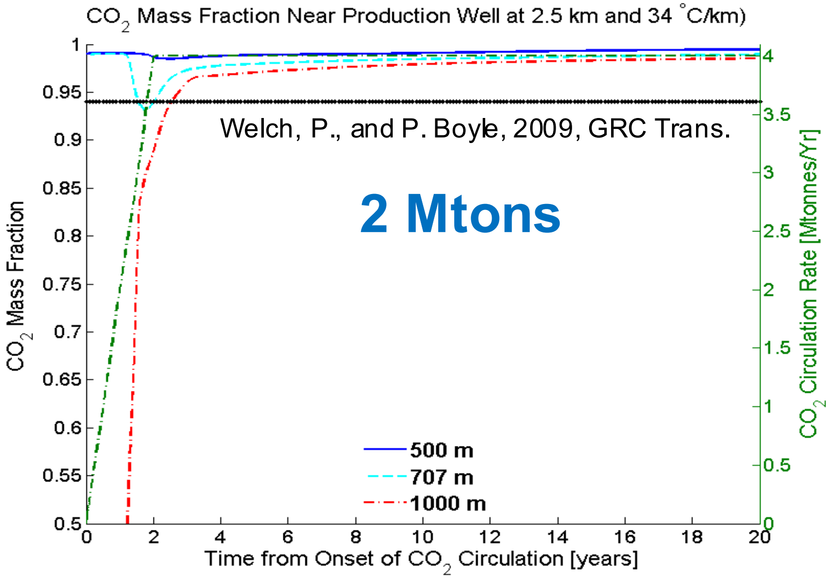
50 m thick
→ plug flow



CO$_2$ Saturation before onset of production







Welch, P., and P. Boyle, 2009, GRC Trans.

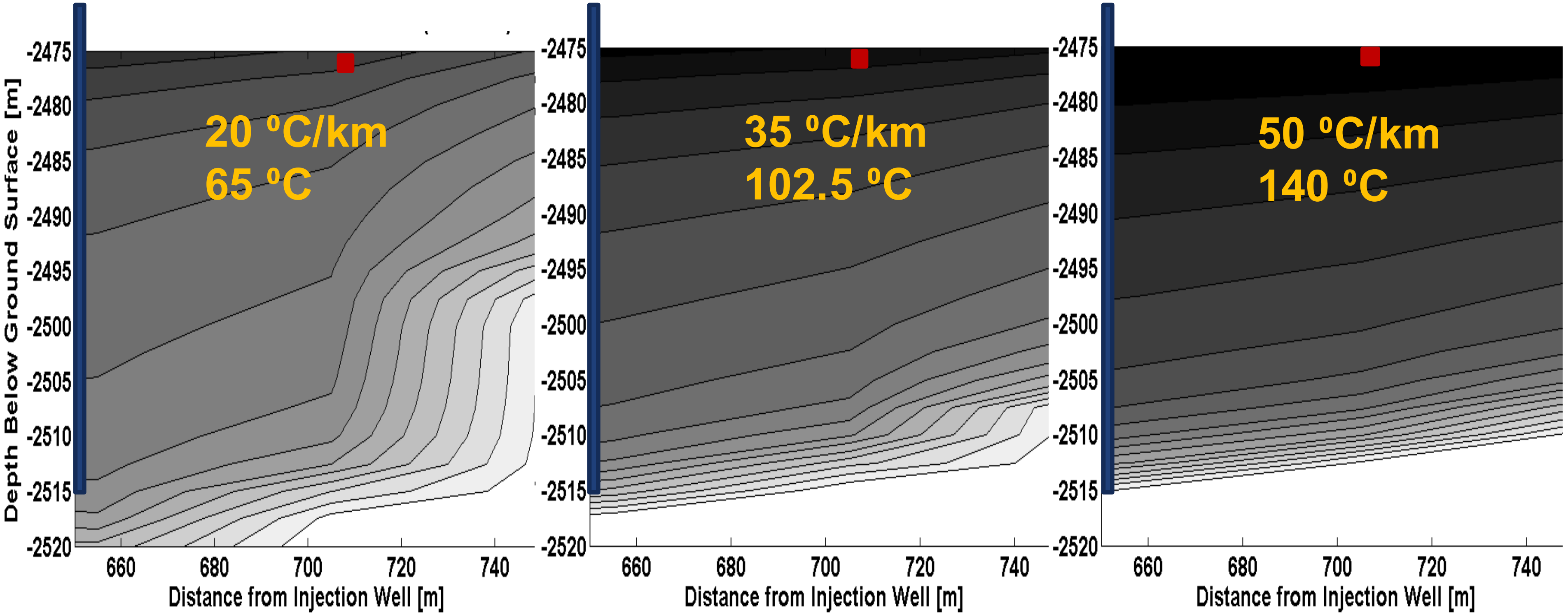
As the well spacing ↑, for the same amount of the CO$_2$ injected the upconing of brine ↑.

Garapati et al., 2015

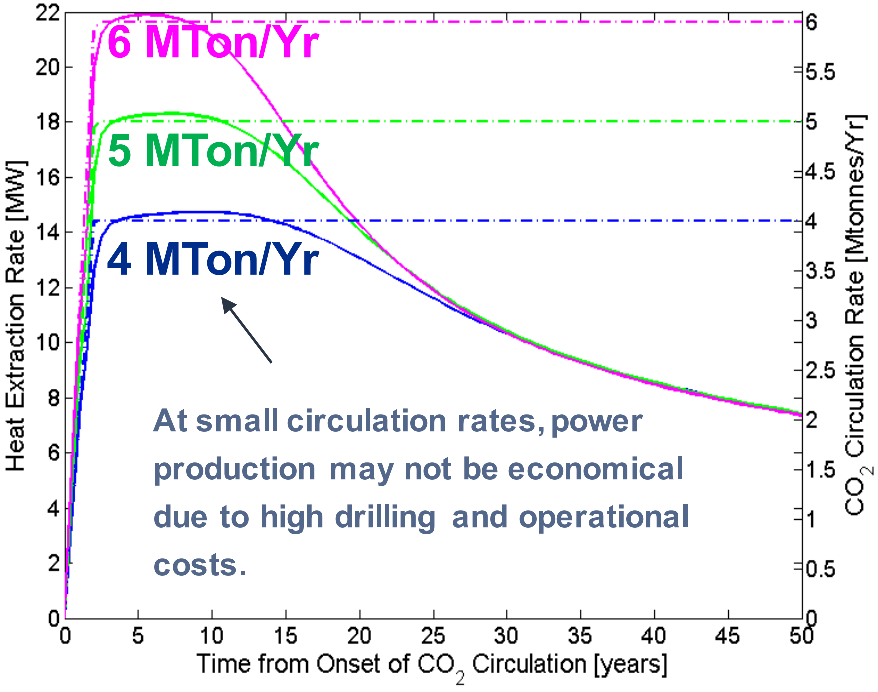
CO_2 Saturation for different Reservoir Ts

Geothermal Gradient (Depth: 2.5 km)

