Combining CO$_2$ capture (CC) and geologic storage (S) with geothermal power generation (U) and subsurface energy storage (U) + DACS (U) → CCUUUS

EuroWorkshop: Geology and the Energy Transition, Delft, 23.5.2019

Binary power system

CO$_2$ capture

District heating

CO$_2$ source (fossil fuel power plant, biofuel plant, etc)

Direct power system

Confining unit (e.g., shale)

Enhanced hydrocarbon recovery (EOR)

Confining unit

Saline aquifer

Crystalline basement

CO$_2$ plume geothermal

CCUUS

CCUS

CO$_2$ plume geothermal (CPG)

EGS

Prof. Martin Saar, Ph.D.

saarm@ethz.ch

Chair Geothermal Energy and Geofluids

And: Jimmy Randolph, Ben Adams, Nagasree Garapati, Jeff Bielicki, Tom Kuehn, Tom Buscheck, Steve Taff, Ellen Longmire, Raphael Allstadt, Justin Ezekiel, Anozie Ebigbo, Daniel Vogler, Allan Leal, Ben Tutolo, Andrew Luhmann, Bill Seyfried, Scott Alexander, ...
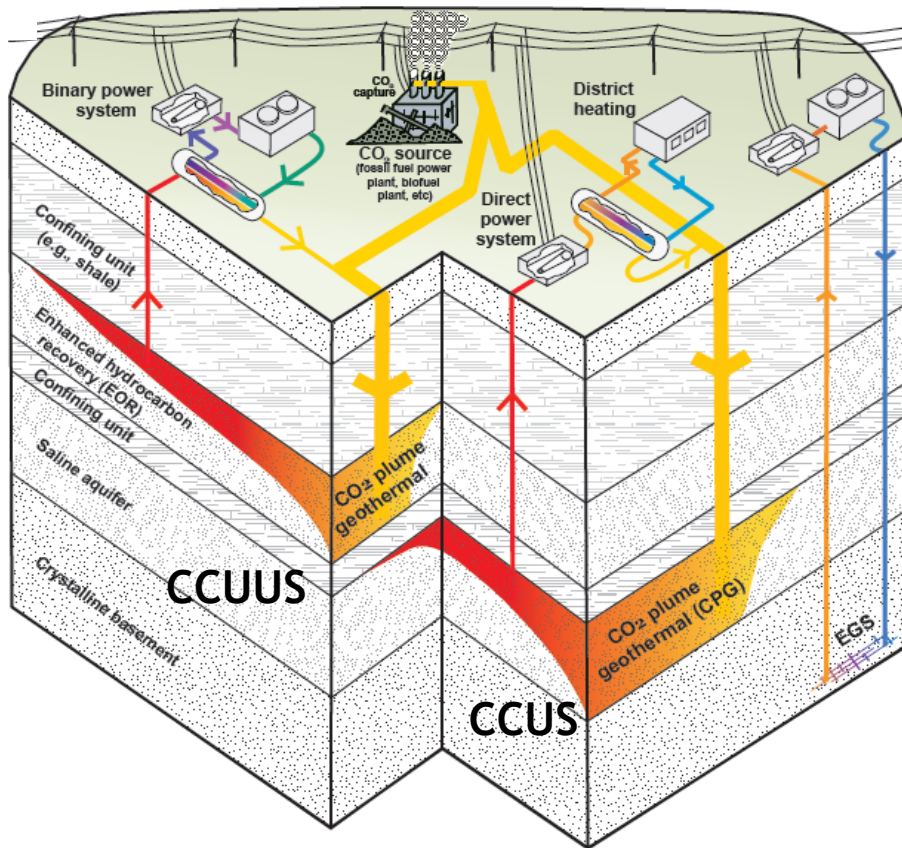
Randolph and Saar, GRL 2011; Energy Procedia 2011
Saar et al., 2012; ...

FNS**NF**

ETH

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SIEMENS *Ingenuity for life*

WSS

WERNER SIEMENS - STIFTUNG

NSF

U.S. DEPARTMENT OF **ENERGY**

European Commission

- DESTRESS
- Elegancy
- HEATSTORE
- ZoDrEx

Geothermal Energy and Geofluids Group (Prof. Saar)
   Dept. of Earth Sciences – ETH Zürich, CH

WSS

WERNER SIEMENS - STIFTUNG

Founded: 2015

Spinoff **ETH**_zürich_

Founded: 2018

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CO2 POWER GmbH, Zurich, CH

Photo from 2017

GEG.ethz.ch

Currently (~30 people):

  6 Senior Research Associates
  6 Postdocs
13 Ph.D. Students
  4 MSc. Students
  3 Scientific Assistants
  1 Technician

Geoscientists
Geo-Engineers
Mechanical Engineer*s*
Techno-Engineers
Computer Scientists
Mathematicians

Numerical modeling (~50%)
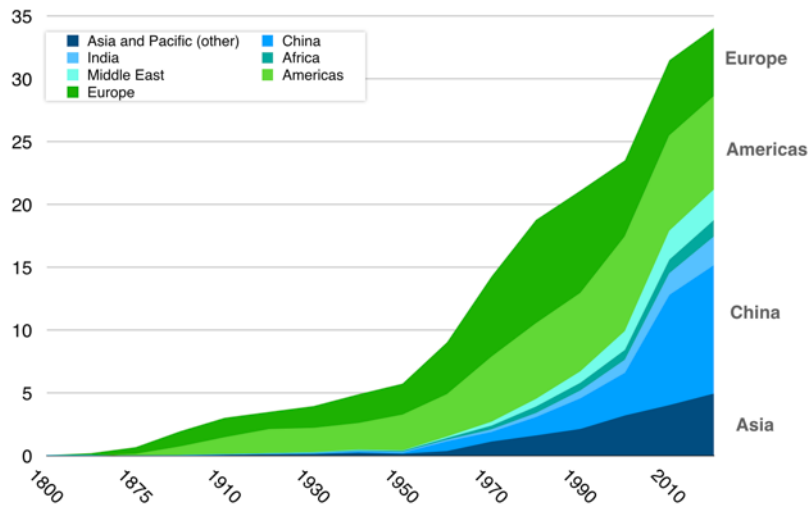Lab experiments (~30%)
Field work (~20%)

Global warming
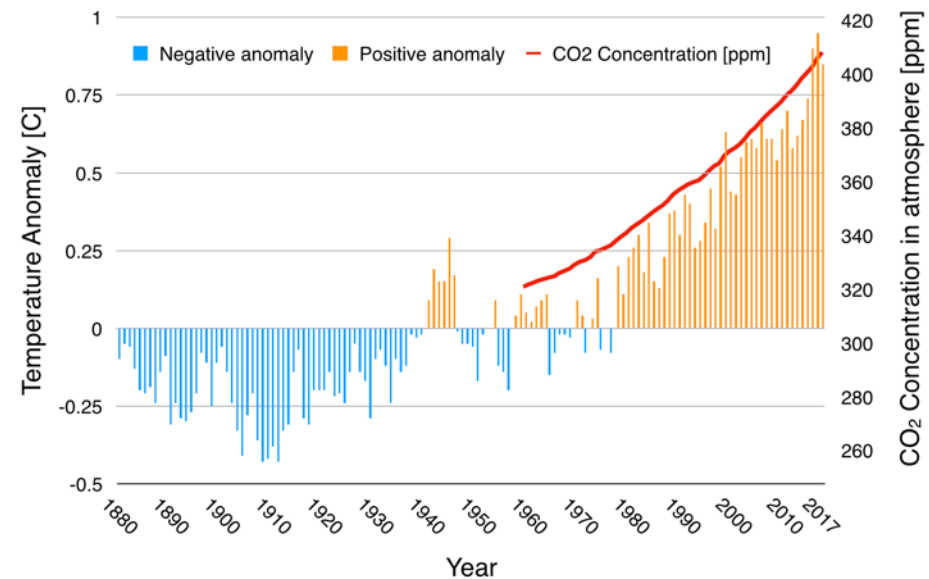
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CO₂ emission rates still rising year-on-year

(annual output in Gt/year)*

Accelerated accumulation in the atmosphere

Atmospheric CO₂ concentrations versus temperature difference compared to the 1951-1980 average (after Fleming, 2019, with data from **and ***)

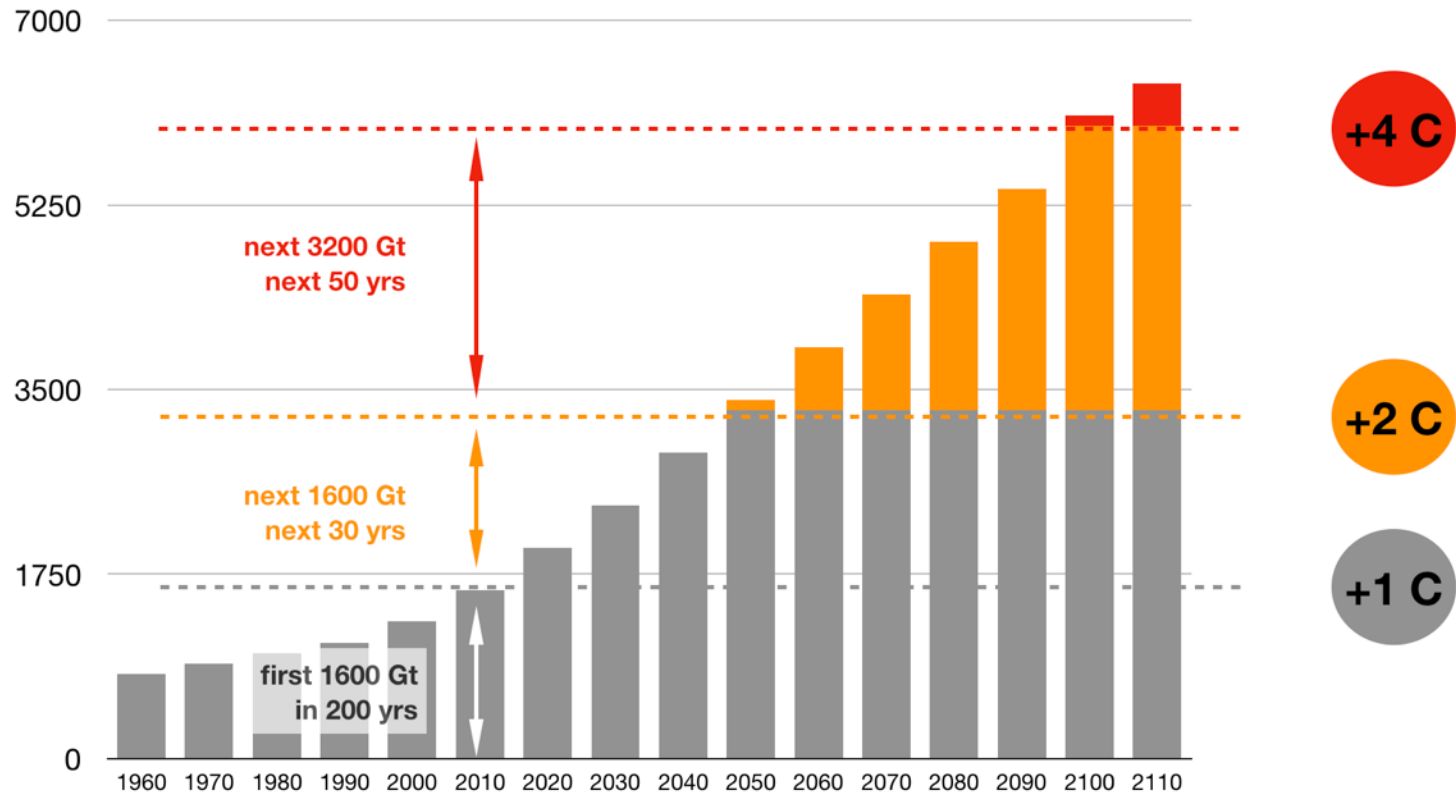*   https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

**   E. Dlugokencky and P. Tans, "ESRL Global Monitoring Division - Global Greenhouse Gas Reference Network." [Online]. Available: https://www.esrl.noaa.gov/gmd/ccgg/trends/gl_data.html. [Accessed: 08-Apr- 2018

*** GISTEMP Team, "GISS Surface Temperature Analysis (GISTEMP)," NASA Goddard Institute for Space Studies, 2018. [Online]. Available: https://data.giss.nasa.gov/gistemp/. [Accessed: 10-Apr-2018].

Global warming

Global warming mitigation measures

Historical and future emission scenarios
(according to scenarios and modeling simulations in IPCC AR5)

Erwärumung relativ zu
1850 – 1900

3.2 – 5.4°C

2.0 – 3.7°C

1.7 – 3.2°C

0.9 – 2.3°C

Historical
CO_2-emissions

CO_2-Emissionen [Gt CO_2/Jahr]
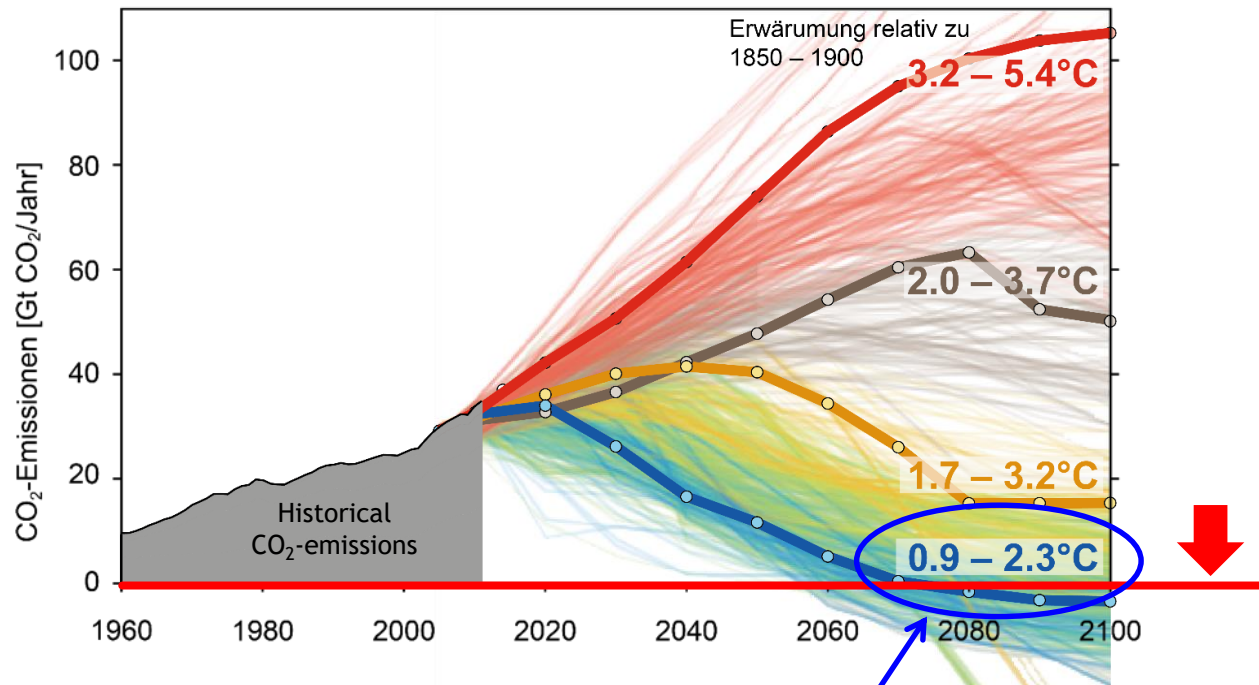
Paris agreement, Dec 2015 – 1.5° C

