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CO_2 Capture Technologies – An Overview

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Whole Value Chain Carbon Capture, Utilization, and Storage (CCUS)

October 15, 2018

AESG
Advanced Energy Systems Group

Presentation Outline

I. Sources of CO_2 and Decarbonization Routes

A. Global emissions and Decarbonizing the energy infrastructure
B. Sources of CO_2 and Thermodynamics
C. Appreciating the scale

II. Types of CO_2 Capture Technologies

A. Pre- and Post-combustion capture
B. Negative carbon emissions (DAC and BECCS)
C. Challenges and Drivers

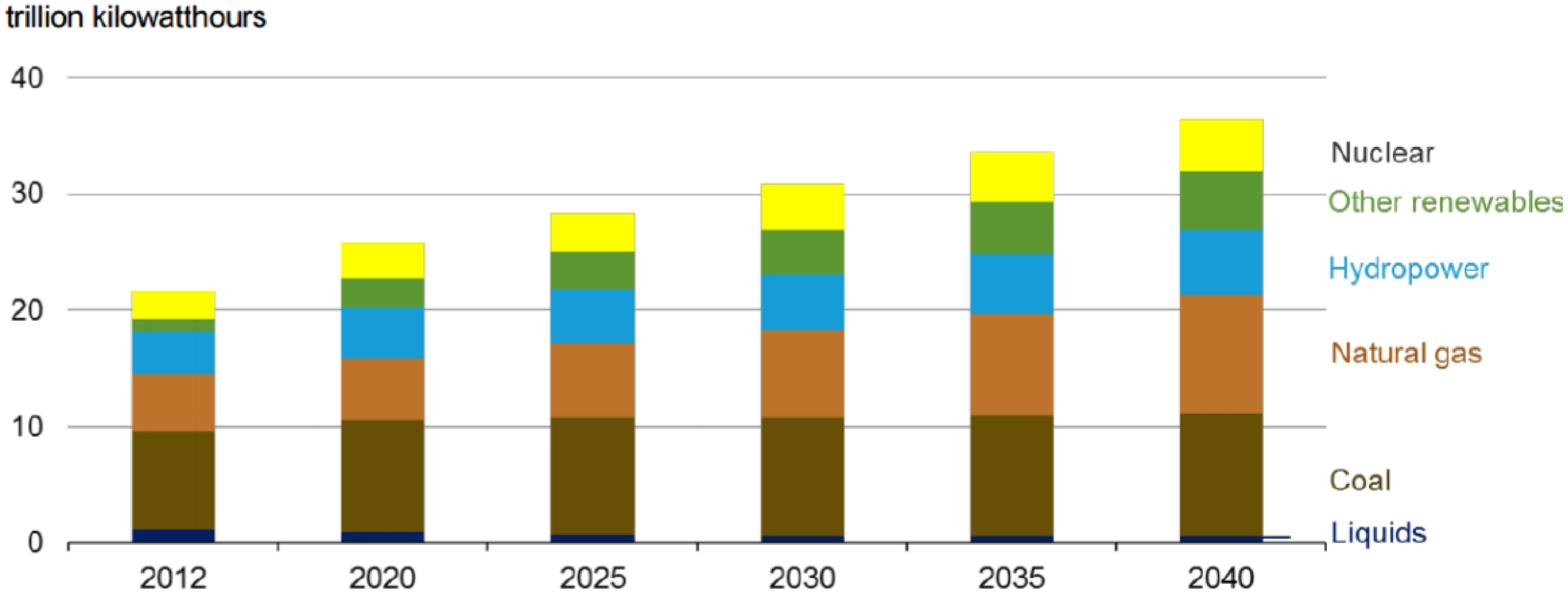
III. Status of CC & Next Generation Capture Technologies