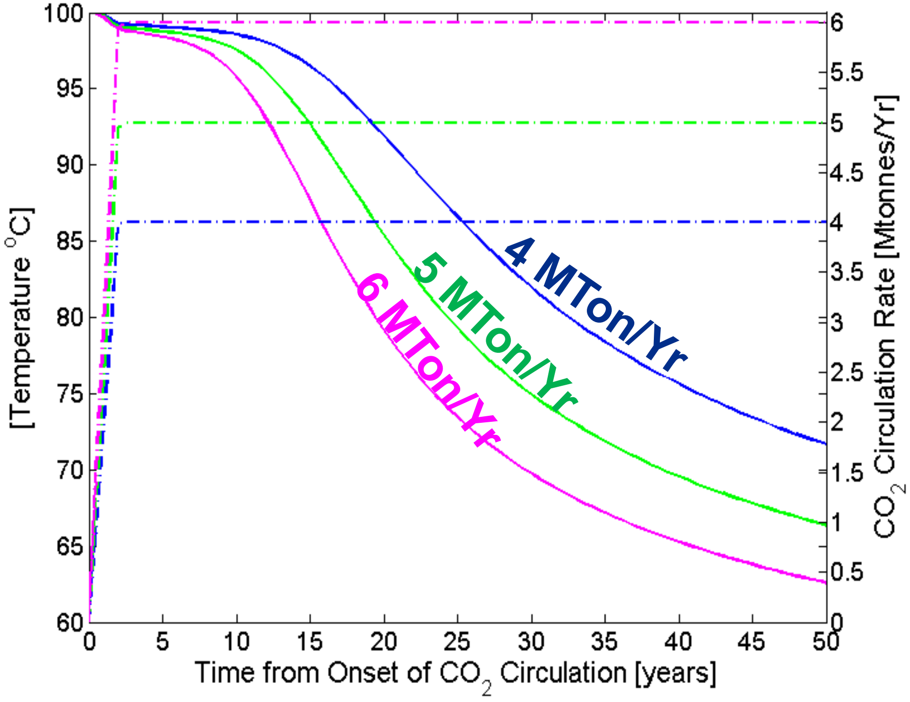
- Amount of CO_2 required is ↑ for locations with ↓ geothermal gradients.
- As the geothermal gradient ↑ the CO_2 saturation near the production well ↑.



Heat Extraction rates and reservoir lifespan



At small circulation rates, power production may not be economical due to high drilling and operational costs.



Garapati et al., 2015

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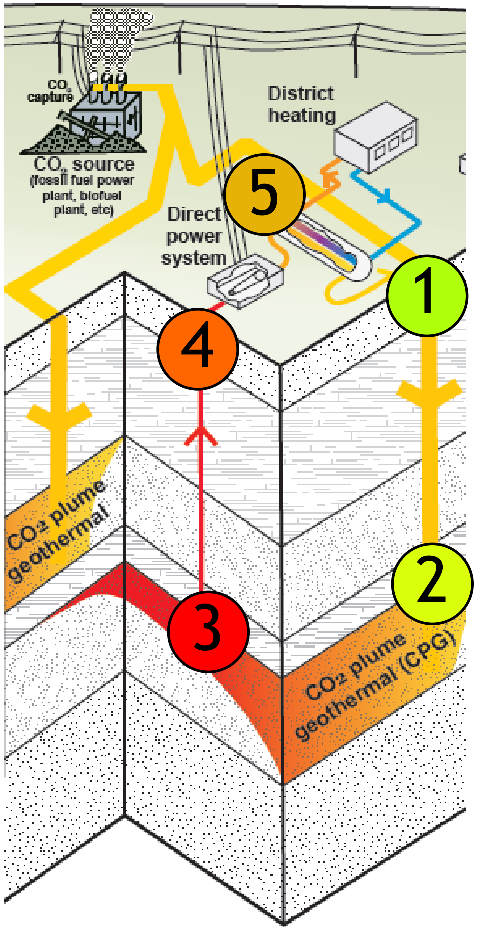
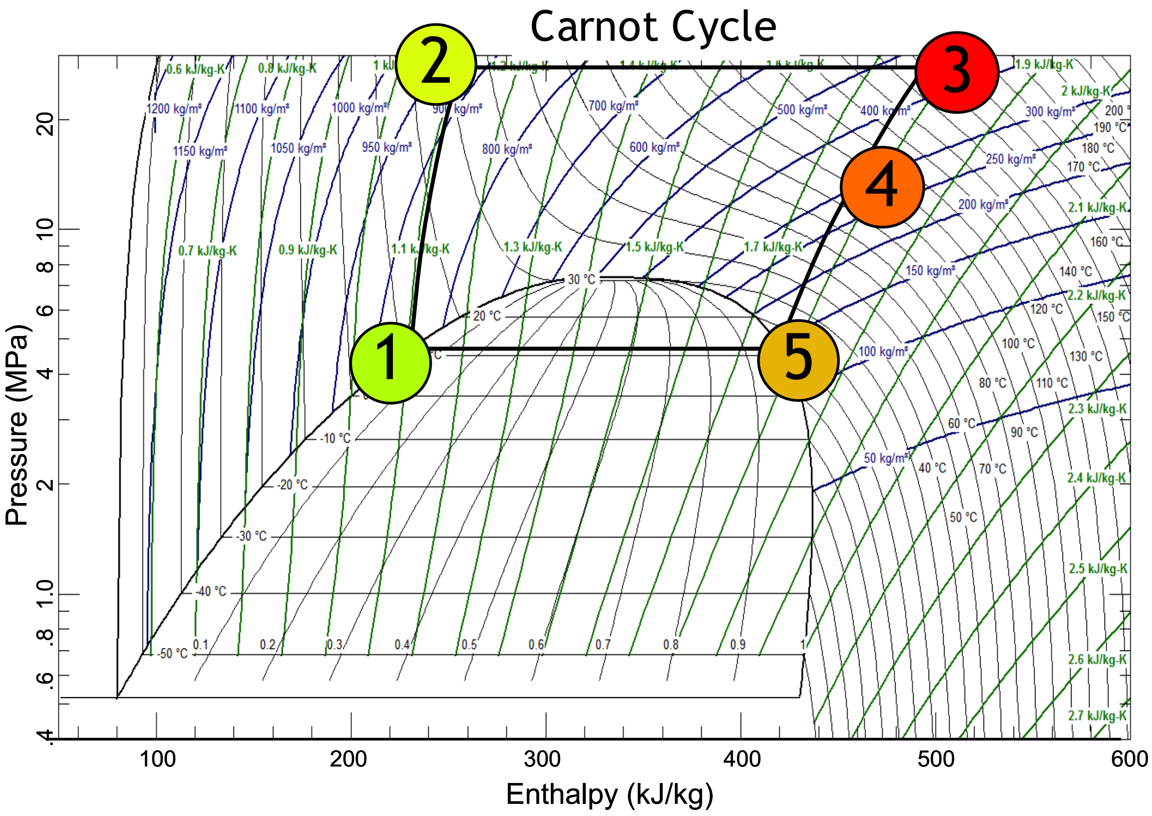
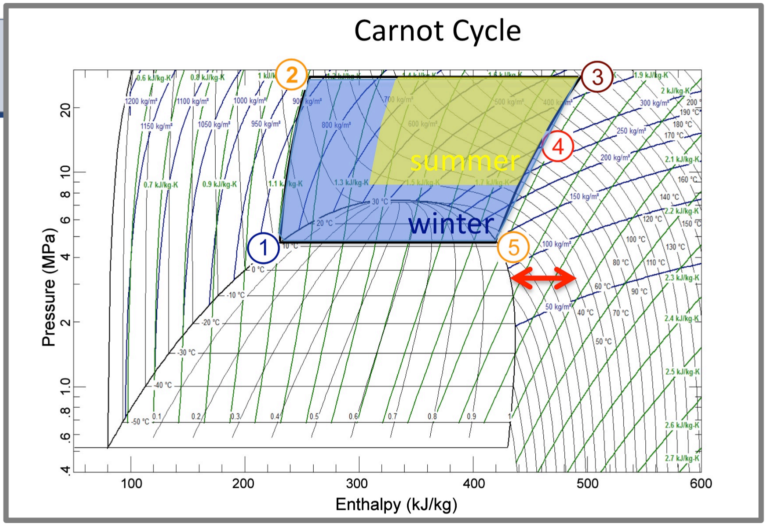
Power generation: Ideal trans-critical power cycle