Portfolio approach
- Renewables
- Energy efficiency
- Mobility
- Energy savings
- Switch of primary fuels
- Carbon dioxide capture and storage (CCS)
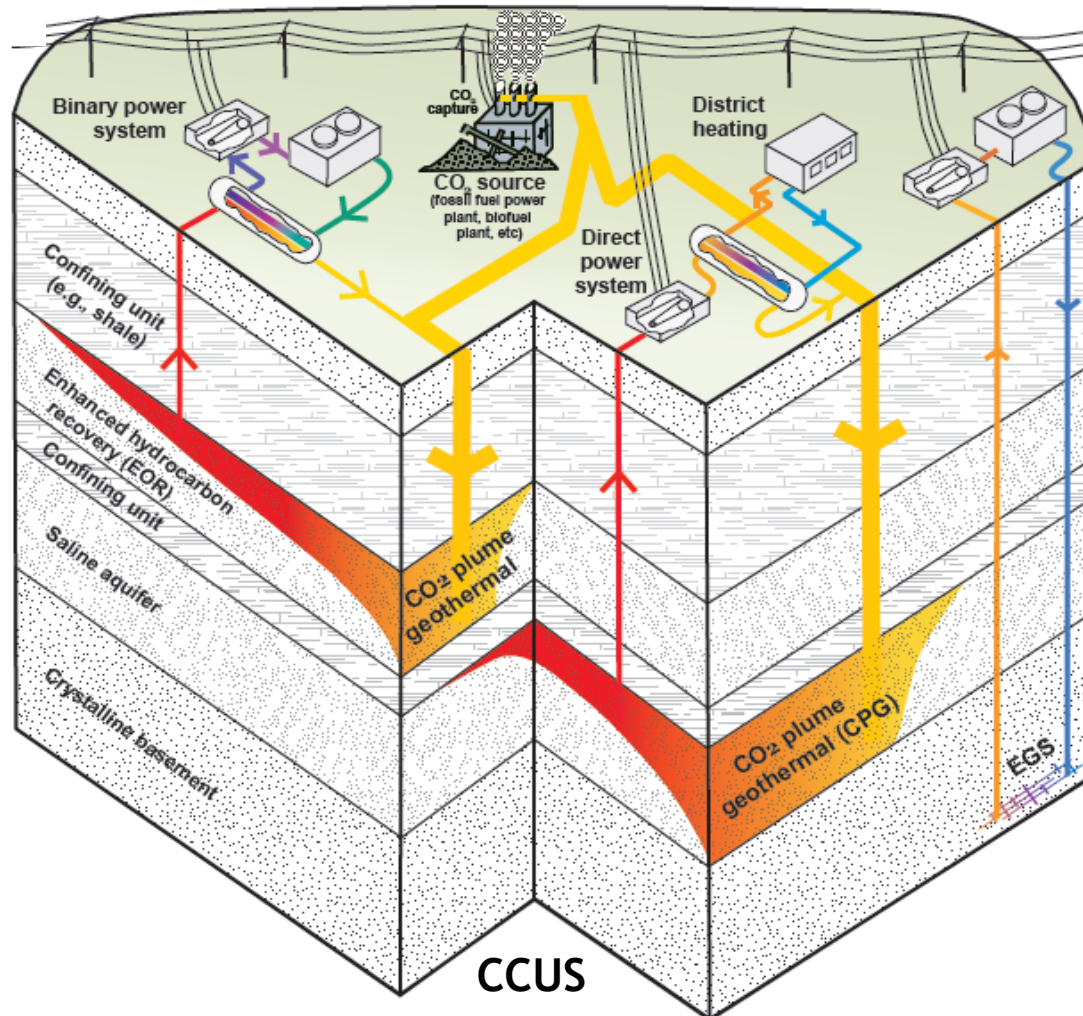- Measures related to agriculture, forestry and other land uses (AFOLU)

Towards zero and negative emissions
- The role of CCS is acknowledged to be decisive within ambitious mitigation scenarios

Global warming mitigation measures
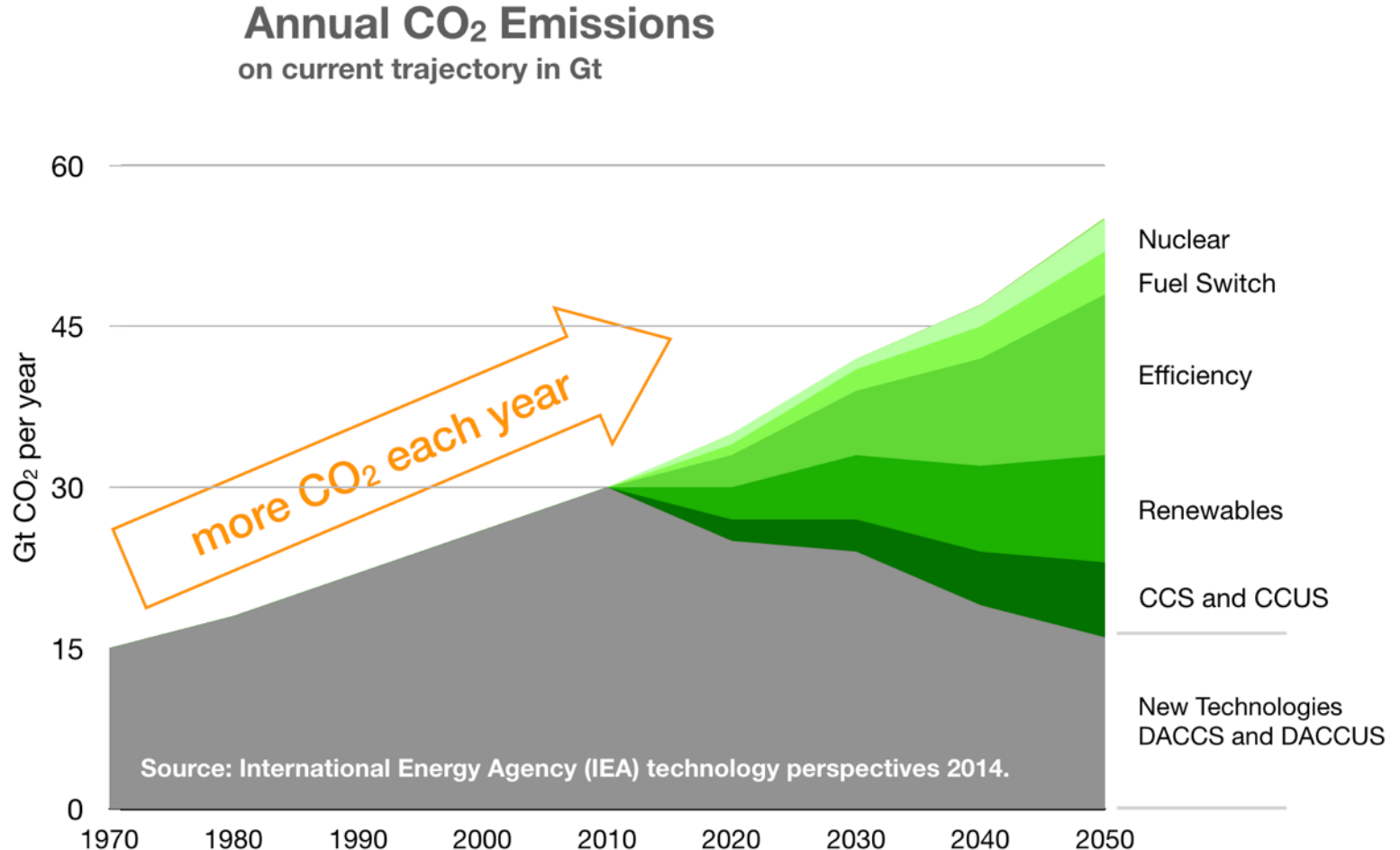
CO$_2$-Plume Geothermal (CPG)

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Randolph and Saar, 2011
Saar et al., 2012

What makes CO_2 a more efficient working fluid than water?

Two main reasons:

1) Ratio of CO_2 to H_2O mobility
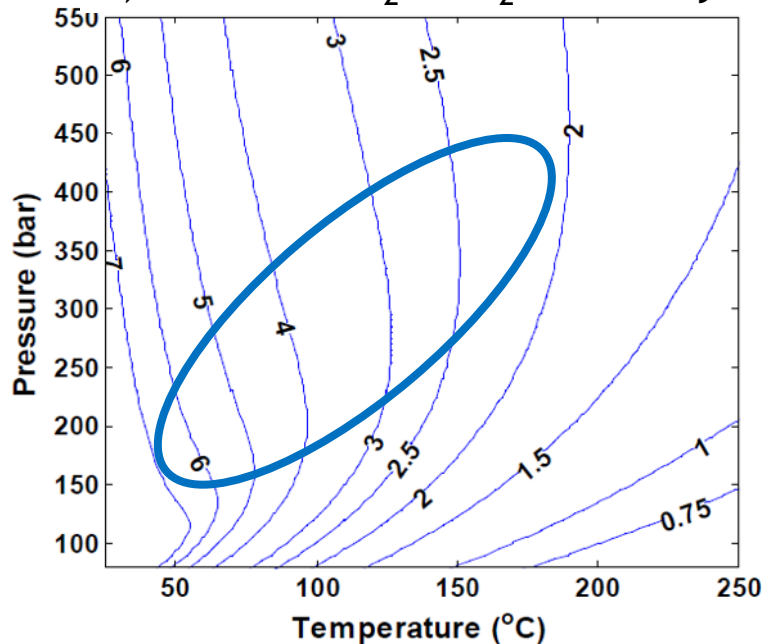
2) Fluid density profiles

Water (2.5km)

Water (1 km)

CO_2 (2.5 km)

CO_2 (1 km)
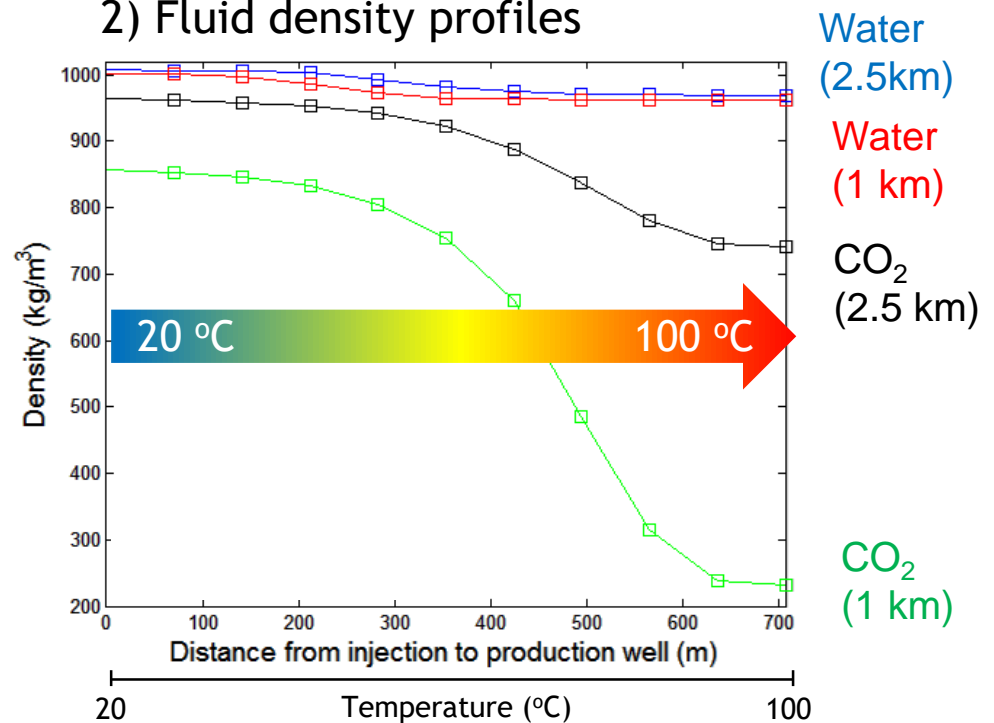
see also: Adams et al., Energy, 2014

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

$$\Delta P_{well,isentropic} = \int_0^z \rho \cdot g \cdot dz$$
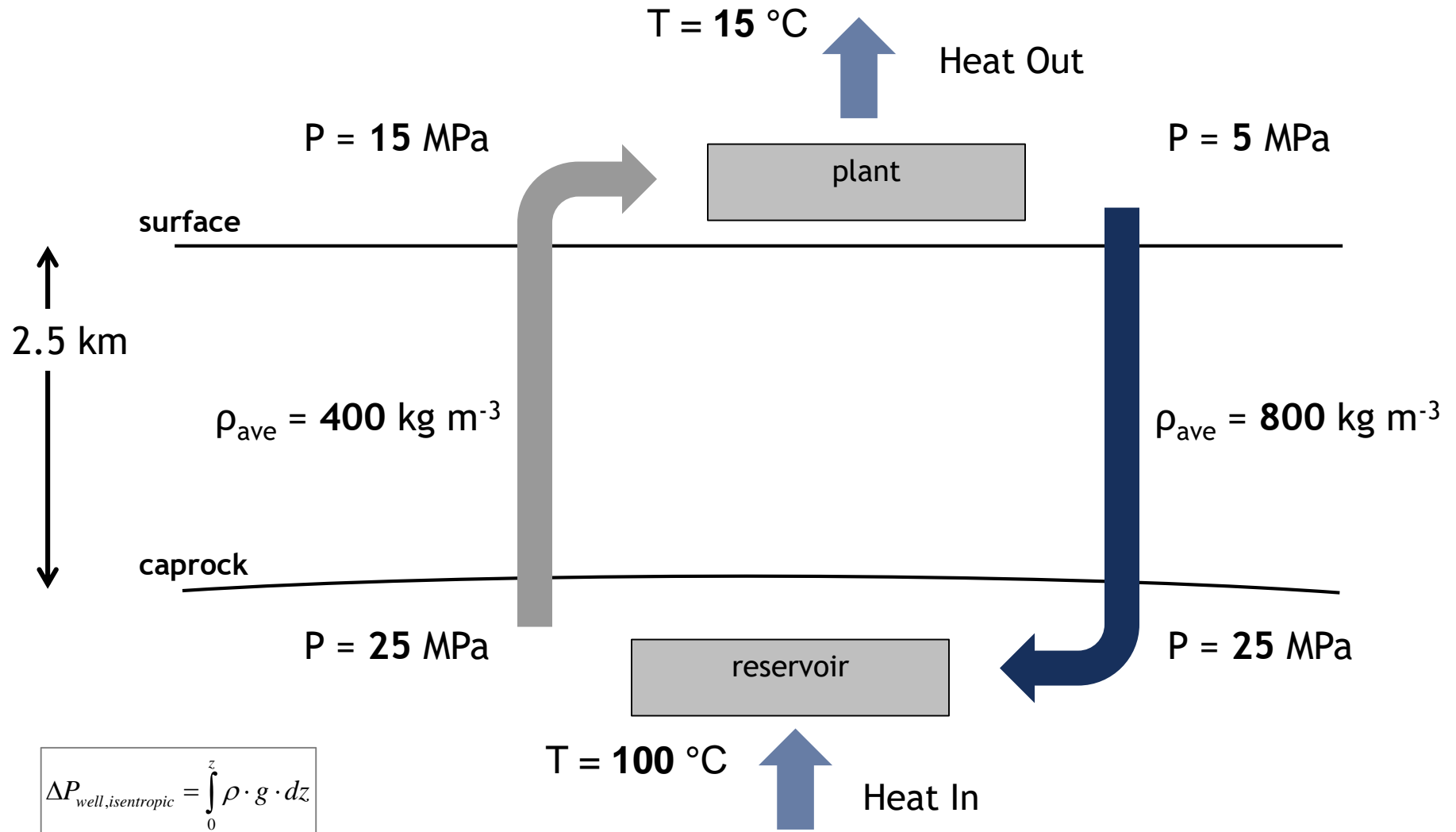
Injection and production wellhead pressure difference generated by thermosiphon

What makes CO_2 a more efficient working fluid than water?

Ratio of CO_2 to H_2O mobility

see also: Adams et al., Energy, 2014
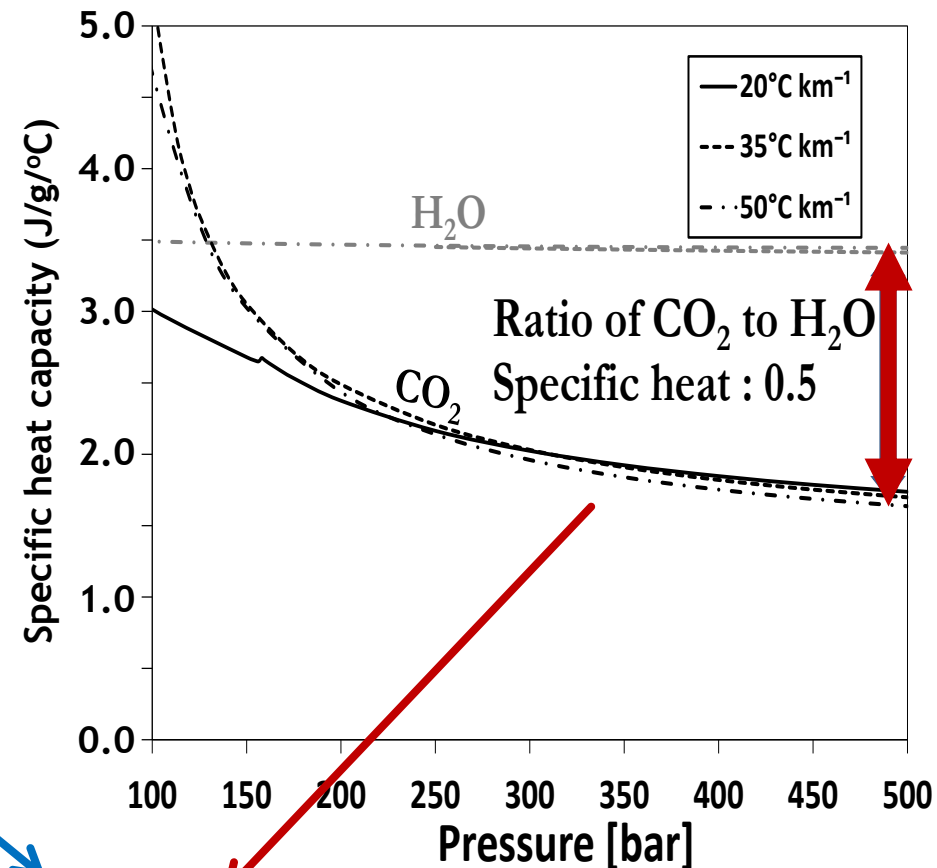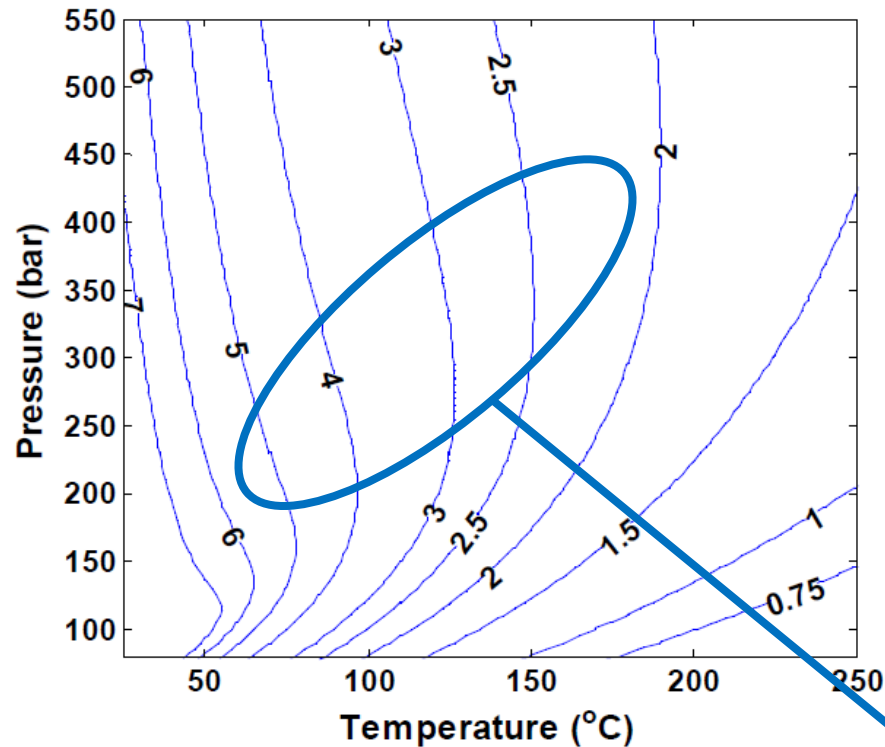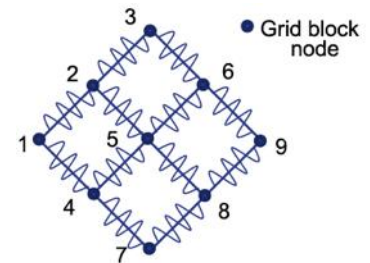
Numerical modeling: Thermal energy extraction of CO_2 reservoir with classic 5-spot well system