A. TRLs, Projects and Demonstrations
B. Other Tech – Carbonate fuel cell systems

IV. Summary Thoughts – A Systems Perspective

Future of World Net Electricity Generation by Source

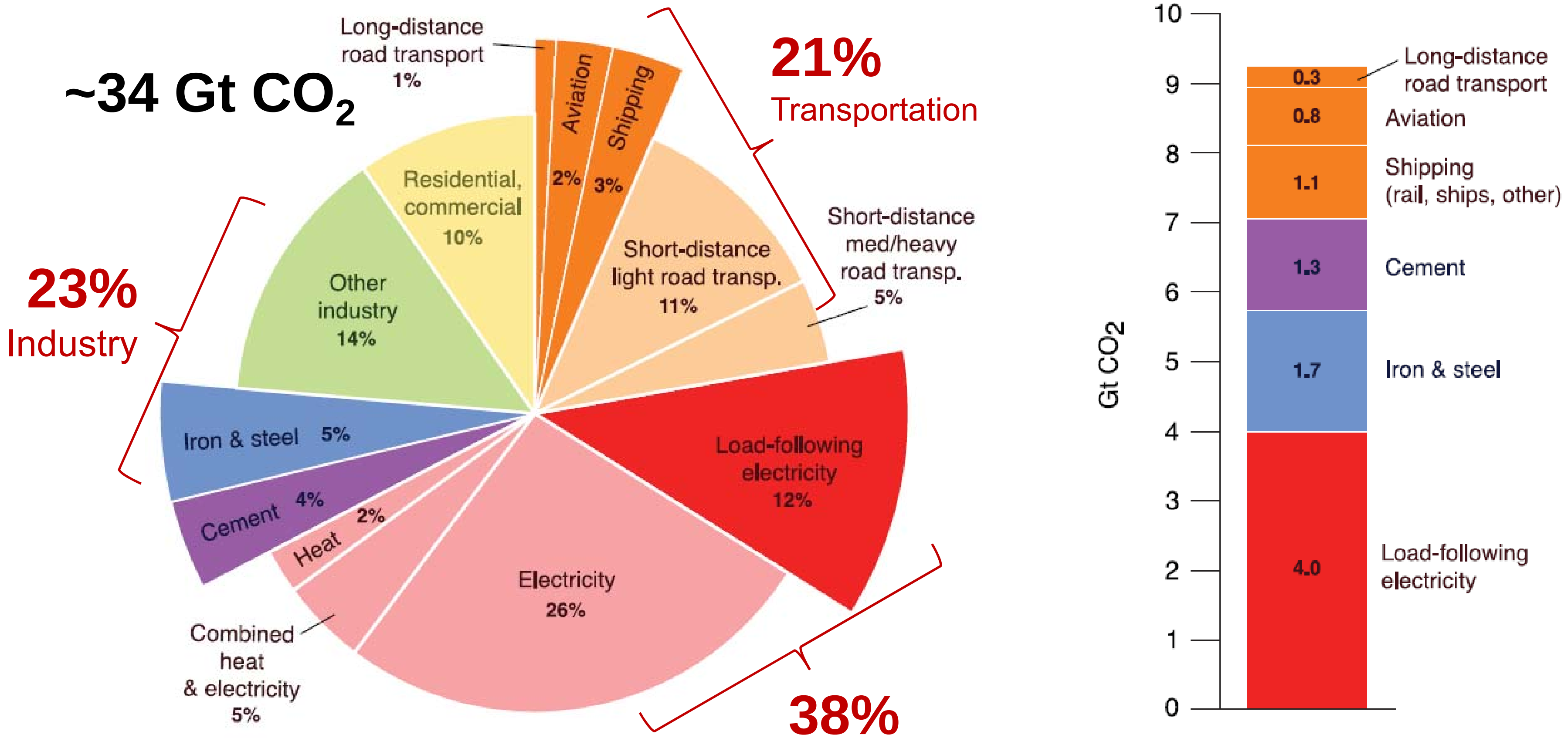
- **Fossil use remains high with renewables growing**
- **In conflict with today's tech trends**
  - Phase out of IC engines seemingly imminent (France, U.K., Sweden,…)
  - Coal power generation down, huge adoption of RE technology in U.S.
  - Large gas turbine sales down (Siemens and GE)



EIA, International Energy Outlook, 2016
R. Gupta, Sustainable power production, ASME ES 2016

A snapshot of global CO_2 emissions - 2014

- 2018 on pace to set record emissions



A Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)