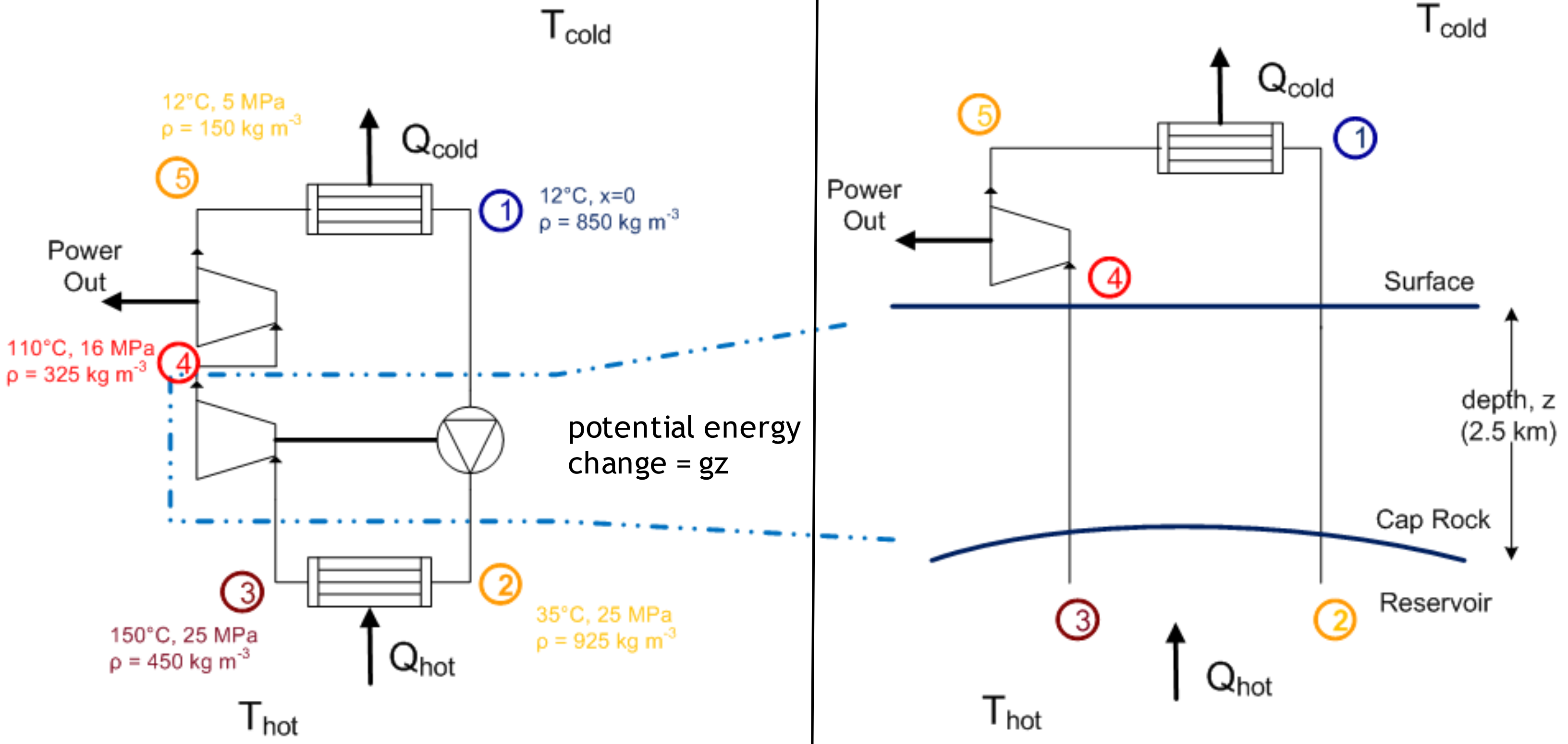




CO_2 power cycle

Adams et al., Energy, 2014



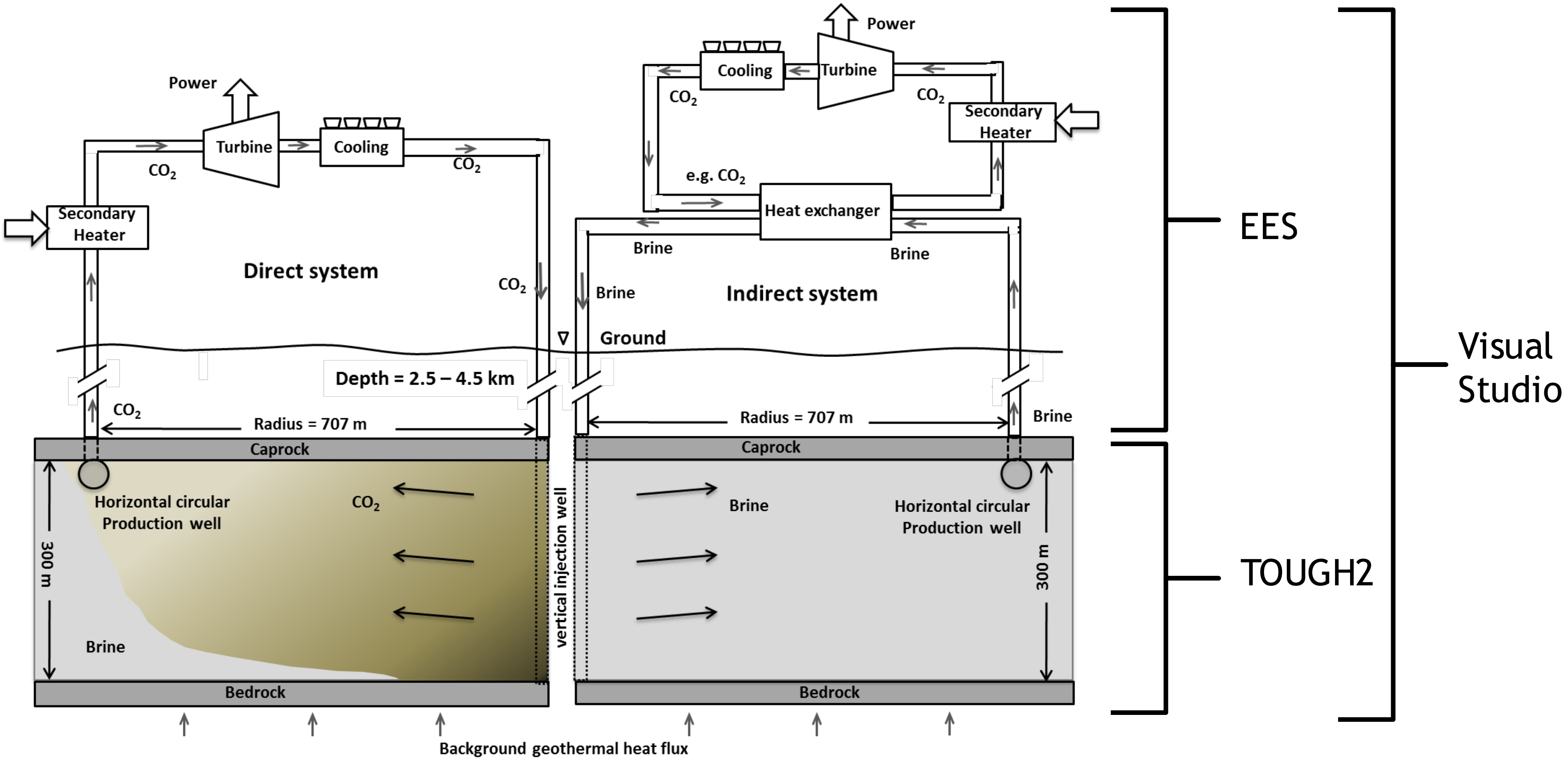


Typical fossil-fuel power cycle

CPG power cycle

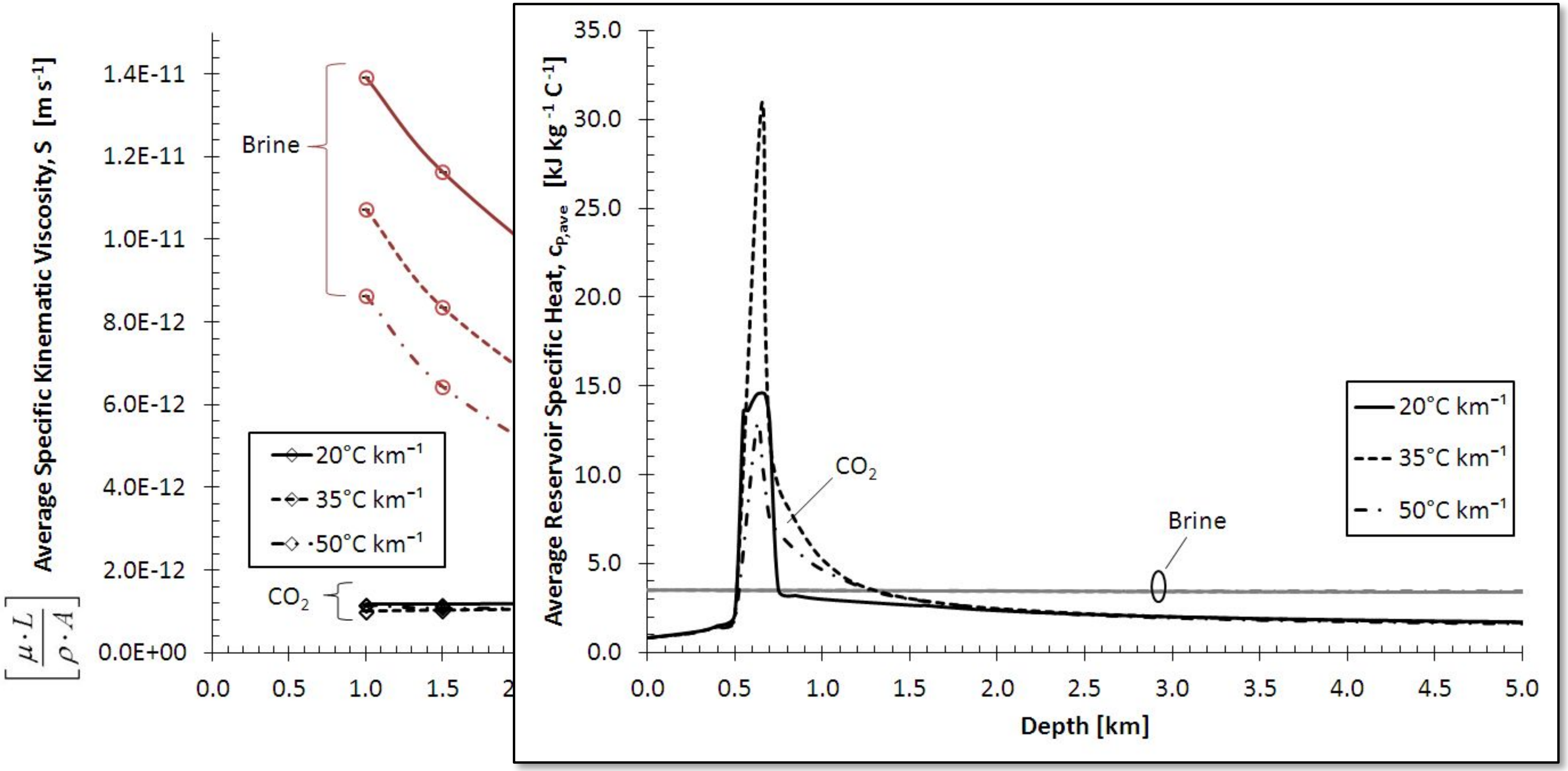