CPG

Map view

707.1 m

Injection

Production

500 m

Naturally permeable (sedimentary) formation
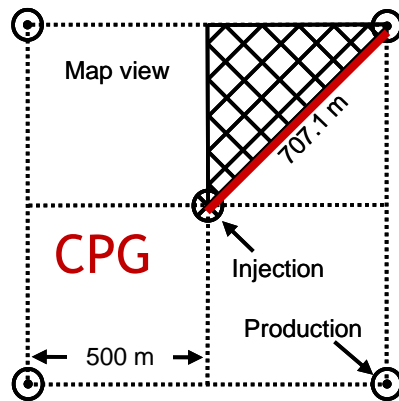
- TOUGH2 Integrated finite difference code (Pruess, 1999, 2000, 2004, 2006, 2008)

- CO_2, H_2O, NaCl: - Geothermal energy
                               - CO_2 sequestration

Grid block node

Map view

Production

Injection

1 amp

EGS w/ CO_2

Fractured formation

500 m

〰 Fracture

— Grid block boundary

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		
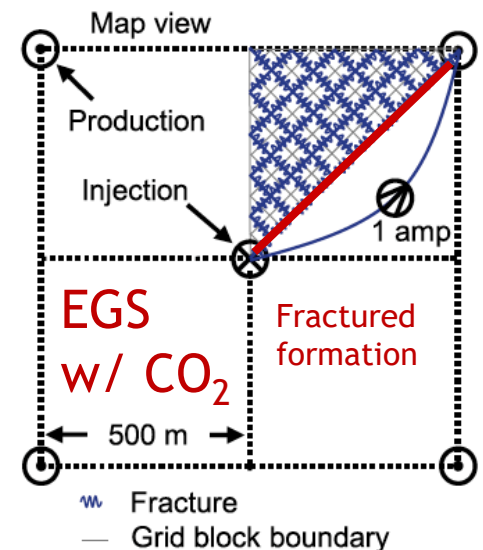
Heat energy (MW$_{th}$) extraction over time for both CO$_2$ and brine (sedimentary basin and EGS)

Randolph and Saar, GRL 2011
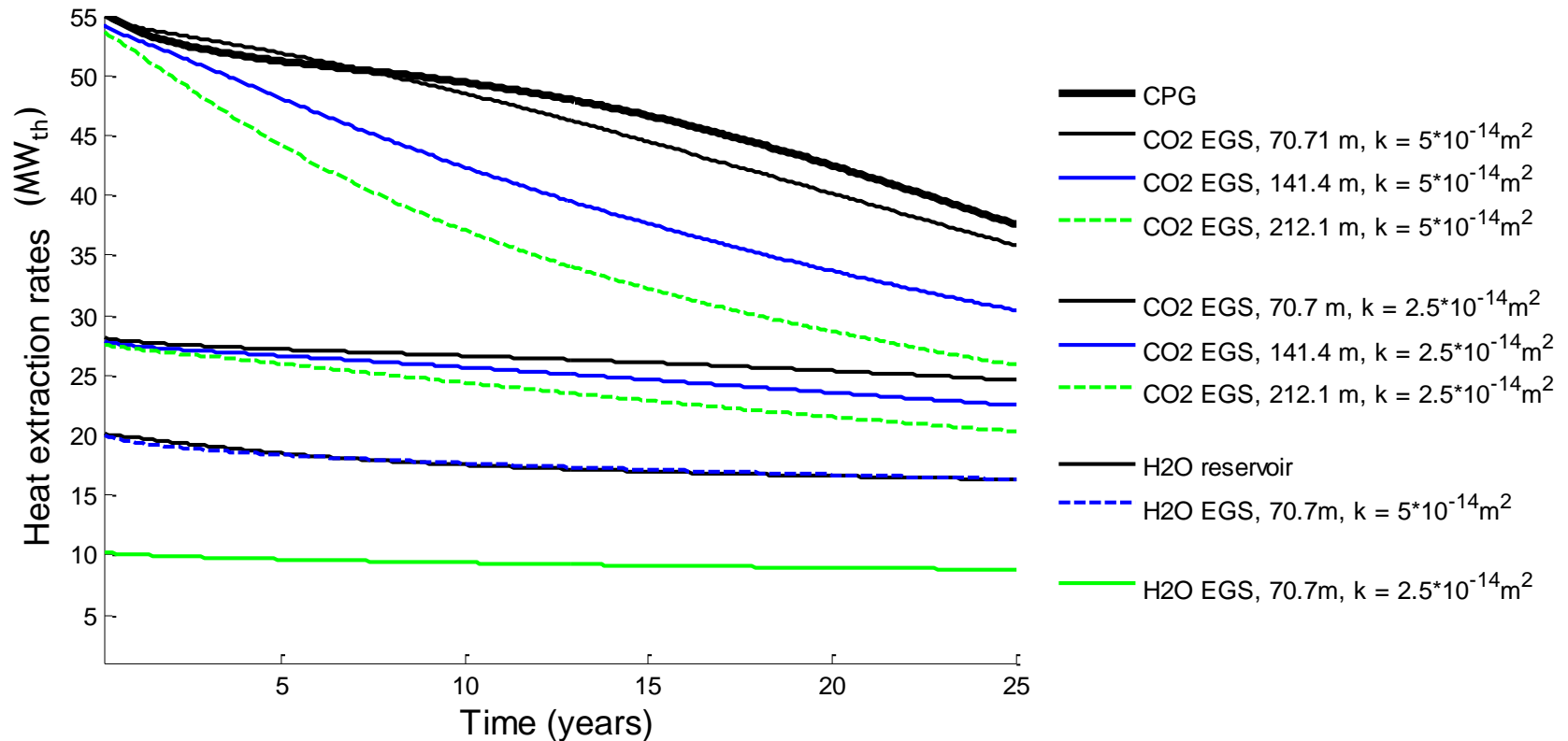
Power generation: Ideal trans-critical power cycle

Carnot Heat Engine Cycle
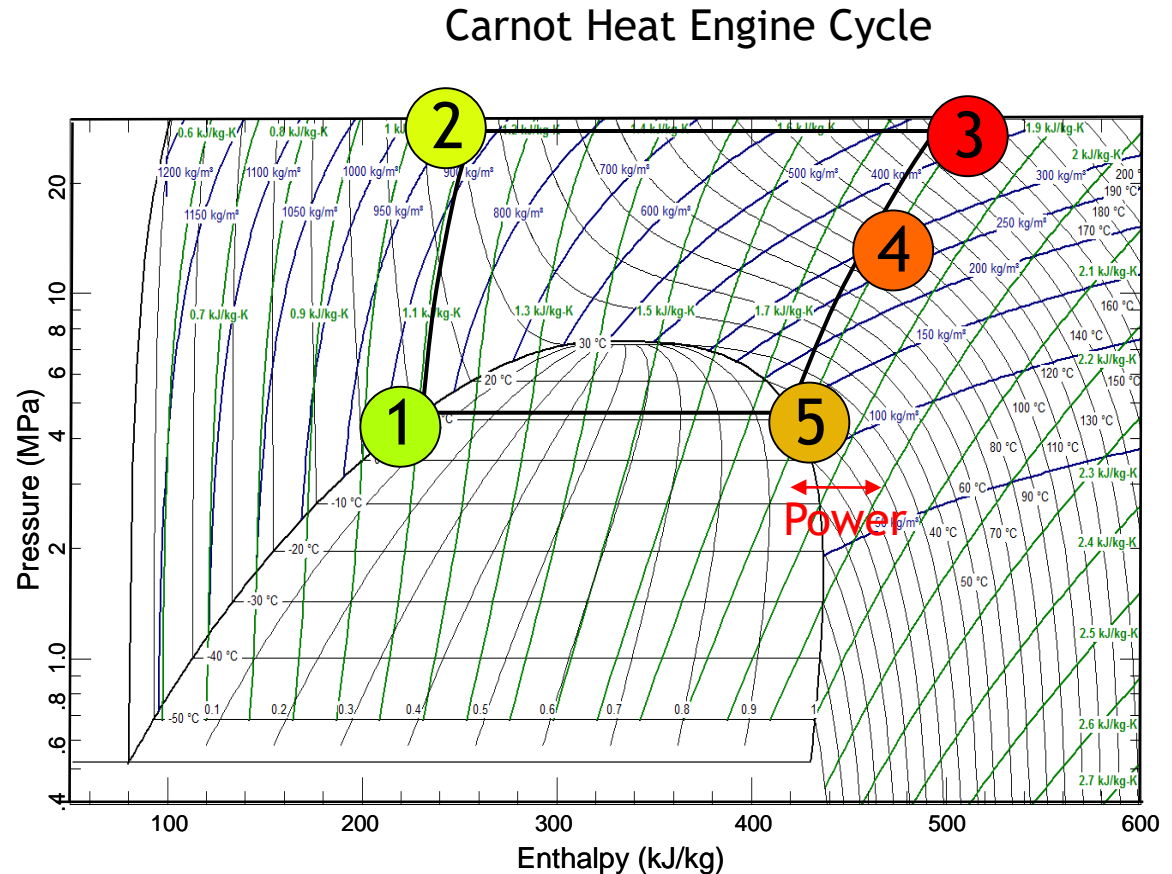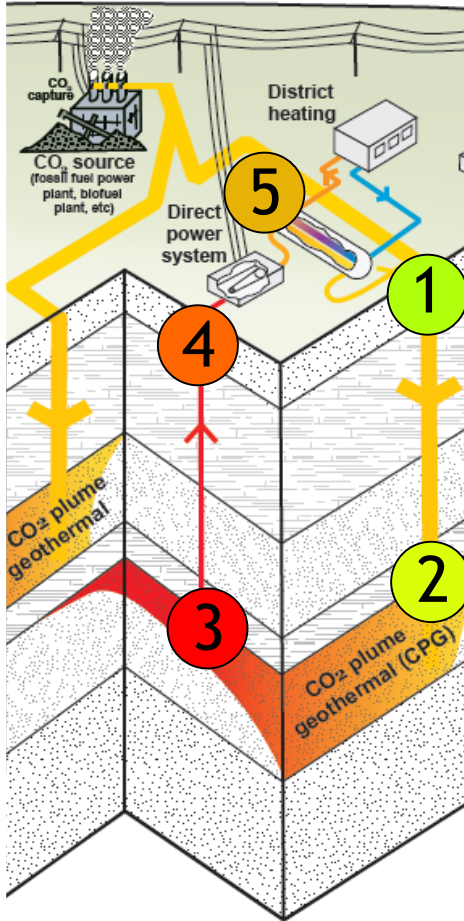
Coupling Engineering Equation Solver (EES) with Reservoir Simulators (own + others) → simulate entire cycle
Also economic analysis → LCOE

CO$_2$ generates substantially greater flow rates at shallow depths
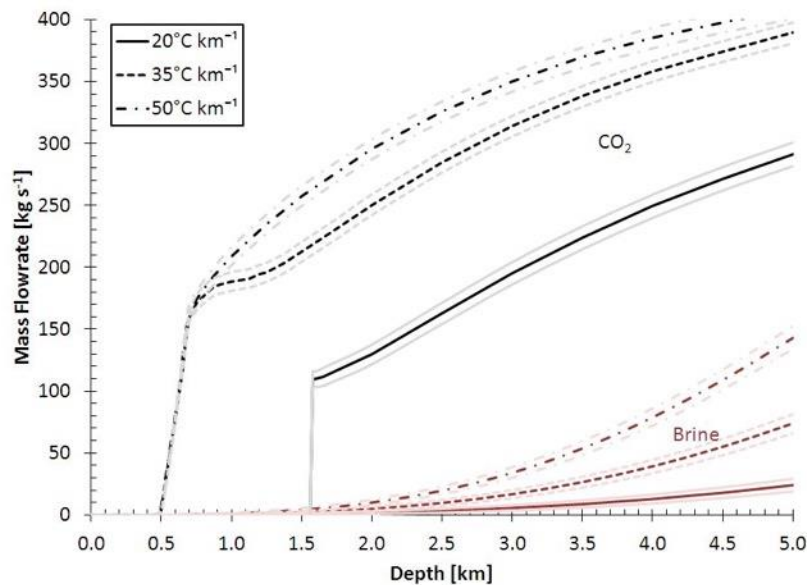
Net power output versus permeability
Per injection-production well pair

Adams et al., Energy (2014)
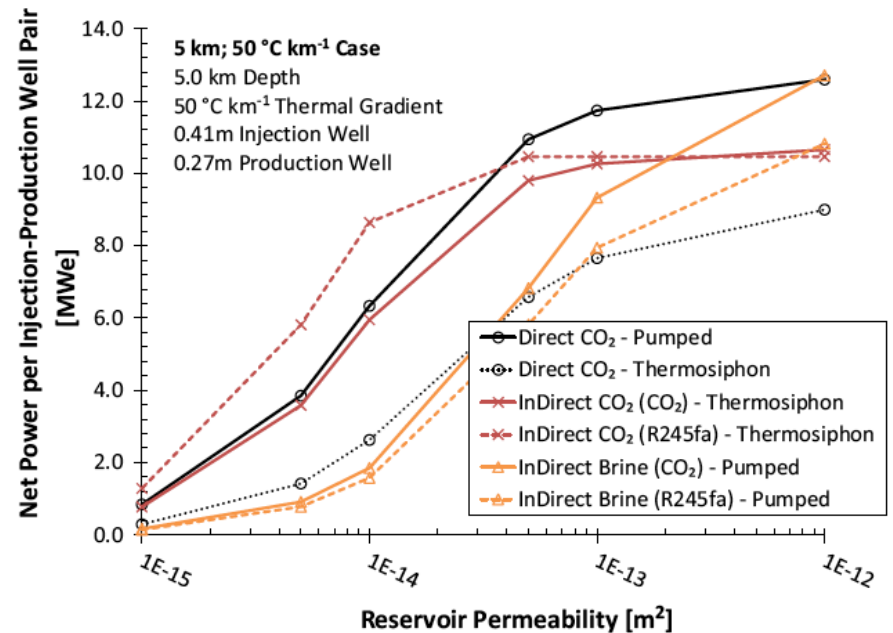
Adams et al., Applied Energy, 2015