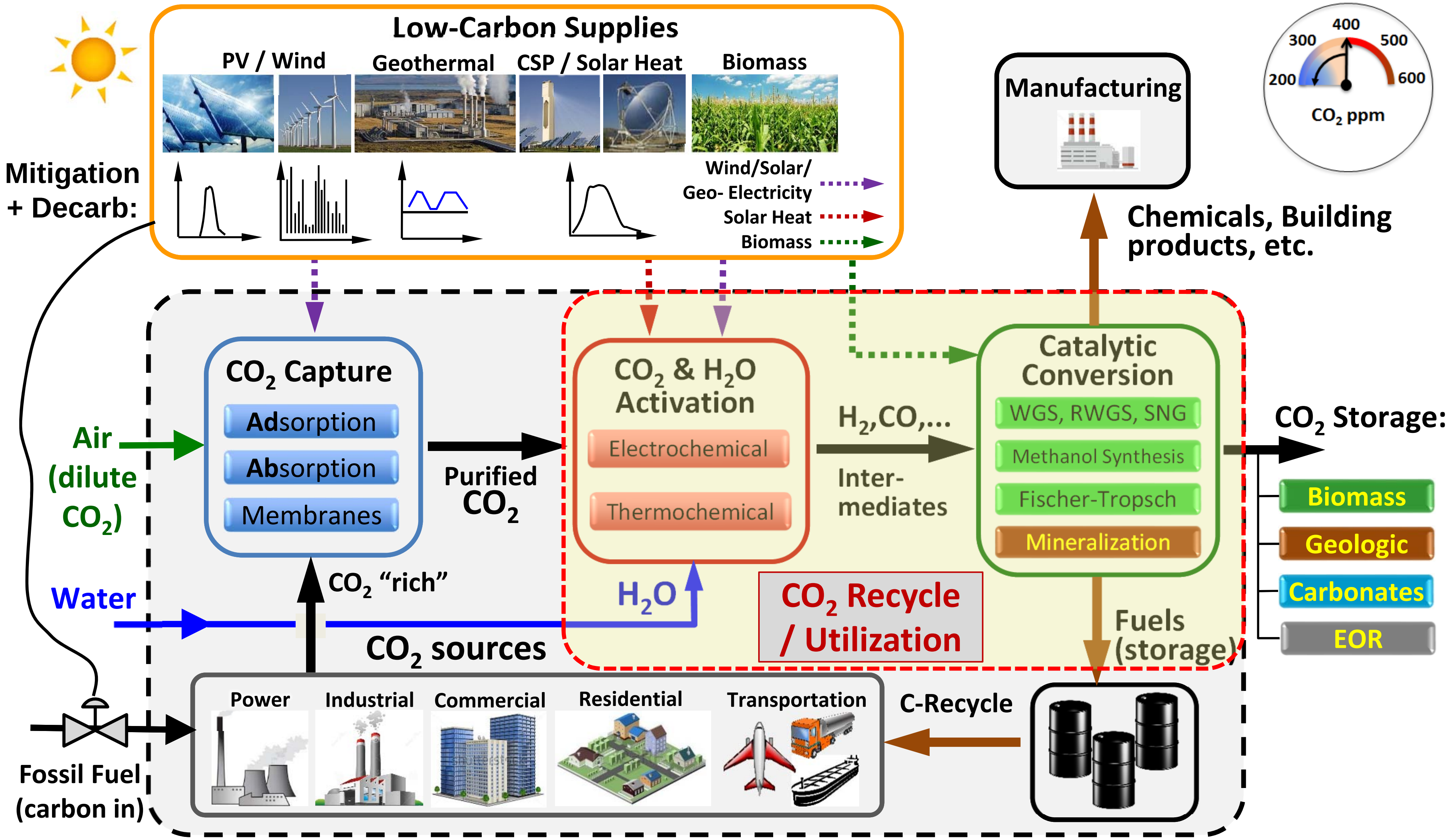
B Difficult-to-eliminate emissions, 2014 (9.2 Gt CO_2)

Davis et al., *Science* **360**, (2018)

HOW TO REDUCE CO_2 EMISSIONS TO MEET $\leq 2°C$ THRESHOLD?

- Let's take a systems-level view first

Decarbonization of energy supply chains for closed-carbon cycle (neutrality) and increased renewables



Low-Carbon Supplies

PV / Wind

Geothermal

CSP / Solar Heat

Biomass

Wind/Solar/ Geo- Electricity

Solar Heat

Biomass

Mitigation + Decarb:

Manufacturing

Chemicals, Building products, etc.

CO_2 ppm

CO_2 Capture

- Adsorption
- Absorption
- Membranes

Air (dilute CO_2)

Water

Purified CO_2

CO_2 "rich"

CO_2 sources

CO_2 & H_2O Activation

- Electrochemical
- Thermochemical

H_2O

H_2,CO,…

Inter-mediates

Catalytic Conversion

- WGS, RWGS, SNG
- Methanol Synthesis
- Fischer-Tropsch
- Mineralization

CO_2 Recycle / Utilization

Fuels (storage)

CO_2 Storage:

- Biomass
- Geologic
- Carbonates
- EOR

C-Recycle

Power

Industrial

Commercial

Residential

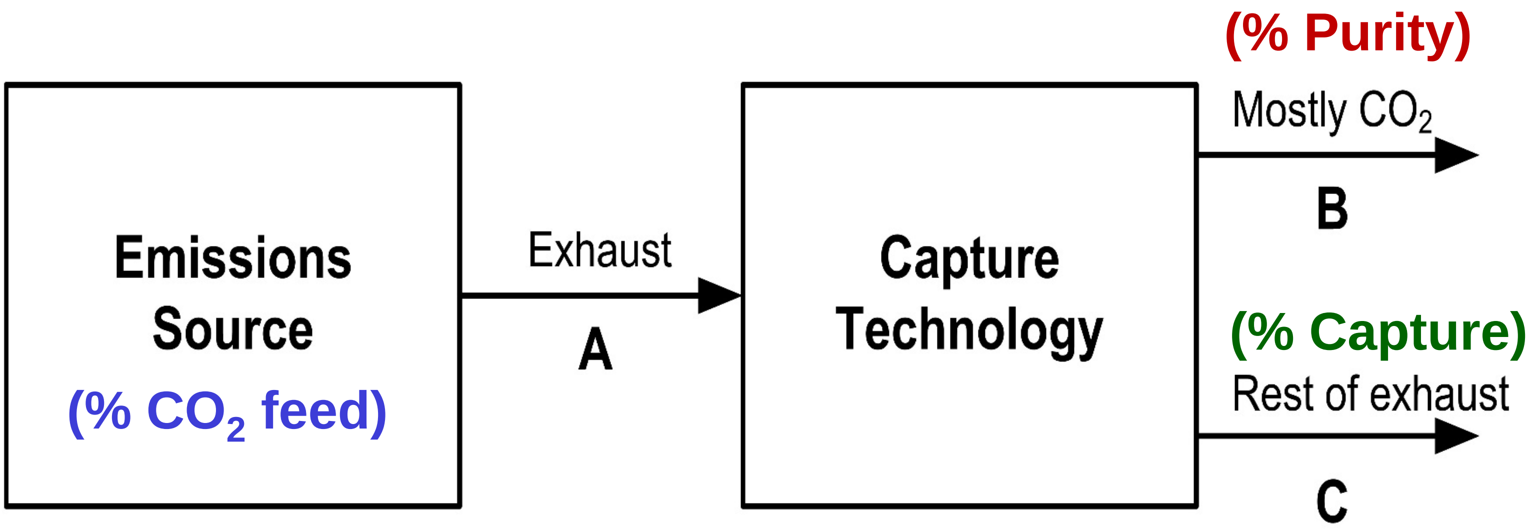
Transportation

Fossil Fuel (carbon in)

The majority of CO_2 sources are moderate to extremely dilute

Category	% CO_2 (vol)	Example	
High Pressure	varies	Gas Wells (e.g., Sleipner) Synthesis Gas (e.g., IGCC)	
High Purity	90-100%	Ethanol Plants Ammonia	
Dilute to Moderate	10-15%	Coal-Fired Power Plants	→ ~ 40% of emissions
Very Dilute	3-7%	Natural Gas Boilers Gas Turbines	→ ~ 20% of emissions
Extremely Dilute	0.04 – 1%	Ambient Air	→ ~ 25% of emissions (transport sector)

Thermodynamics sets the *minimum* work requirements for separation processes



(% Purity)

Mostly CO_2

B

Emissions Source

(% CO_2 feed)

Exhaust

A

Capture Technology

(% Capture)

Rest of exhaust

C

$$W_{\min} = RT\left[\overbrace{n_B^{CO_2}\ln(y_B^{CO_2}}^{\text{Desired Purity}}) + n_B^{B-CO_2}\ln(y_B^{B-CO_2})\right] + RT\left[\overbrace{n_C^{CO_2}\ln(y_C^{CO_2}}^{\text{\% Capture amount}}) + n_C^{C-CO_2}\ln(y_C^{C-CO_2})\right]$$

$$-RT\left[\underbrace{n_A^{CO_2}\ln(y_A^{CO_2}}_{\text{\% } CO_2 \text{ in source}}) + n_A^{A-CO_2}\ln(y_A^{A-CO_2})\right]$$

**for constant pressure*

Wilcox, *Carbon Capture*, Springer, 2012

The minimum work of separation decreases with increasing CO_2 concentration

- Energy scales with dilution
  - Can amount to 10% of power produced
- DAC is about ~20 kJ/mol CO_2, regardless of % capture and purity
- Natural gas and coal range from 5-9 kJ/mol