Direct and indirect (binary) power systems

Direct CO_2 Indirect brine



Garapati et al., in prep

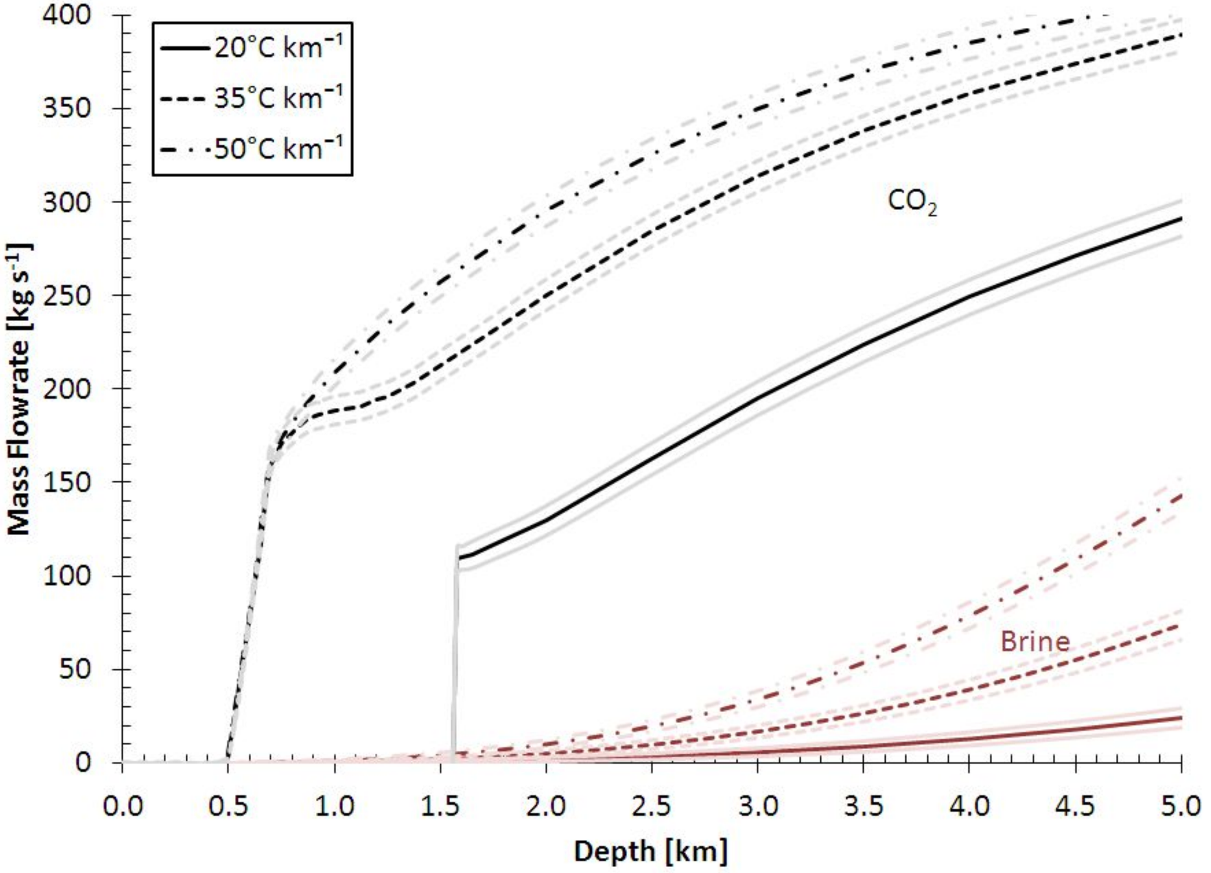
CO_2 best suited to remove energy at shallow depths