Expansion of geothermal resource base (e.g. USA)
Here purely temperature-based

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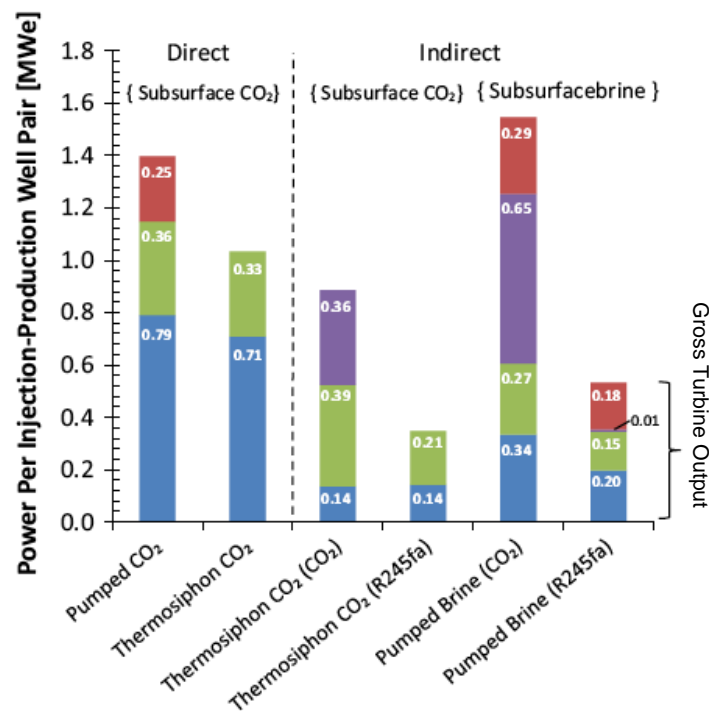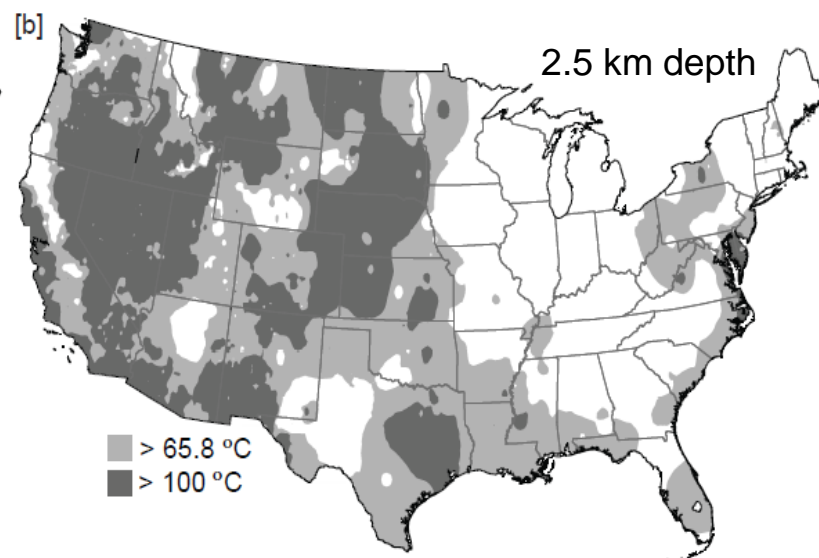
2.5 km depth

sed reservoir geothermal (CPG), 2.5 km depth
sed reservoir geothermal, 2.5 km depth

Adams et al. and Saar, Applied Energy (2015)

Randolph and Saar, 2011

CO_2 is, and will be, sequestered in sedimentary basins

International Energy Agency (2011)

World Geological Storage Suitability
- Highly Suitable, Sedimentary Basins or Continental Margins
- Suitable, Sedimentary Basins or Continental Margins
- Possible, Sedimentary Basins or Continental Margins
- Unproven. Extrusive volcanic rocks

March 2011

2017

Global CCS facilities in operation and under construction

Global CCS Institute

Levelized Cost of Electricity (LCOE)
Measured as $/MWh

	LCOE range
Solar PV Utility Scale	$46 – $53
Solar PV Thermal & Storage	$98 – $181
Geothermal H_2O	$77 – $117
Geothermal CO_2 (CPP)	$50 – $120
Biomass Direct	$55 – $114
Wind	$30 – $60
Gas Peaking	$156 – $210
Nuclear	$112 – $183
Coal	$60 – $143
Gas Combined Cycle	$42 – $78

CO_2-Plume Geothermal (CPG) power
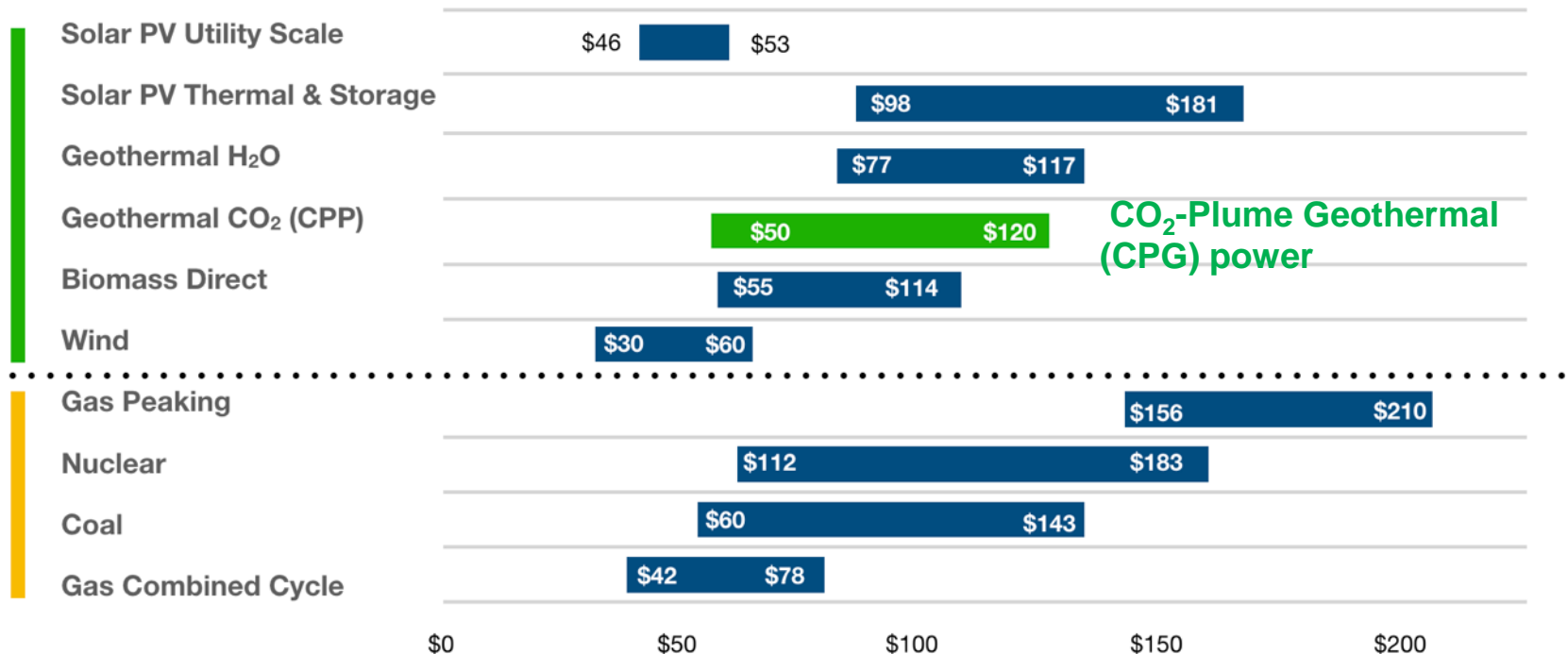
Source: Lazard 2017, https://www.lazard.com/perspective/levelized-cost-of-energy-2017/

Expansion of geothermal resource base (e.g. USA) Now LCOE-based

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Bielicki et al. and Saar (in prep.)
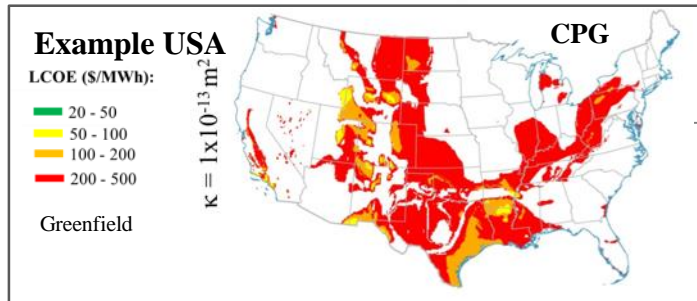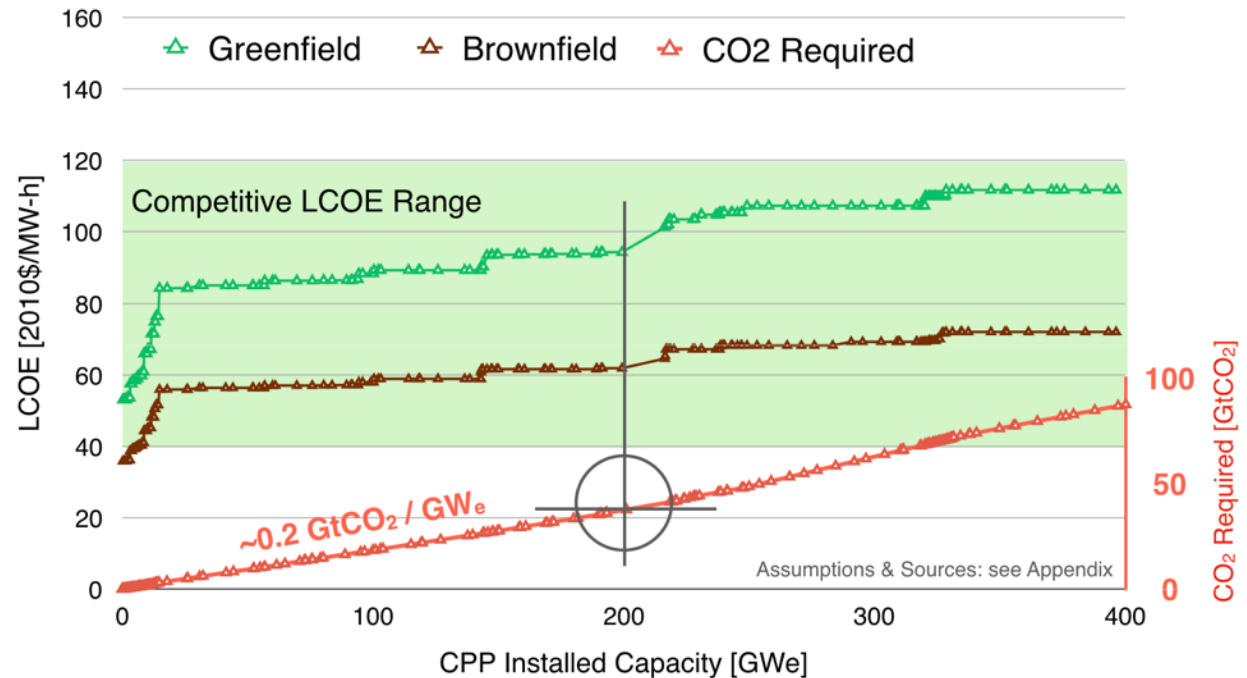
Combining EGR with CPG,

where CPG = combination of CCS with geothermal

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CCS	Carbon or CO_2 Capture and (geologic) Storage
CCUS and	Carbon Capture Utilization Storage
EGR	Enhanced (natural) Gas Recovery (typically through injection of CO_2)
CPG	CO_2-Plume Geothermal (CPG): **combines CCS with geothermal energy extraction** → CCUS

CPG
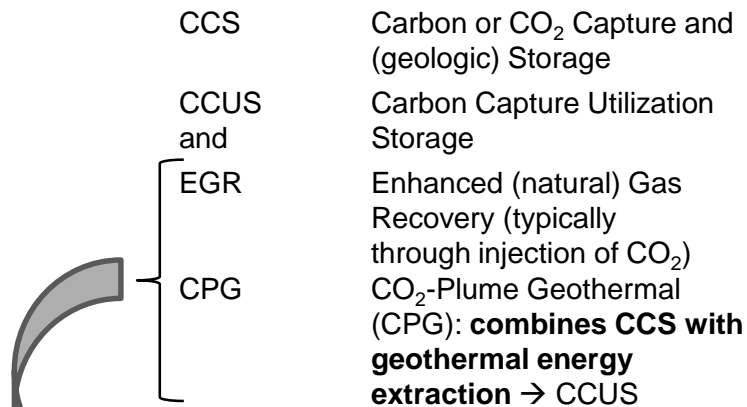
Presented next:
**Combining EGR
with CPG**

turbine (CO_2 expansion and cooling) electricity generator

hot CO_2 (with better heat extraction and energy conversion properties than hot water)

warm CO_2

cooling tower

CO_2 from emitter (e.g., coal-fired power plant)

CO_2 compressor

cold CO_2

1 to 4 km

Hotter with depth

low-permeability rock

caprock / trap (very low permeability)

large-scale geothermal reservoir (high porosity and permeability)

unusable, salty H_2O or **hydrocarbons**

at great depths, groundwater is typically salty

permanent CO_2 storage

CO_2 rises and heats up due to heat present

CO_2

natural geothermal heat flow: partially reheating reservoir

Selected CPG Publications and Patents:
Randolph, J.B., and M.O. Saar, Combining geothermal energy capture with geologic carbon dioxide sequestration, Geophysical Research Letters, doi.org/10.1029/2011GL047265, 38, L10401, 2011.
Saar, M.O., Randolph, J.B., Kuehn, T.H., & the Regents of the U. of MN, Carbon dioxide-based geothermal energy generation systems and methods related thereto, U.S.Patent US8,316,955 B2 (2012); Canada Patent 2.753.393 (2013); Europe Patent 2406562 (2014); Australia Patent 2010223059 (2015).
Adams, B.M., T.H. Kuehn, J.M. Bielicki, J.B. Randolph, and M.O. Saar, On the importance of the thermosiphon effect in CPG (CO_2 Plume Geothermal) power systems, Energy, doi.org/10.1016/j.energy.2014.03.032, 69:409-418, 2014.
Adams, B.M., T.H. Kuehn, J.M. Bielicki, J.B. Randolph, M.O. Saar, A Comparison of Electric Power Output of CO_2 Plume Geothermal (CPG) and Brine Geothermal Systems for Varying Reservoir Conditions, Applied Energy, doi.org/10.1016/j.apenergy.2014.11.043, 140:365–377, 2015.
Garapati, N., J.B. Randolph, and M.O. Saar, Brine displacement by CO_2, energy extraction rates, and lifespan of a CO_2-limited CO_2 Plume Geothermal (CPG) system with a horizontal production well, Geothermics, doi.org/10.1016/j.geothermics.2015.02.005, 55:182–194, 2015.

Example of a combined EGR-CPG system

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For example off-shore NL;
Initial discussions started with:
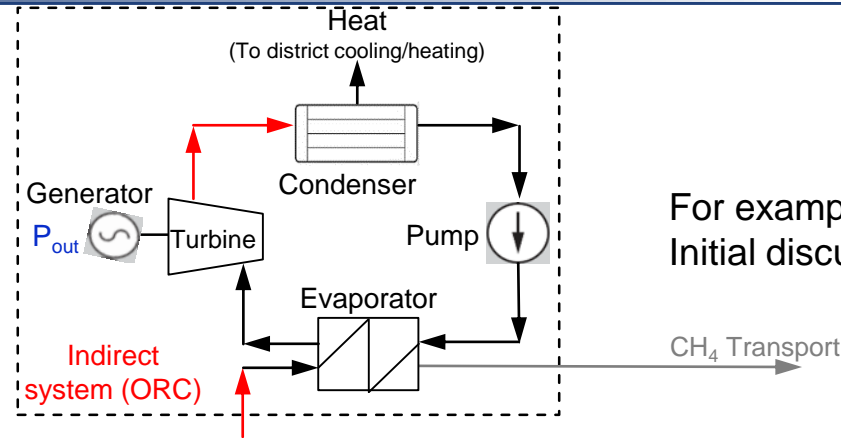
Figure 1: 2D schematic of a general implementation process of the combined system for generation of electricity.
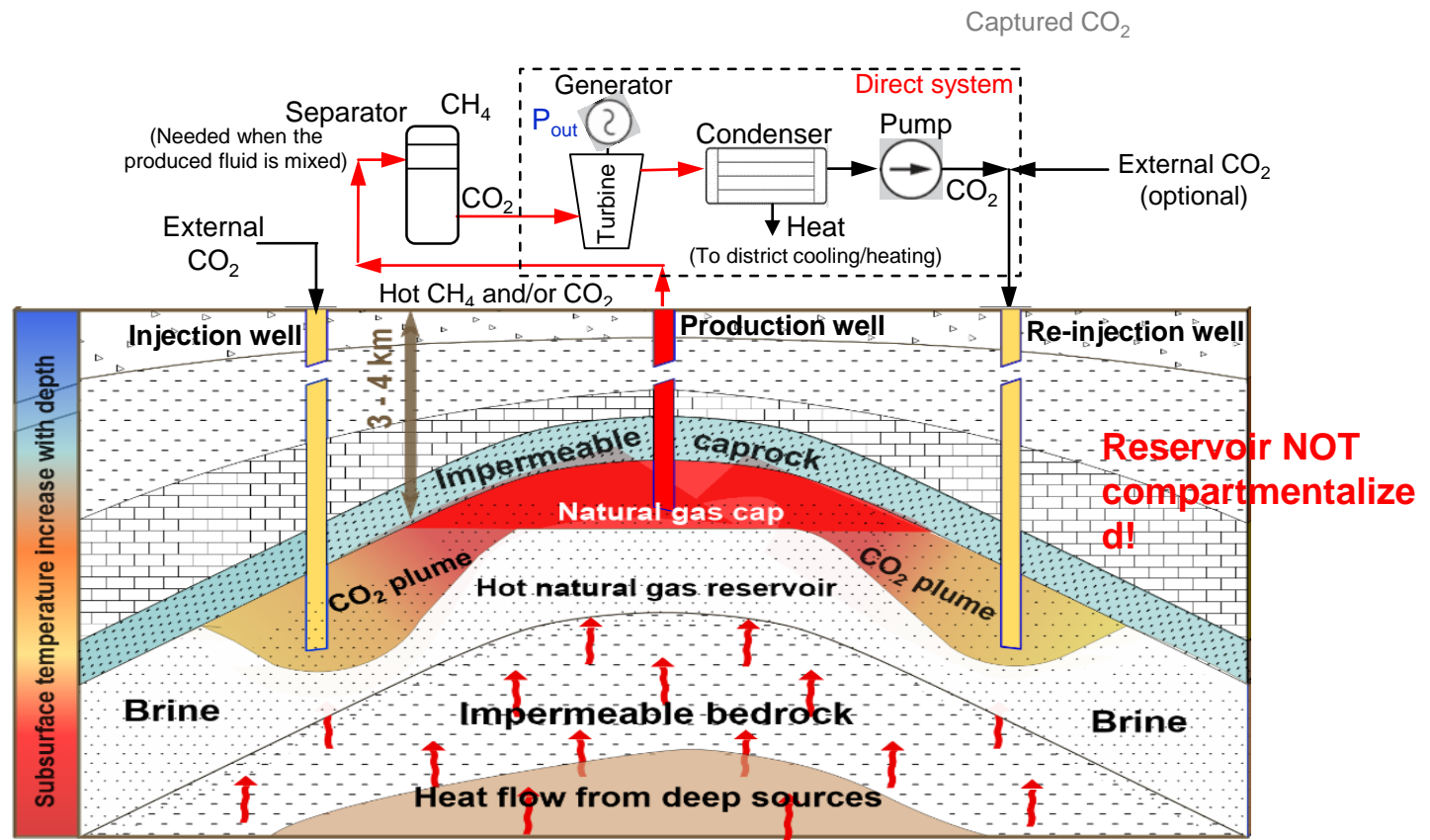
Why combining EGR with CPG

1. Increasing the total amount of producible energy (natural gas and geothermal energy).

2. Some existing infrastructure (surface facilities, wells, etc.) and multidisciplinary datasets (on reservoir parameters) can be shared, thereby reducing investment costs significantly.