Darcy Equation: $\Delta P = \left[\frac{\mu L}{\rho A}\right]\frac{\dot{m}}{\kappa}$

Adams et al. (2014, 2015)

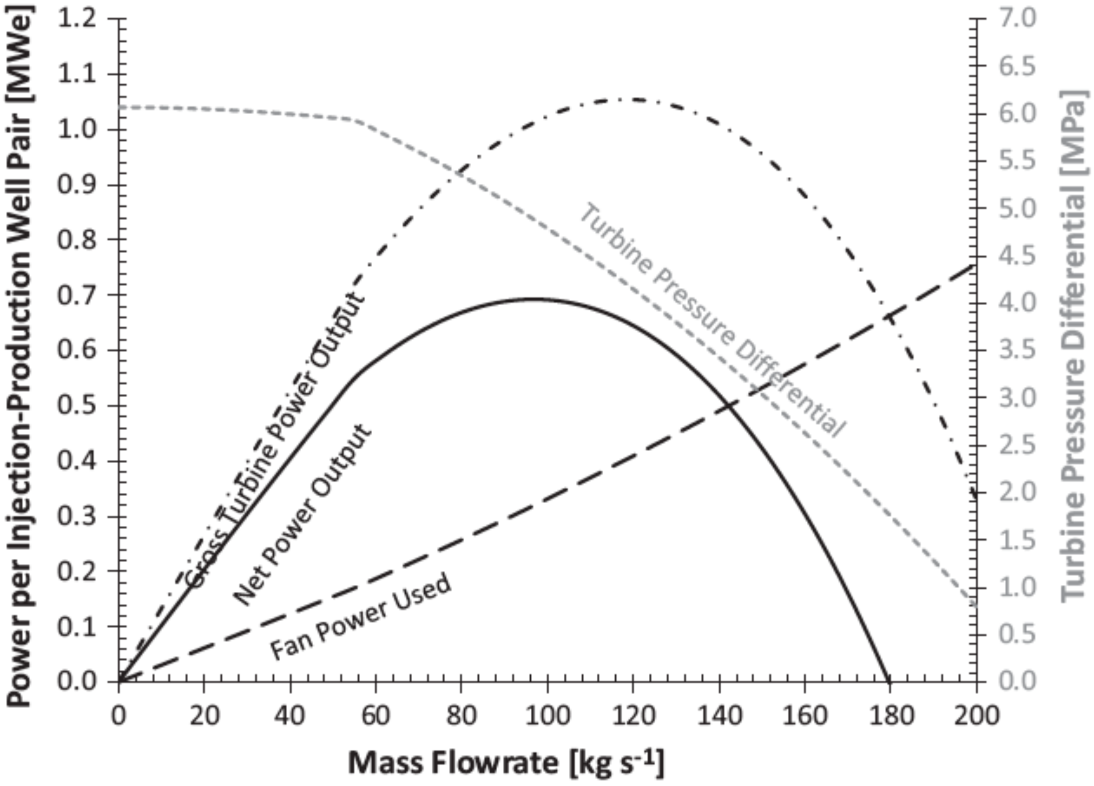
CO_2 generates substantially greater flowrates at shallow depths



Adams et al. (2014)

Power output of a direct CPG system vs. $\dot{m}$

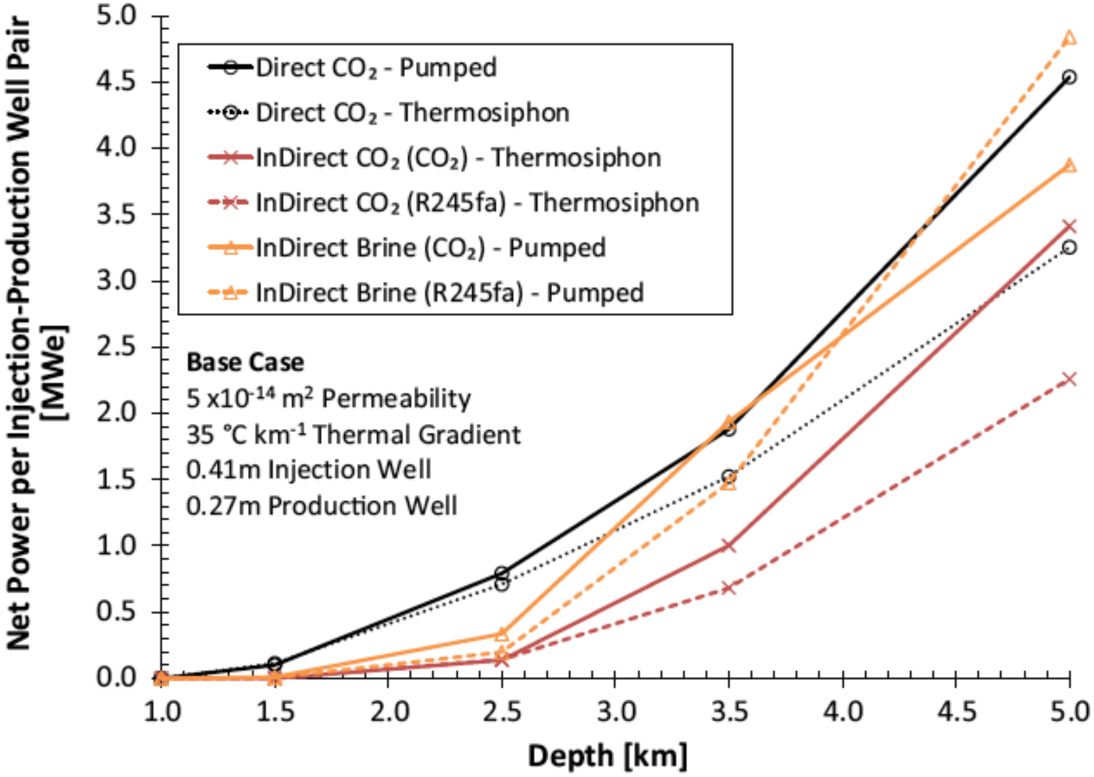
Per injection-production well pair



Adams et al., Applied Energy, 2015

Net power output of various geothermal systems vs. depth

Per injection-production well pair

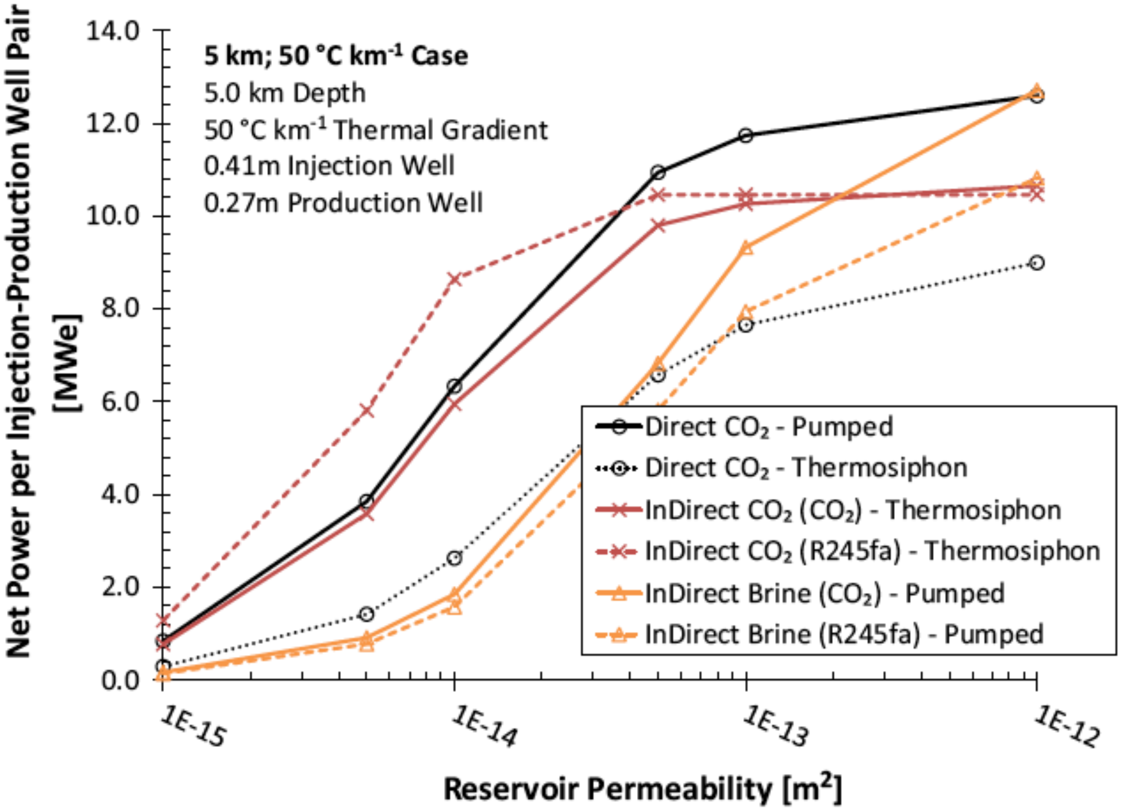


2.5 km depth
100°C reservoir

Adams et al., Applied Energy, 2015

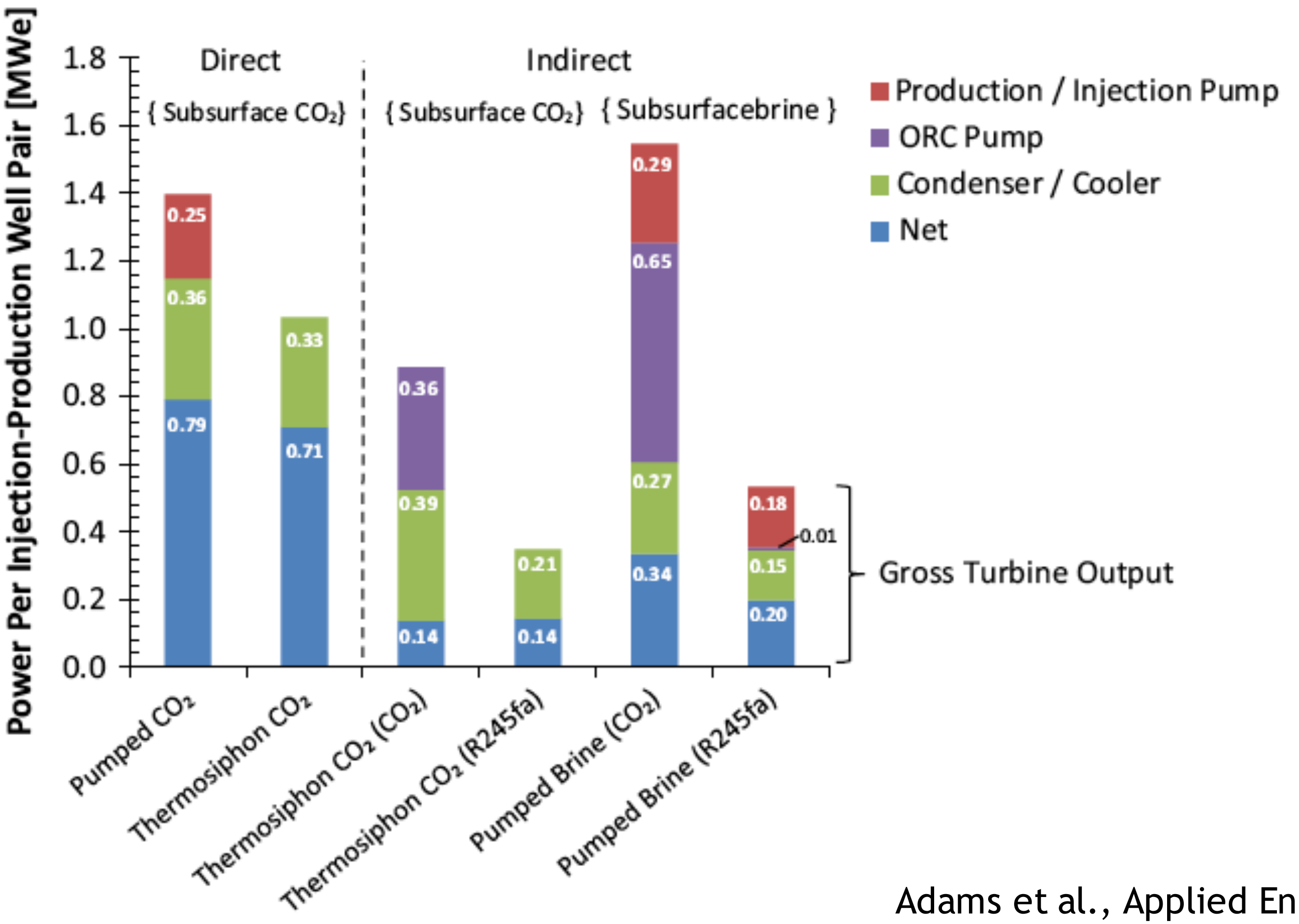
Net power output of geothermal systems vs. permeability

Per injection-production well pair



Adams et al., Applied Energy, 2015

Power requirements and output of various geothermal systems



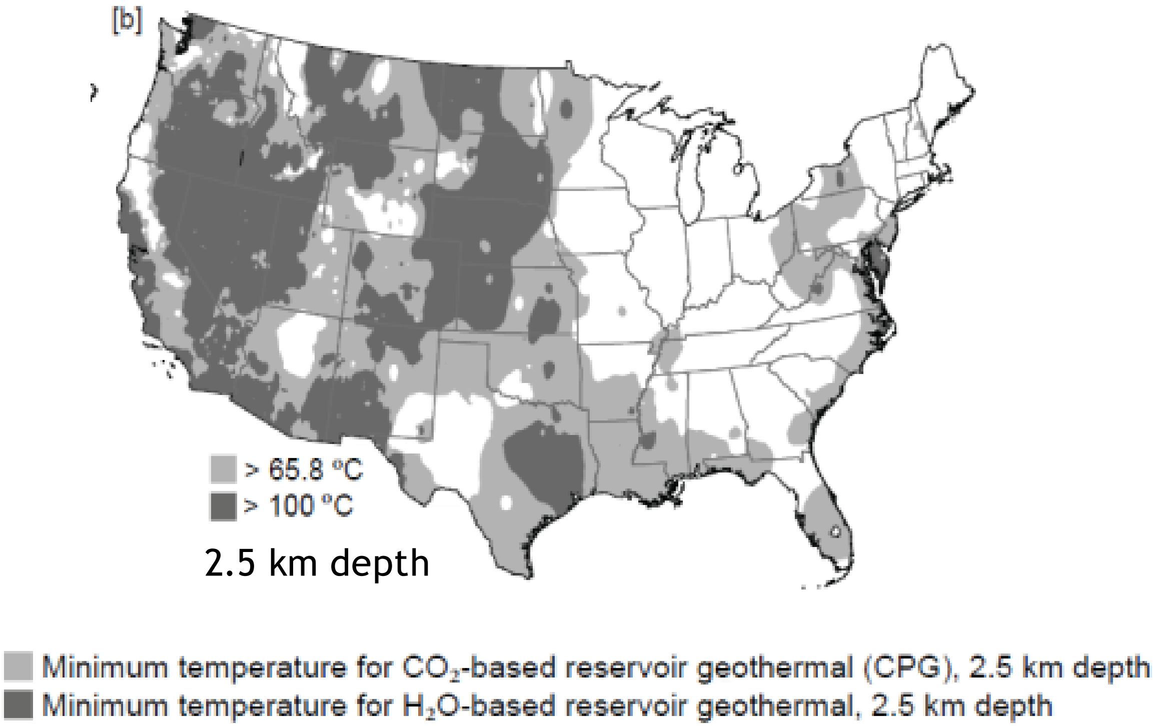
Adams et al., Applied Energy, 2015

Expansion of geothermal resource base (e.g. USA)