3. Providing energy (electricity, heat) to, and compensating for the cost of, both CCS and gas-field operations.

4. Extending the useful lifetime of the gas field, hence postponing the expensive clean-up and abandonment stages of the field.

Examples of deep (and thus hot) natural gas reservoirs

Example

Gas reservoir	Khuff, Dukhan field, Qatar	Altensalzwedel sub-field in Altmark Gas field, Germany	Groningen giant gas field, Netherlands	Judge Digby, Onshore Gulf of Mexico, USA	Rousse, Lacq Basin, France	Arun giant gas field, Indonesia
Lithology	Carbonate (dolomite)	Fluviatile siltstones and sandstones	Slochteren sandstone and the Ten Boer claystone	Carbonate	Fractured dolomites and dolomite breccias	Carbonate (limestone)
Depth, m	2989 (top)	3400	3000	5400 – 7000	4500	2867 – 3200
Thickness, m	518	–	70-240	365	> 120 m	330
Res. volume, 10^9 m^3	167.8	–	63 – 216	–	–	30.53
Porosity [-]	0.05 (Average)	–	0.17 (Average)	0.2 (Average)	0.03 (Average)	0.16
Perm., mD	30 (Average)	–	0.1 – 3000 (Average 260)	1000 (Average)	< 1 (pores), 5 (fractures)	1466
Temperature, °C	174	125 (Average)	102.2 (Average)	204	150	178
Pressure, MPa	42.6 (at 3050 m)	42.5	34.7 (at 2875 m)	100	48.5	48.9
GIIP, Bscm	104	270	2900	–	–	457
Start of production	1978	2003	1963	1977	–	1971
Well Diameter, m *	<0.25		0.12 – 0.15			0.17 – 0.24
Current status	Buffer store for excess gas from the North Field. Production still ongoing	Almost depleted, about 96% GIIP already produced. Planned for EGR and CO_2 storage.	Production still ongoing. Some parts in the North are being used for natural gas storage.	Gas production is still going on.	Site of a completed CO_2 storage pilot project.	Gas production is still going on

Table 1: An overview of some examples of the world's deep (i.e. hot) natural gas reservoirs.

GIIP – Gas initially in place.

* Most oil and gas wells typically appear to have 5 inch (~12 cm) or 7 inch (~17 cm) diameter at the target intervals.

Reservoir and fluid properties + initial conditions

Simulating compartmentalized reservoirs (as in NL) next.
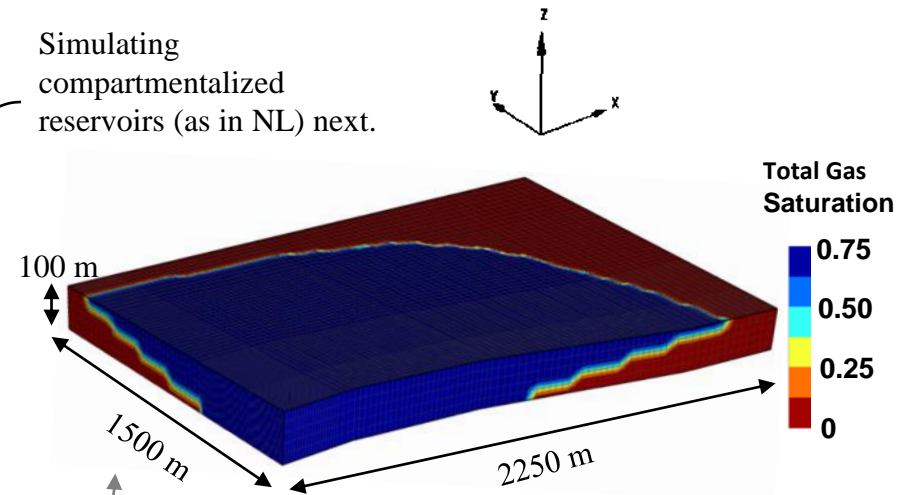
Figure 3: Initial total gas saturation in the reservoir pore space. Due to symmetry, only 1/4th of the reservoir is shown (see later slide).

In the center of the dome, reaching max. possible value of 0.75 after 200,000 years of ramp-up simulation.

Reservoir type	Non-compartmentalized (open sides)
Reservoir size (m)	4500 x 3000 x 100
Porosity	0.20
Horizontal permeability (m²); Anisotropy, k_h/k_v	10^{-13} ~100 mD; 10
Depth (m)	3000
Initial fluid pressure (MPa)	Hydrostatic (30 MPa at the reservoir base)
Reservoir temperature (ºC)	150
Initial natural gas composition	99% methane (CH_4) and 1% CO_2
Initial methane gas saturation	Fig. 3
Residual liquid saturation	0.25
Well diameter (m)	0.14
Vertical boundary conditions	No fluid flow and no heat flow
Lateral boundary condition	Dirichlet boundary condition

Table 2: Model parameters

Operational stages

Stage transition shortly before liquid water saturation starts increasing (i.e. total gas saturation starts decreasing)

Production and injection rate change when gas connection between injection and production well occurs.

Before the CNGR stage, 200,000 years model ramp-up were simulated.

Stage name change from EGR to CPG set (arbitrarily) when the CO_2 mass fraction in the produced gas reaches 96%.

CPG stage (arbitrarily) set to end when the reservoir temperature at the production well decreases by 45°C.

Stage	Conventional Natural Gas Recovery (CNGR)	EGR		CPG	Post-CPG (only CO_2 storage)
Duration (years)	26	1	1	32	-
Start → End (year)	0 → 26	26 → 27	27 → 28	28 → 60	
Production rate (kg/s/well)	2.5	6	27.5	27.5	-
CO_2 injection rate (kg/s/well)	-	18	27.5	27.5 (possibly includes injection and storage of additional, external CO_2 – not shown)	-

Reservoir pressures

Stage	Conventional Natural Gas Recovery (CNGR)		EGR		CPG
Duration (years)	26		1	1	32
Start → End (year)	0 → 26		26 → 27	27 → 28	28 → 60
Production rate (kg/s/well)	2.5		6	27.5	27.5
CO_2 injection (kg/s/well)	-		18	27.5	27.5

CNGR	EGR	CPG

Legend:
- Pressure @ prod. well at the bottom-hole
- Pressure @ inj. well at the bottom-hole (along x-axis)
- Pressure @ inj. well at the bottom-hole (along y-axis)
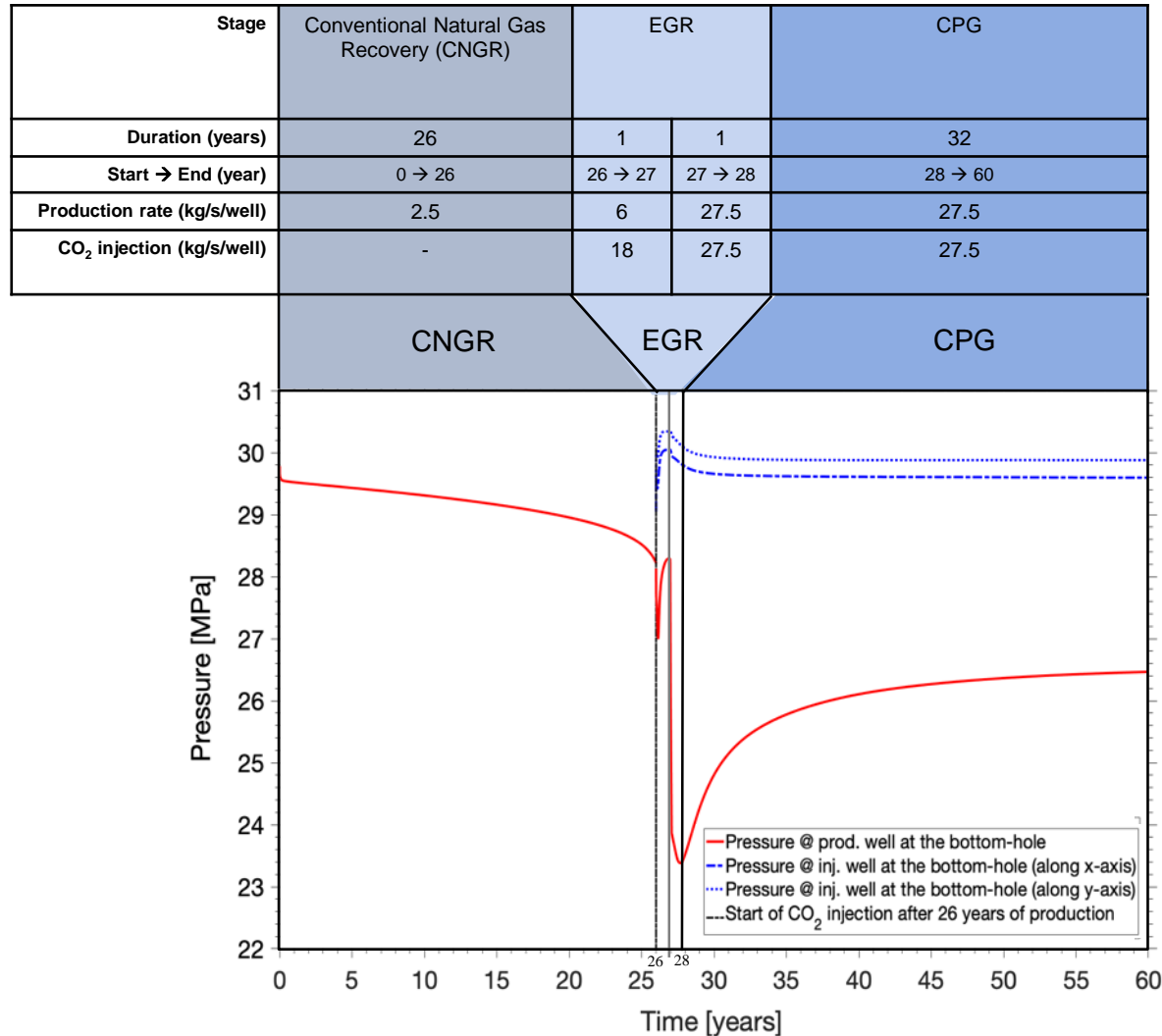- Start of CO_2 injection after 26 years of production

Figure 5a: Time series of bottom-hole pressure at the production well and at the injection wells.

Reservoir temperatures

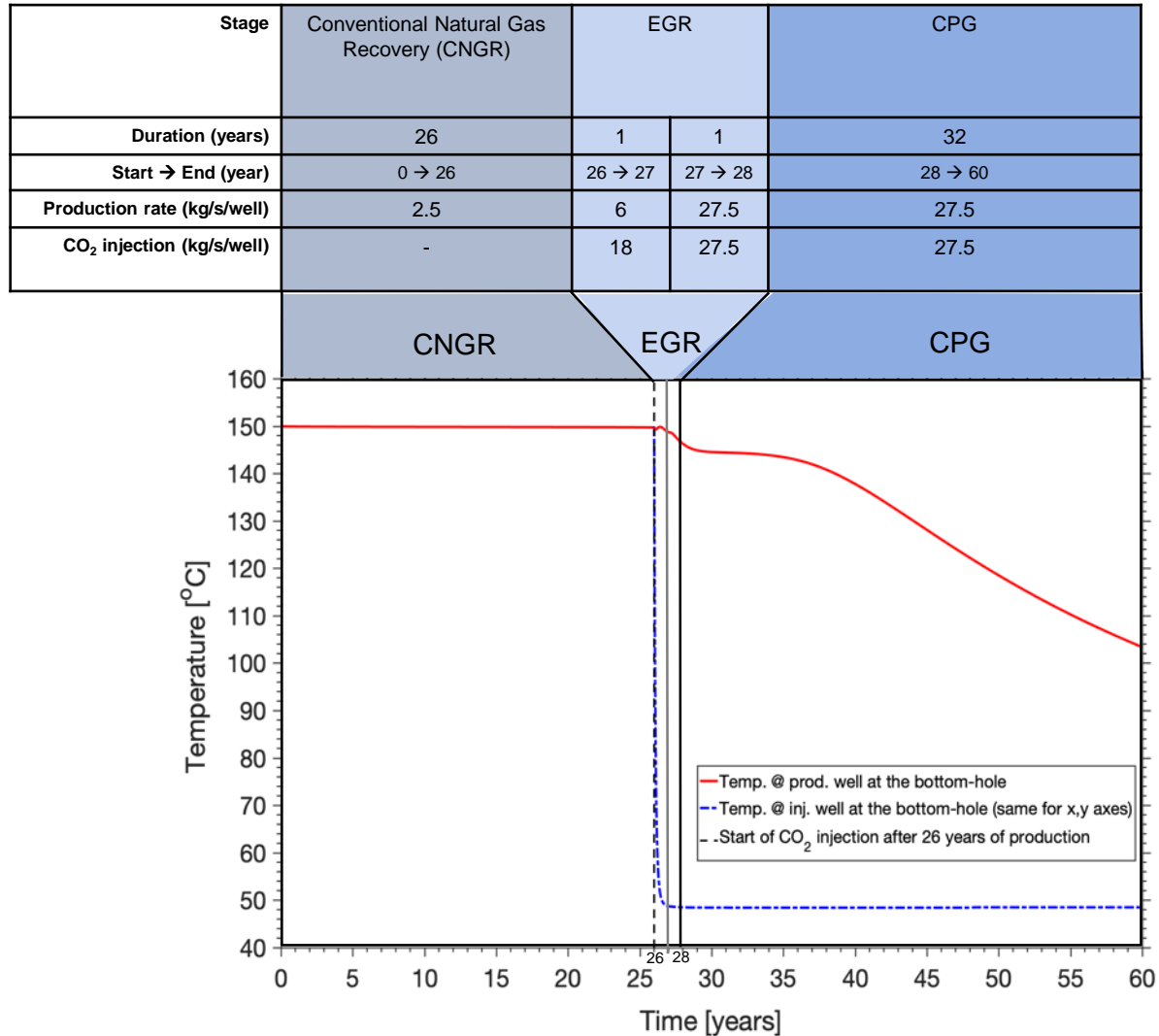| Stage	Conventional Natural Gas Recovery (CNGR)	EGR		CPG
Duration (years)	26	1	1	32
Start → End (year)	0 → 26	26 → 27	27 → 28	28 → 60
Production rate (kg/s/well)	2.5	6	27.5	27.5
CO_2 injection (kg/s/well)	-	18	27.5	27.5