CPG CO_2 mass flow rates are 4.7 to 5.9 times those of hydrothermal systems

CPG heat mining rates are 2.3 to 2.9 times those of hydrothermal systems

CPG heat mining rates are 4.3 to 5.7 times those of H_2O-based EGS



2.5 km depth

Randolph and Saar, 2011

OUTLINE

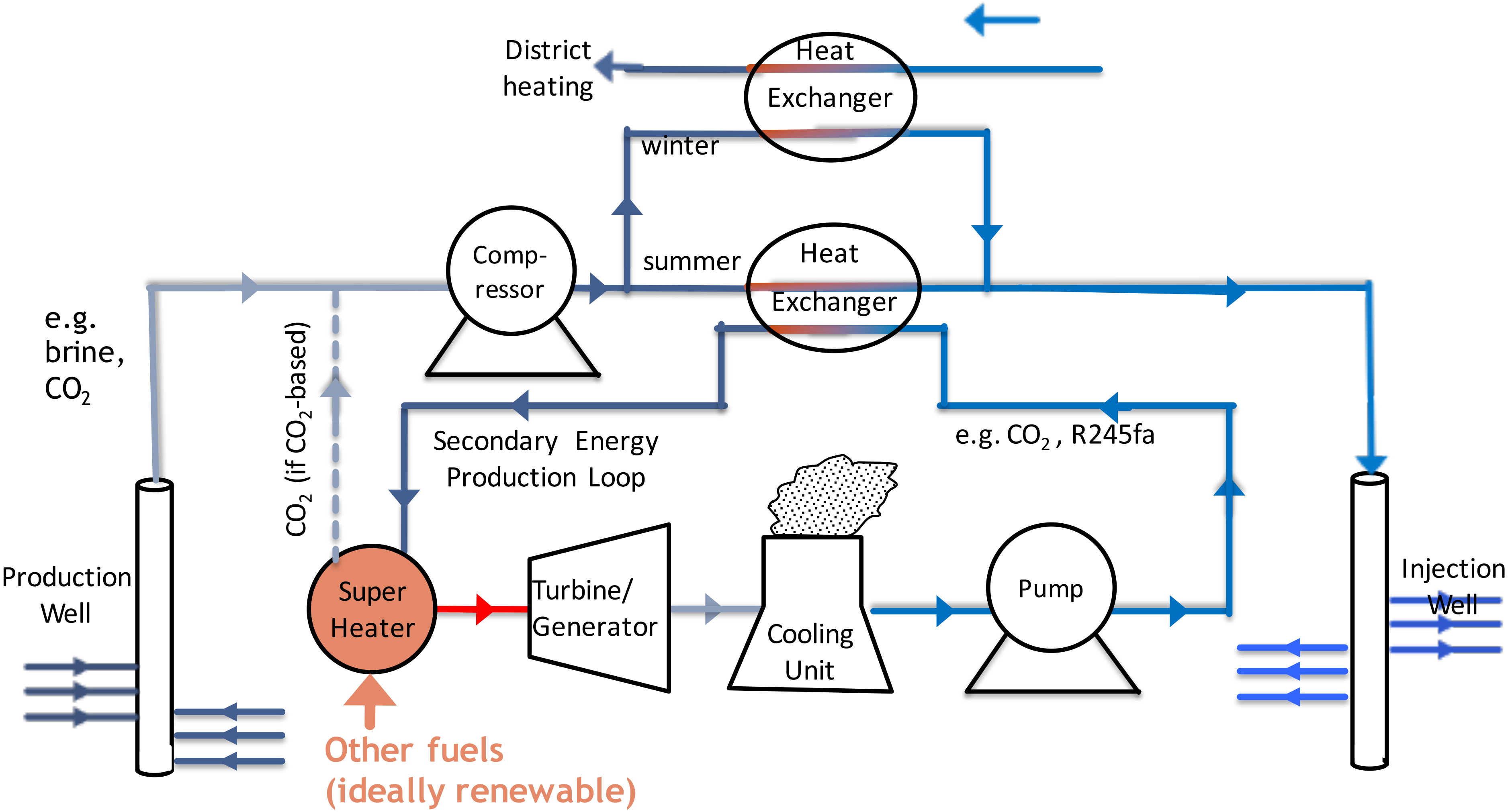
1) Subsurface energy extraction with CO_2 (combining CCS with geothermal) → comparison to water
   a) 5-spot well system
   b) circular production well

2) Geothermal energy conversion to electricity (power): water vs. CO_2

3) Auxiliary heating of geothermally preheated geofluids: water vs. CO_2 (circular production well)

4) Summary

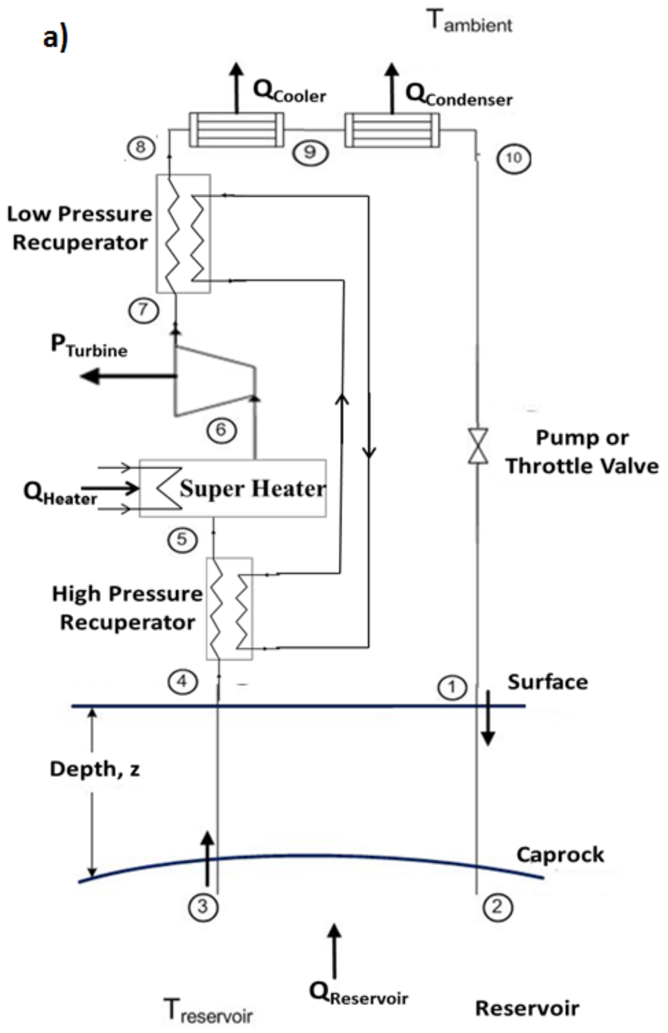
Auxiliary heating of geothermally preheated fluids