Figure 5b: Time series of bottom-hole temperature at the production well and at the injection wells.
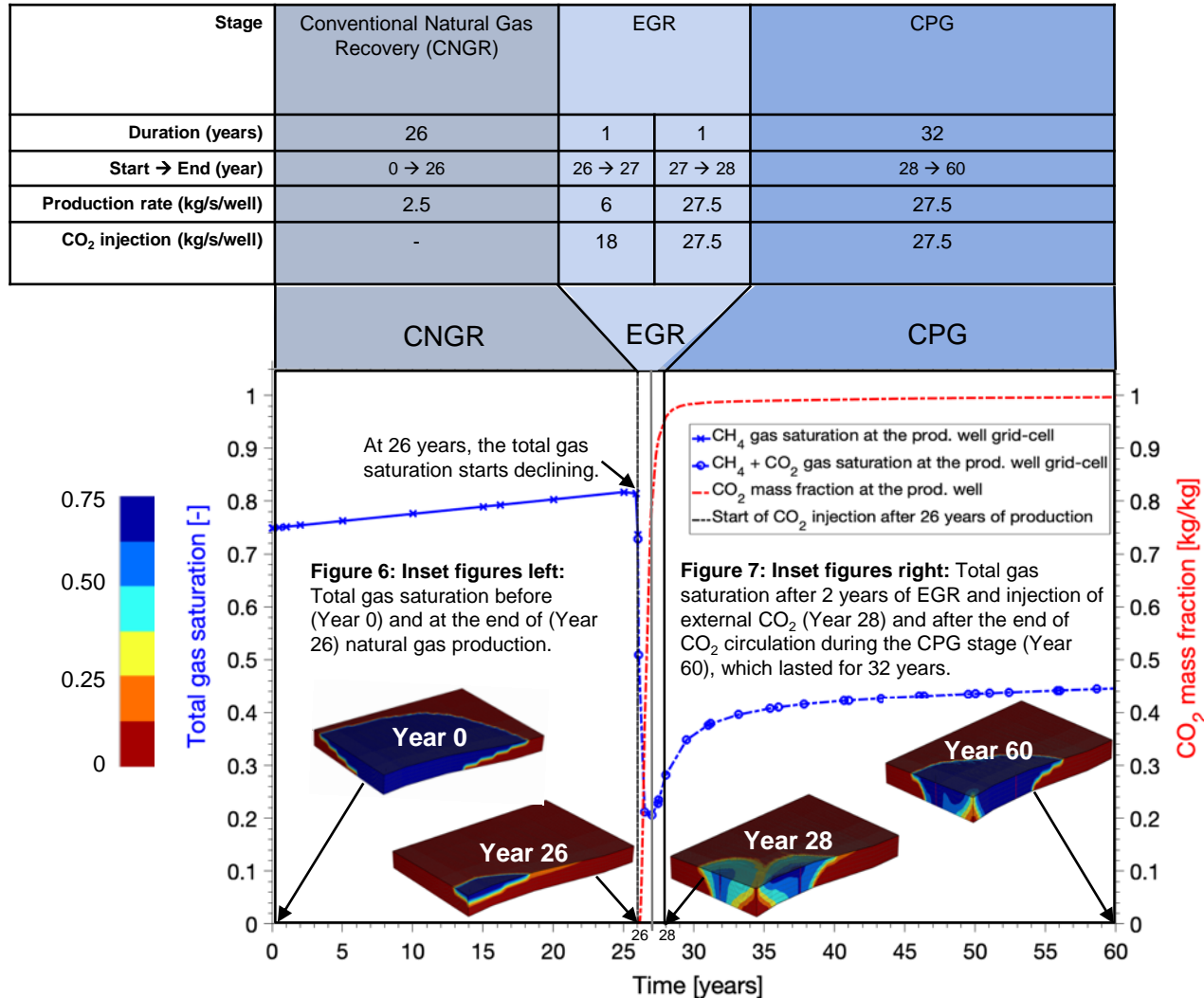
Reservoir total gas saturation and gas composition

Stage	Conventional Natural Gas Recovery (CNGR)	EGR		CPG
Duration (years)	26	1	1	32
Start → End (year)	0 → 26	26 → 27	27 → 28	28 → 60
Production rate (kg/s/well)	2.5	6	27.5	27.5
CO$_2$ injection (kg/s/well)	-	18	27.5	27.5

Figure 5C: Time series of gas saturation and CO$_2$ mass fraction (in the gas phase) at the production and the injection wells.
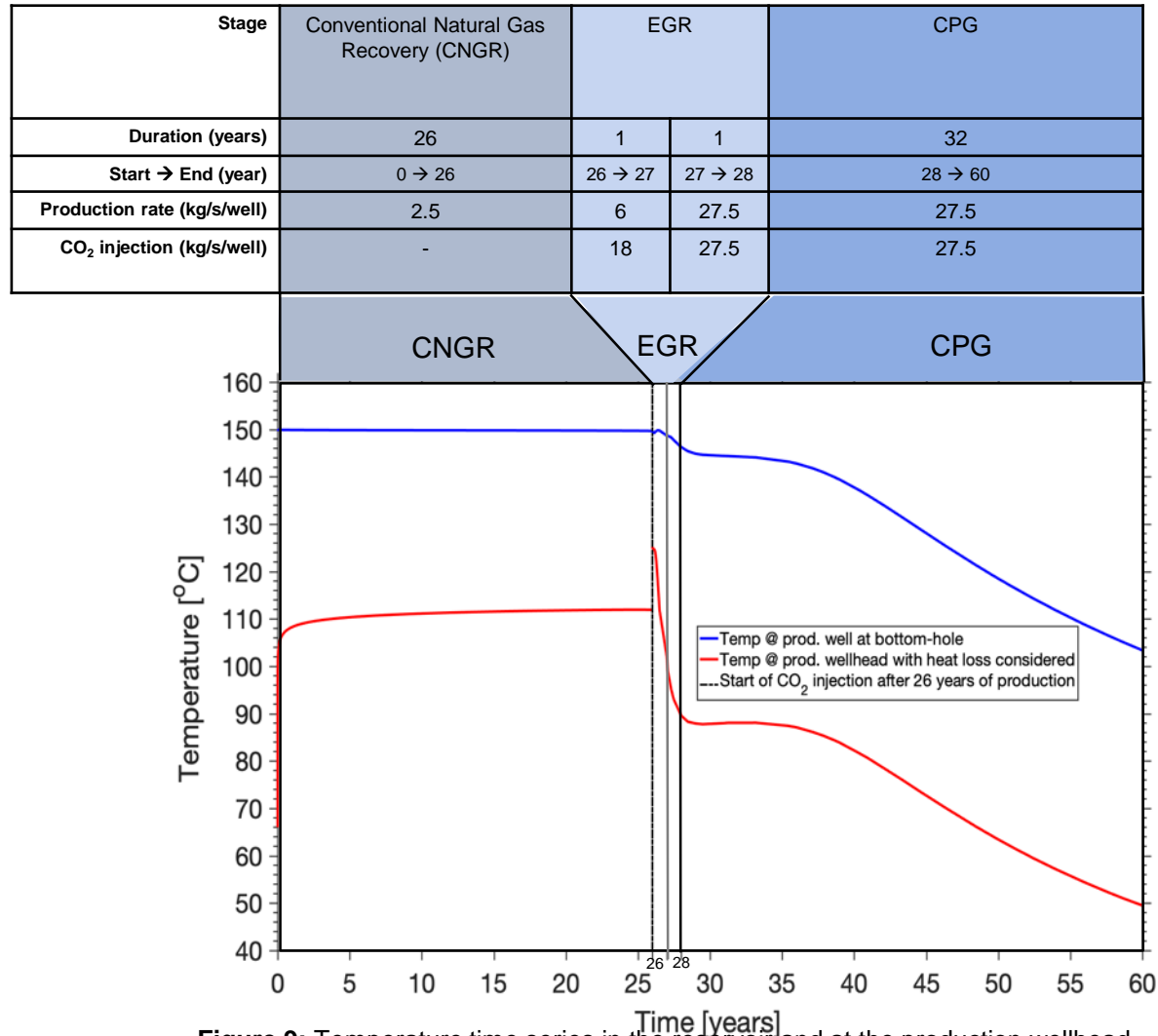
Wellhead vs. reservoir fluid temperature

Stage	Conventional Natural Gas Recovery (CNGR)	EGR		CPG
Duration (years)	26	1	1	32
Start → End (year)	0 → 26	26 → 27	27 → 28	28 → 60
Production rate (kg/s/well)	2.5	6	27.5	27.5
CO_2 injection (kg/s/well)	-	18	27.5	27.5

Figure 9: Temperature time series in the reservoir and at the production wellhead.

Wellhead vs. reservoir fluid pressure

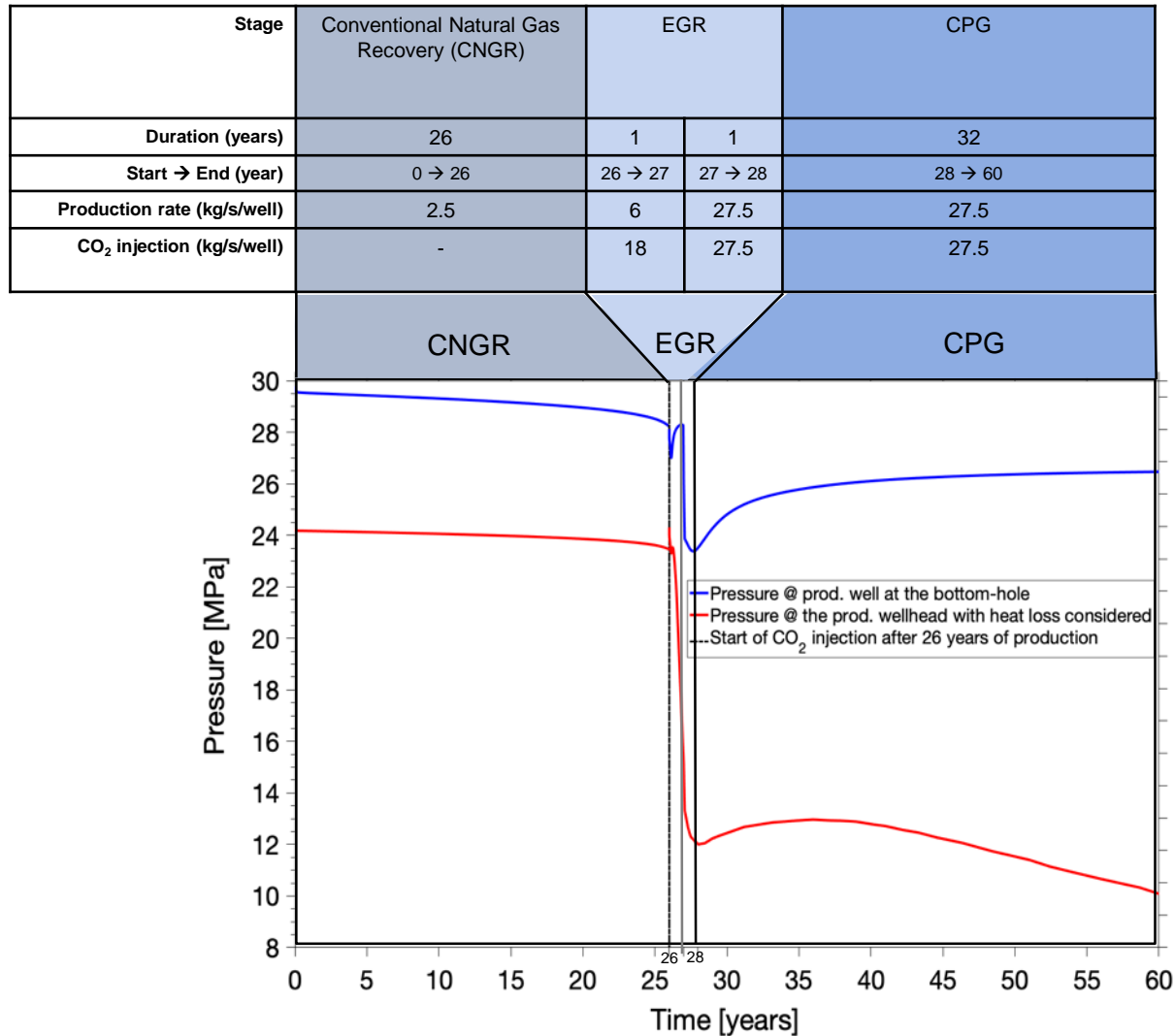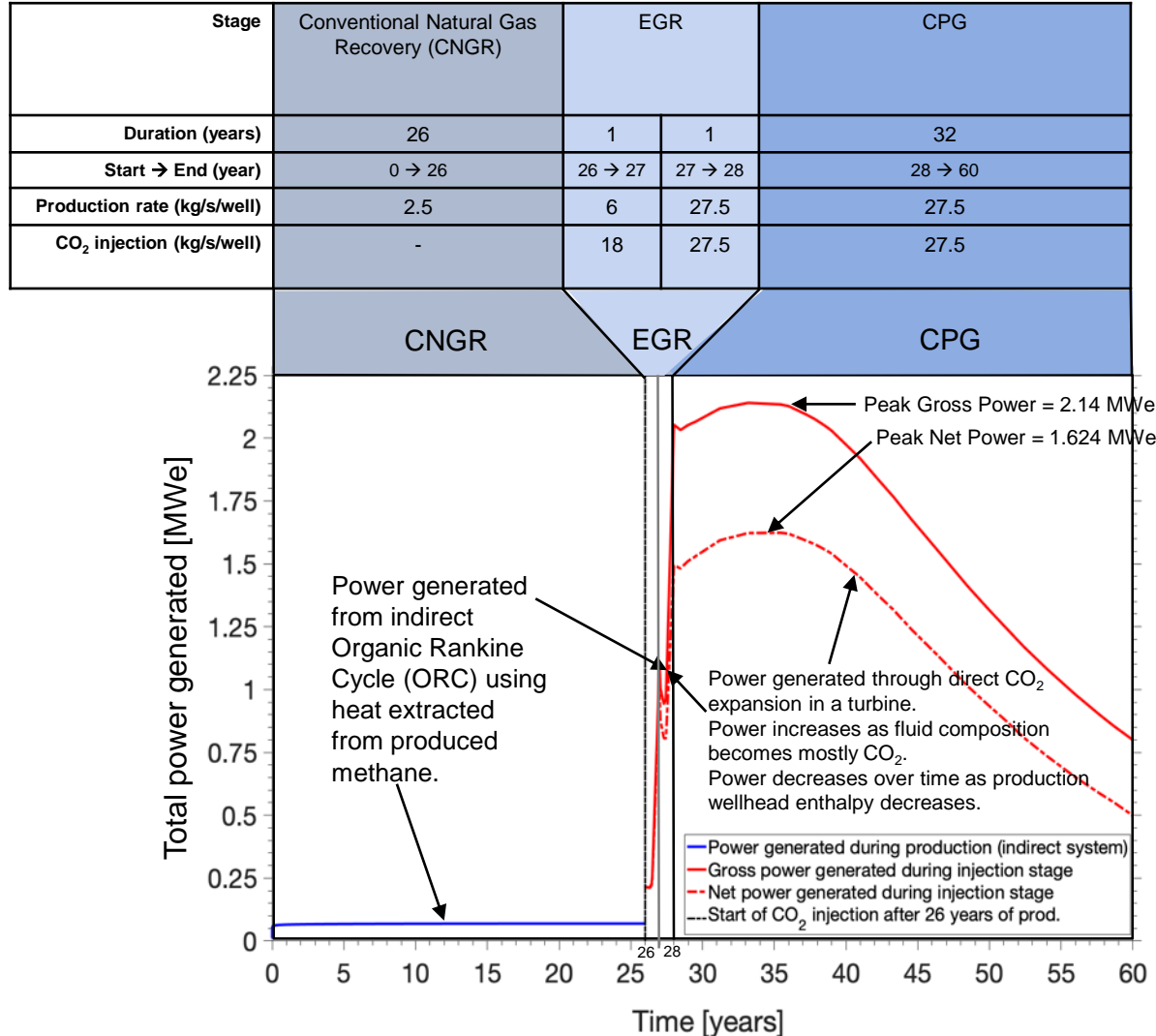| Stage	Conventional Natural Gas Recovery (CNGR)	EGR		CPG
Duration (years)	26	1	1	32
Start → End (year)	0 → 26	26 → 27	27 → 28	28 → 60
Production rate (kg/s/well)	2.5	6	27.5	27.5
CO$_2$ injection (kg/s/well)	-	18	27.5	27.5

Figure 10: Pressure time series in the reservoir and at the production wellhead.

Geothermal electricity generated over the lifetime of the field

Stage	Conventional Natural Gas Recovery (CNGR)	EGR		CPG
Duration (years)	26	1	1	32
Start → End (year)	0 → 26	26 → 27	27 → 28	28 → 60
Production rate (kg/s/well)	2.5	6	27.5	27.5
CO_2 injection (kg/s/well)	-	18	27.5	27.5

Indirect system (for methane component)

$h_{in} = f(P_{wellhead}, T_{wellhead})$;
$h_{out} = f(P_{wellhead}, T_{out})$;
T_{out} = 332 K, calculated from the R245fa approximation plot (Adams et al. 2015).
$\text{Heat}_{extracted} = \dot{m} * (h_{in} - h_{out})$;

$$\text{Power}_{indirect} = \eta_{th} * \text{Heat}_{extracted}$$

Where η_{th} is the correlated thermal efficiency (kW_e/kW_{th}) of an R245fa cycle. Average of 0.05 is calculated using the prevailing inlet temperature.

Direct system (for CO_2 component)

$S_{in}, h_{in} = f(P_{wellhead}, T_{wellhead})$; @ the turbine
$h_{out,s} = f(P_{cond}, S_{in})$;
$h_{out} = h_{in} - \eta_i * (h_{in} - h_{out,s})$; accounted for isentropic expansion

$\text{Power}_{turbine} = \dot{m} * (h_{in} - h_{out})$; i.e. Gross power
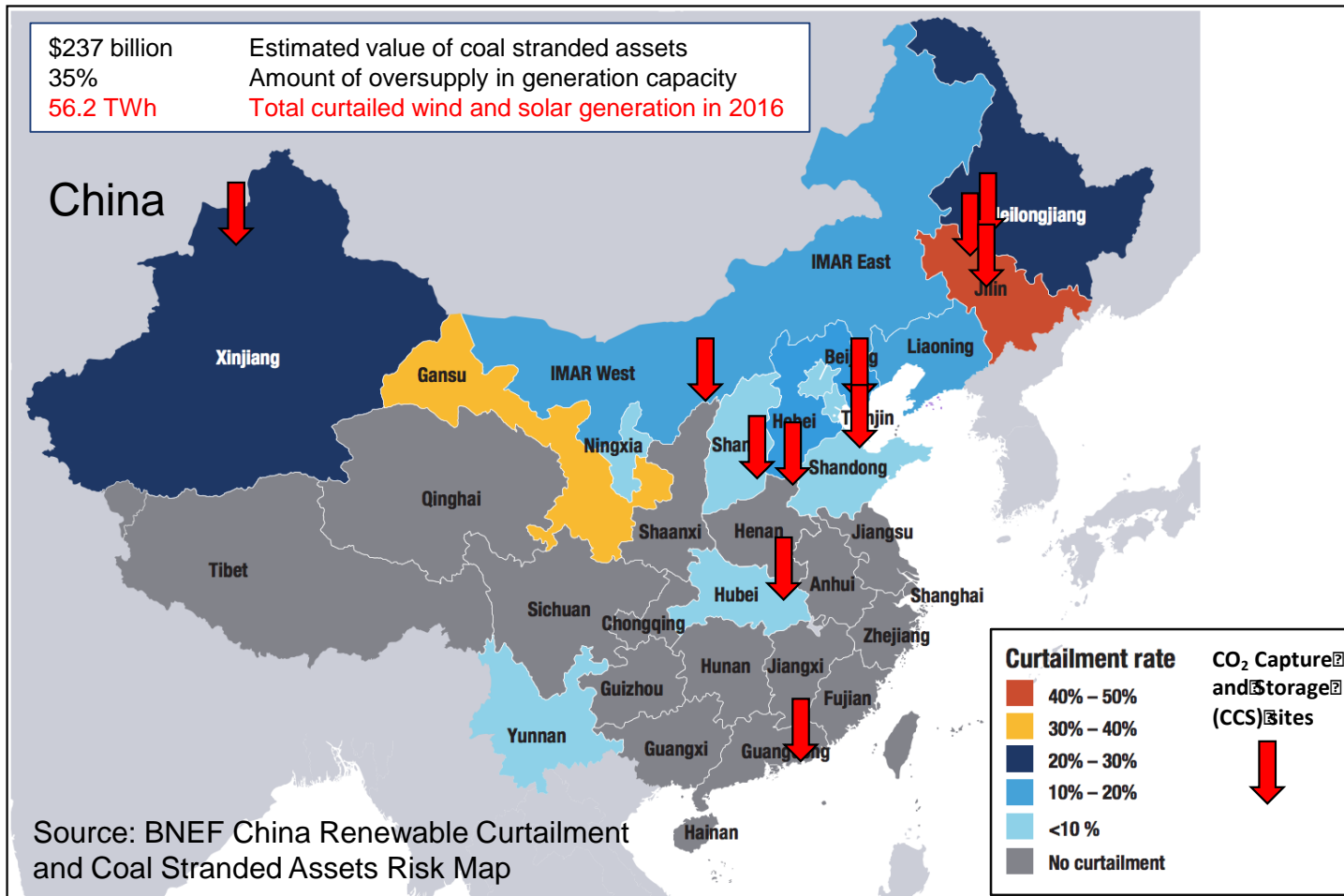$\text{Power}_{net,direct} = \text{Power}_{turbine} - \text{Power}_{fan,cool} - \text{Power}_{pump}$; i.e. Net power

η_i is the turbine isentropic efficiency, 0.78 is used (Adams et al. 2015).

Adams B.M., et al. (2015). A comparison of electric power output of CO_2 Plume Geothermal (CPG) and brine geothermal systems for varying reservoir conditions. Appl. Energy, 140:365–77.

Figure 11: Time series of total geothermal electricity generated from all 4 production wells over 60 years. Calculations are made based on the concept that power is generated from the heat extracted from the produced methane via a Rankine cycle (indirect system) and power is generated from the produced CO_2 via a CO_2 turbine expansion (direct) system.

Wind and Solar Power Curtailment in China + CCS

Massive grid-scale energy storage needed worldwide!

$237 billion	Estimated value of coal stranded assets
35%	Amount of oversupply in generation capacity
56.2 TWh	Total curtailed wind and solar generation in 2016

China

Xinjiang · Gansu · IMAR West · Heilongjiang · IMAR East · Jilin · Liaoning · Beijing · Ningxia · Hebei · Tianjin · Shanxi · Shandong · Qinghai · Shaanxi · Henan · Jiangsu · Tibet · Hubei · Anhui · Shanghai · Sichuan · Chongqing · Zhejiang · Hunan · Jiangxi · Guizhou · Fujian · Yunnan · Guangxi · Guangdong · Hainan

Curtailment rate
- 40% – 50%
- 30% – 40%
- 20% – 30%
- 10% – 20%
- <10 %
- No curtailment

CO_2 Capture and Storage (CCS) sites

Source: BNEF China Renewable Curtailment and Coal Stranded Assets Risk Map

Germany: >100 TWh/yr in energy storage needed soon
Saudi Arabia: $200B for solar power and new city of Neom ($500B) → all solar power

Earth Battery Extension (EBE)

CO2POWER
MAKE CO2 WORK™
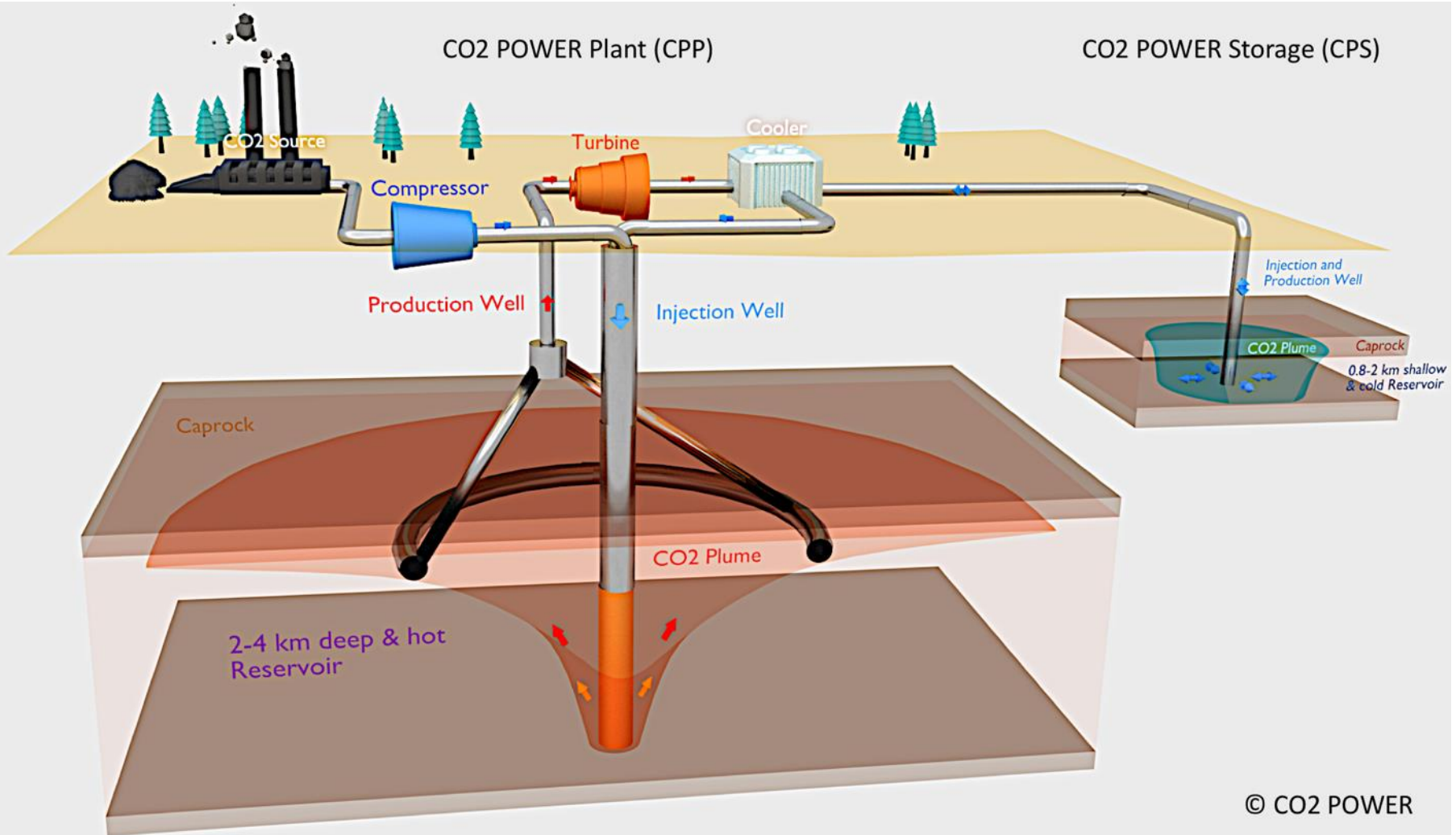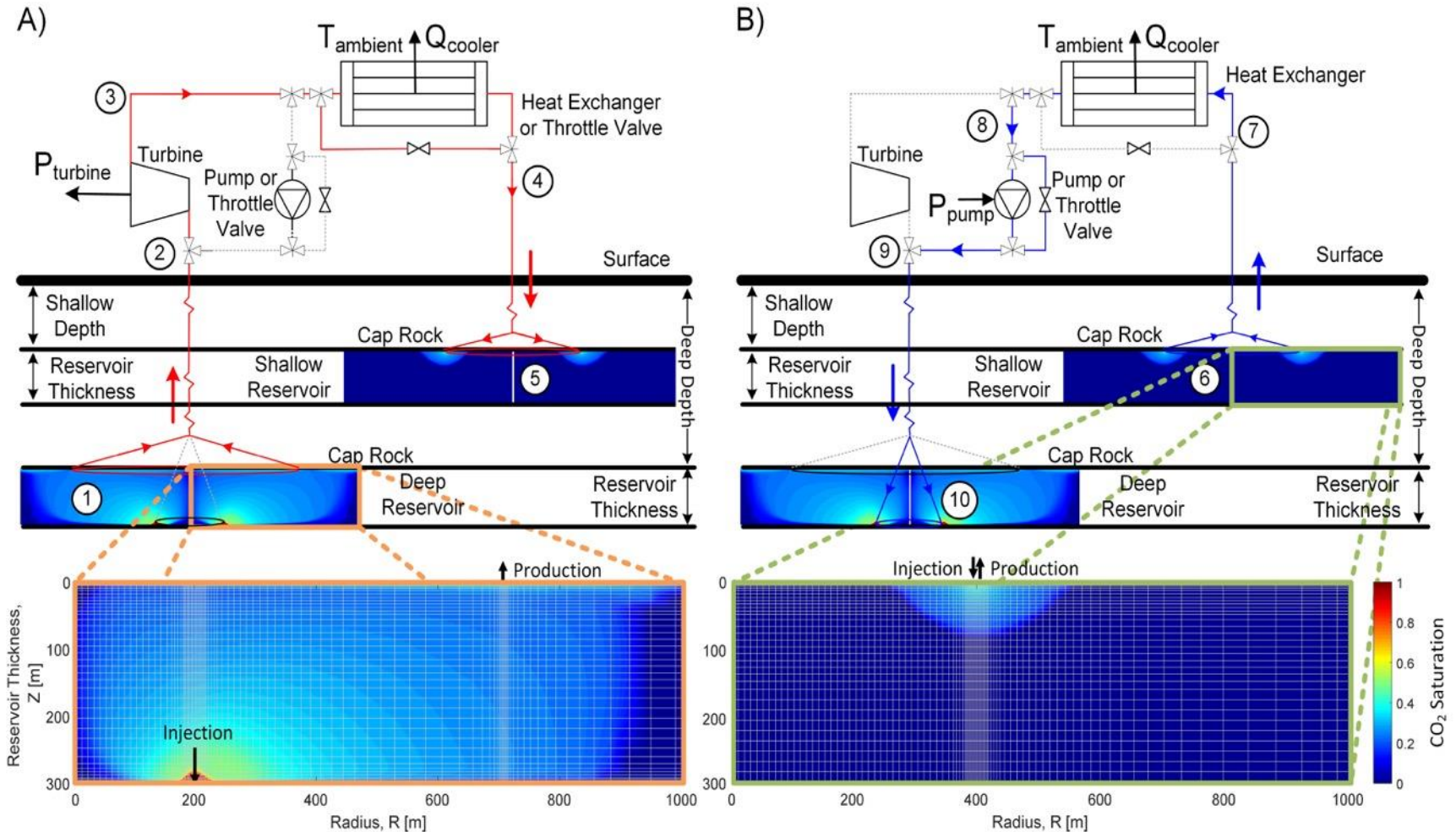
Energy is stored as heat and pressure in the deep subsurface using CO_2

Fleming et al. and Saar (2018)

Earth Battery Extension (EBE)

Example: 24-hour cycle

System Parameters	
Ambient Temperature	15 °C
Daily Power Generation Duration	16 hours
Mass Flow Rate during Power Generation	200 kg/s
Daily Energy Storage Duration	8 hours
Mass Flow Rate during Energy Storage	380 kg/s
Well Internal Diameter	0.41 m
Turbine Efficiency	78%
Isentropic Pump Efficiency	90%

Reservoir Parameters/Conditions	
General Parameters	
Horizontal Permeability	5.0×10^{-14} m^2
Vertical Permeability	2.5×10^{-14} m^2
Thermal Conductivity	2.1 W/m/°C
Porosity	10%
NaCl Concentration	20%
Geothermal Gradient	35 °C/km
Surface Temperature	15 °C
Reservoir Thickness	300 m
Rock Density	2650 kg/m^3
Rock Specific Heat	1000 J/kg/°C
Simulated Radius	100 km
Initial Conditions	Hydrostatic equilibrium, pore space occupied by brine
Deep Reservoir	
Mean Reservoir Depth	2.5 km
Mean Reservoir Temperature	102.5 °C
Injection Well Radius	200 m
Production Well Radius	707 m
Number of grid cells, vertical	42
Number of grid cells, horizontal	117
Shallow Reservoir	
Mean Reservoir Depth	1.5 km
Mean Reservoir Temperature	67.5 °C
Well Radius	400 m
Number of grid cells, vertical	34
Number of grid cells, horizontal	121

Fleming et al. and Saar (2018)

Earth Battery Extension (EBE)