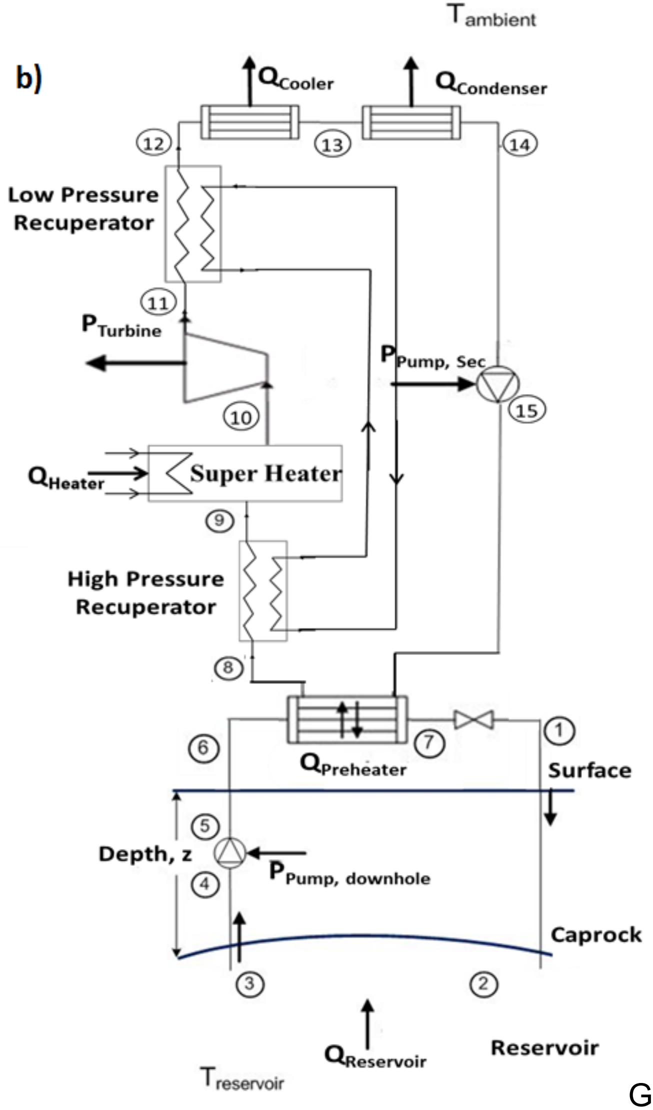
Garapati et al., in prep

Auxiliary heating of:

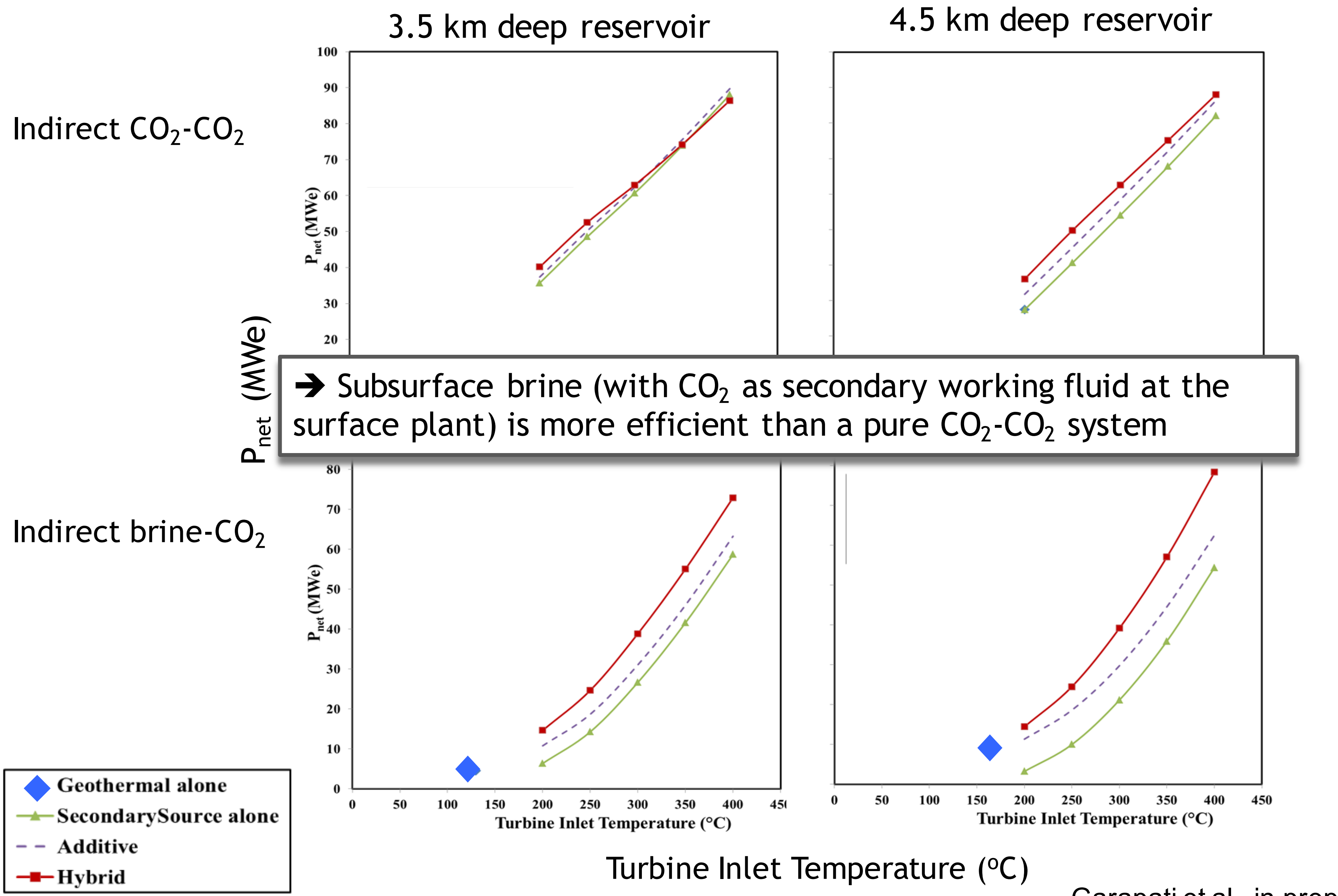
a) direct CPG system



b) indirect brine system



Garapati et al., in prep



3.5 km deep reservoir

4.5 km deep reservoir

Indirect CO_2-CO_2

Indirect brine-CO_2

P_{net} (MWe)

➔ Subsurface brine (with CO_2 as secondary working fluid at the surface plant) is more efficient than a pure CO_2-CO_2 system

Turbine Inlet Temperature (°C)

Garapati et al., in prep

OUTLINE

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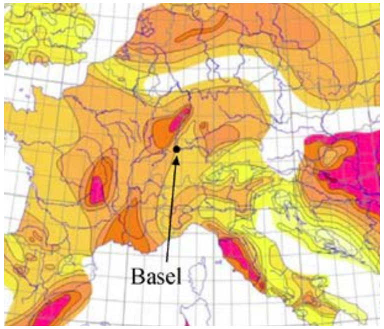
SUMMARY (geothermal power production)



- Low- to moderate enthalpy geothermal "resources" are most common worldwide
- For those and/or if permeabilities, *k*, (i.e., fluid flow rates) are low, unconventional geothermal systems/power plants are required to generate power:
  - EGS: go deep to increase *T* + requires increasing permeability
  - CO_2-geothermal (with EGS or for sedimentary basins: CPG)
    → use CO_2 as working fluid to enhance efficiency (by a factor of about 2) (lower *T* and/or *k* can be used)
    → CPG: Combine with CCS → CCUS: geothermal PP with a negative C footprint (but all benefits of and problems with CCS apply)
  - Auxiliary heating of geothermally preheated geofluids (lower *T* still useful)
    → potentially useful for synthetic fuel production

Thank you!

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