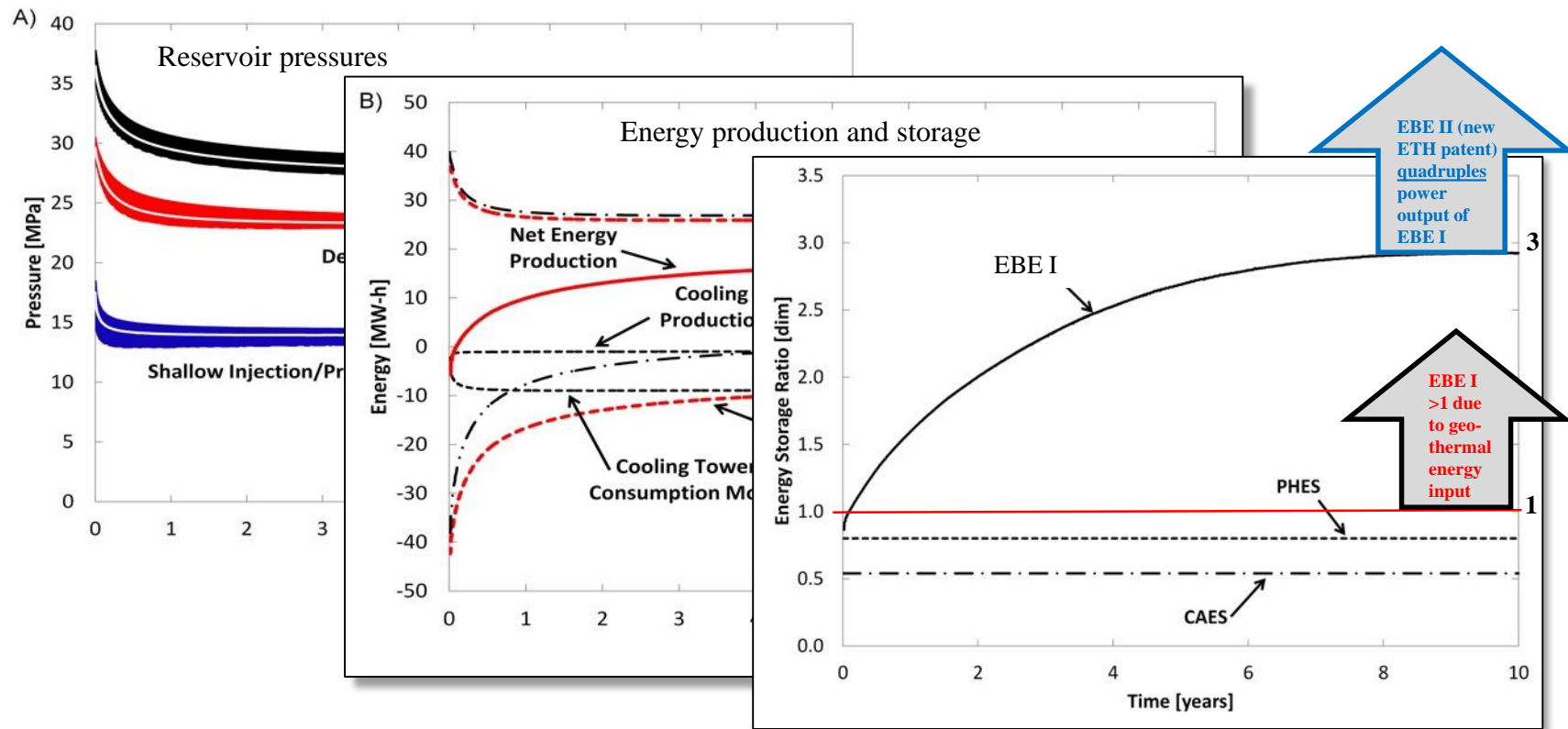## Example: 24-hour cycle

Reservoir pressure values during system operation for the representative diurnal cycle (A) and the net and component power output (B).
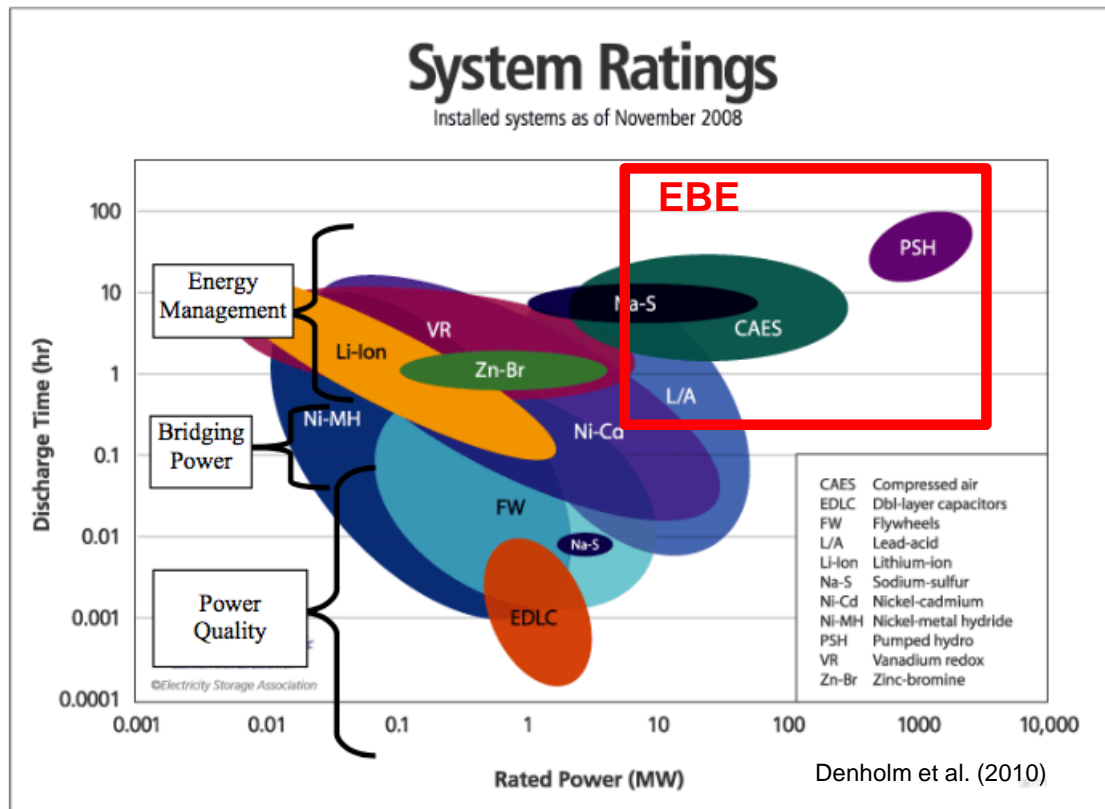
The diurnal cycle illustrated shows a representative day, occurring 10 years after the system began operating.

Fleming et al. and Saar (2018)

Earth Battery Extension (EBE)

CO2POWER
MAKE CO2 WORK

A) Reservoir pressures

B) Energy production and storage

EBE II (new ETH patent) **quadruples power output of EBE I**

EBE I >1 due to geo-thermal energy input

Net Energy Production

Cooling Production

Cooling Tower Consumption Mo

Shallow Injection/Pr

De

EBE I

PHES

CAES

Earth Battery Extension (EBE)

Denholm et al. (2010)

- EBE stores energy from minutes to months
- EBE stores energy in the GW range

CO2POWER
MAKE CO2 WORK™

Levelized Cost of Energy Storage
in $/MWh
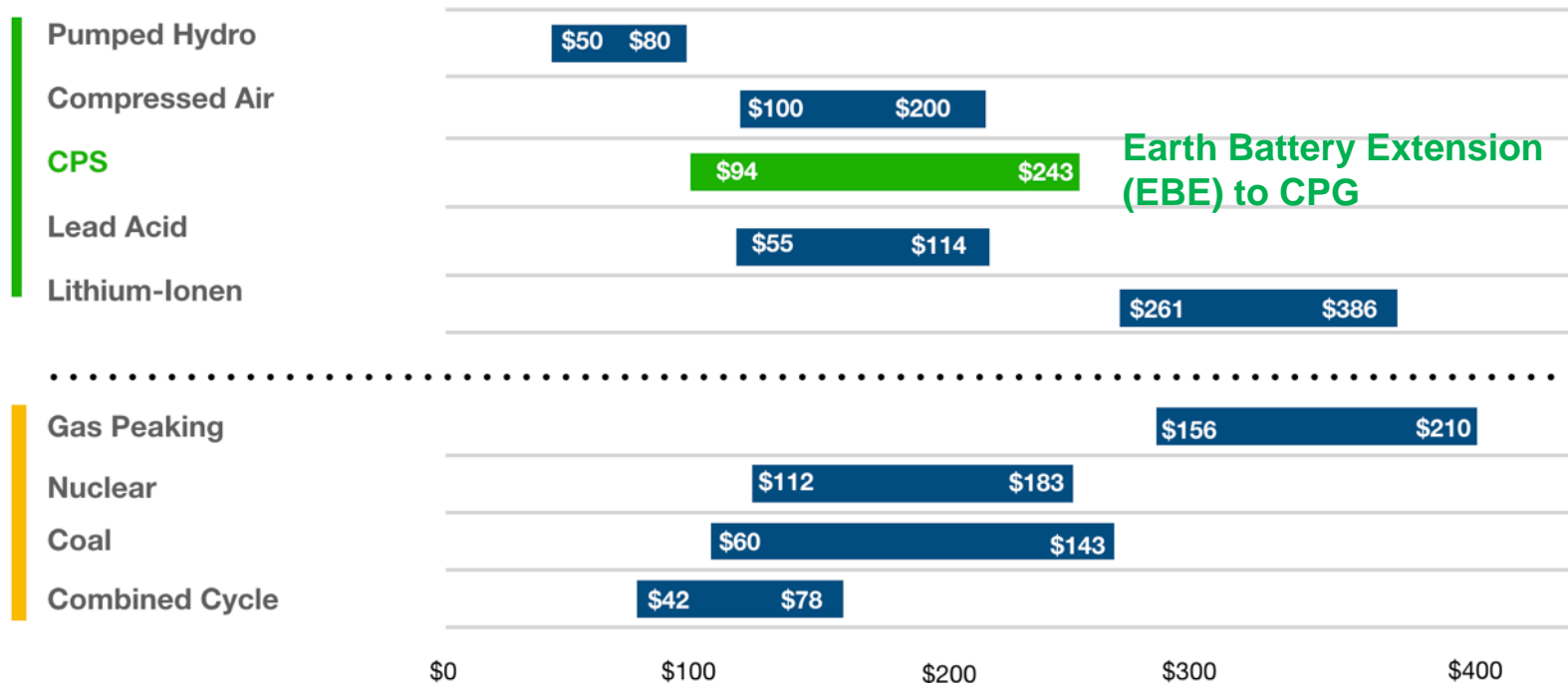
Source: Lazard 2017, https://www.lazard.com/perspective/levelized-cost-of-energy-2017/

Earth Battery Extension I: Specific Energy Capital Cost Estimates
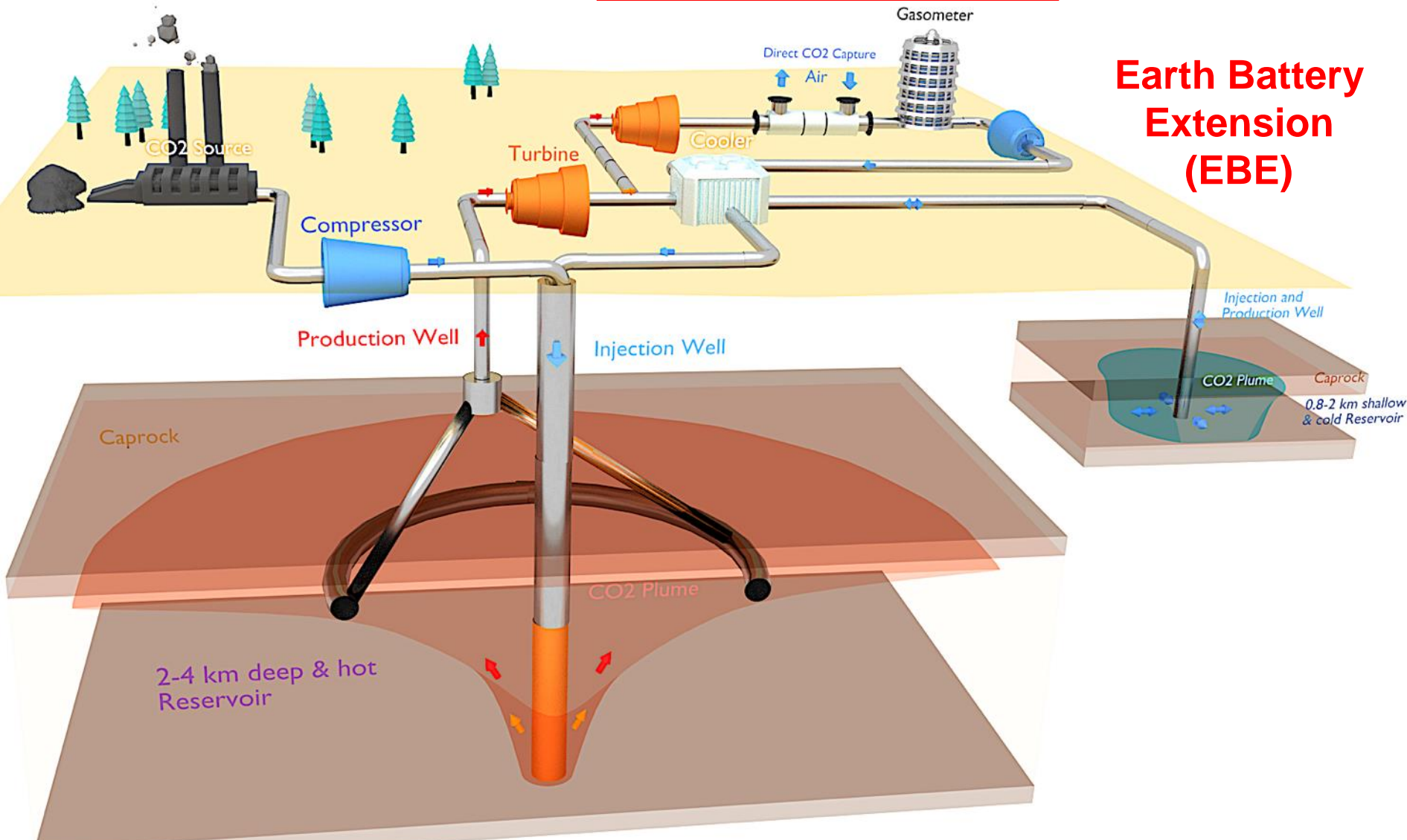## (Examples: USA, Middle East; Comparison with Tesla Battery in Australia)

CO$_2$-Plume Geothermal (CPG) Power Plant

Cryogenic Direct Air CO$_2$ Capture (DAC)

CO2POWER
MAKE CO2 WORK™

Earth Battery Extension (EBE)

Summary: CCUUUS   GEG.ethz.ch

CO 2 POWER
MAKE CO2 WORK

CO_2 can be used to generate geothermal electricity at 2 to3 times the efficiency of water
→ increases the geothermal resource base and reduces LCOEs

All of the CO_2 is permanently stored → true CCUS

Helps make CCS economical due to power generation

U1

By replacing the shallow reservoir with a gasometer, power dispatch is quadrupled and cryogenic Direct Air CO2 Capture and Storage (DACS) is possible

U3

CO2-Plume Geothermal (CPG) Power Plant

Cryogenic Direct Air CO2 Capture (DAC)

Gasometer

Direct CO2 Capture   Air

Turbine   Cooler

Compressor

Earth Battery Extension (EBE)

Injection and Production Well

CO2 Plume   Caprock

0.8-2 km shallow & cold Reservoir

U2

The Earth Battery Extension (EBE) to CPG enables massive, utility-scale energy storage (e.g. of wind/solar energy) and very high efficiencies → low LCOS

Production Well   Injection Well

Caprock

CO2 Plume

2-4 km deep & hot Reservoir
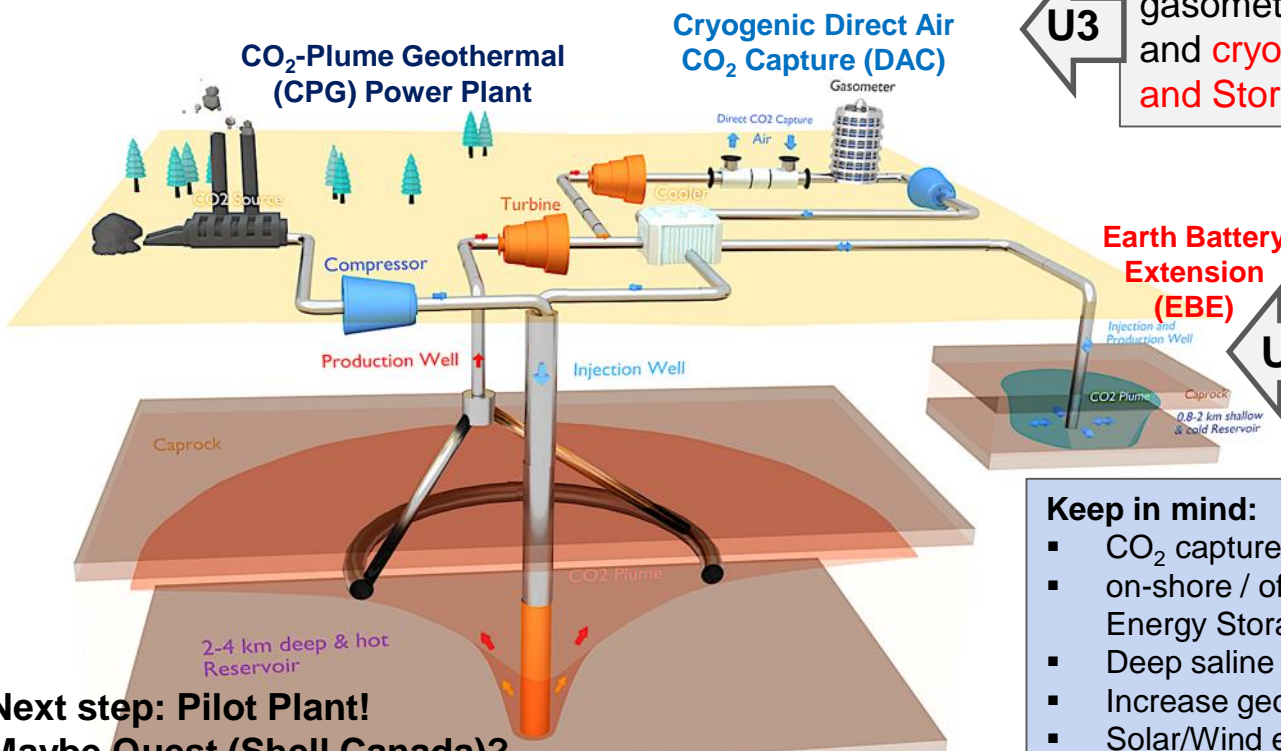
Keep in mind:
- CO_2 capture at point source / DACCS / BECCS
- on-shore / off-shore CO_2 storage and CPG + Energy Storage
- Deep saline aquifers / gas reservoirs, oil reservoirs
- Increase geothermal power generation efficiency
- Solar/Wind energy storage
- Can do DACCS itself

Next step: Pilot Plant!
Maybe Quest (Shell Canada)?
Or France (Total) or Norway (Equinor)?   **Thank you!**