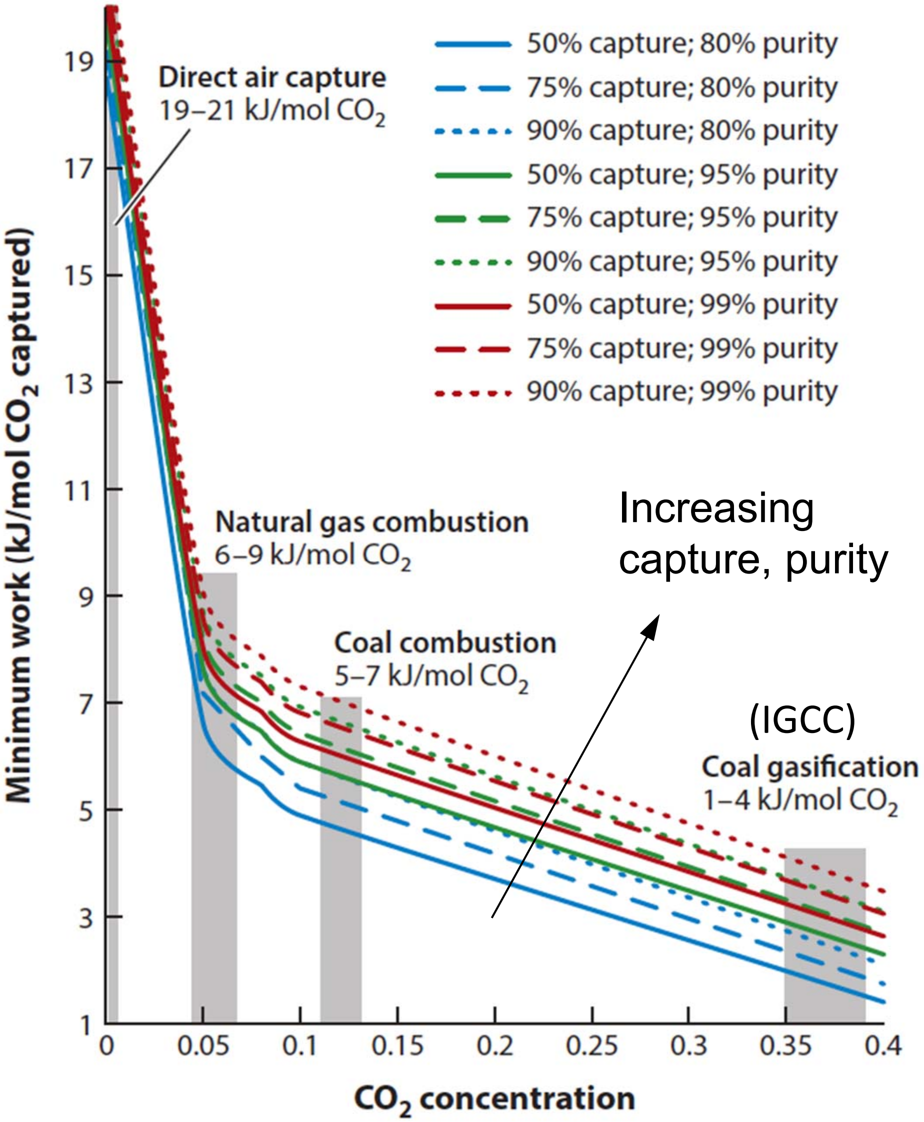
Other notes:

- Density changes with purity

  95% CO_2 + 5% N_2 = 681 kg/m^3

  80% CO_2 + 20% N_2 = 343 kg/m^3

- ~0.5 kJ/mol CO_2 additional compression energy!



Increasing capture, purity

(IGCC)

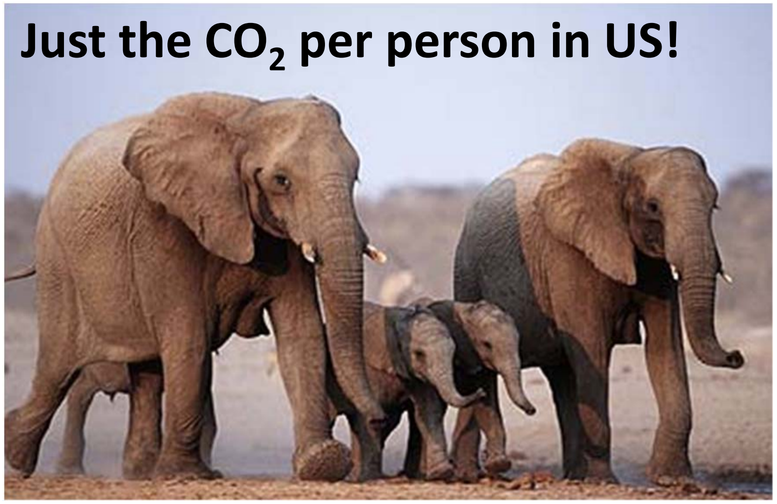
Bui et al, *Energy Environ. Sci.*, 2018, **11**, 1062-1176

Appreciating the per capita scale of carbon capture

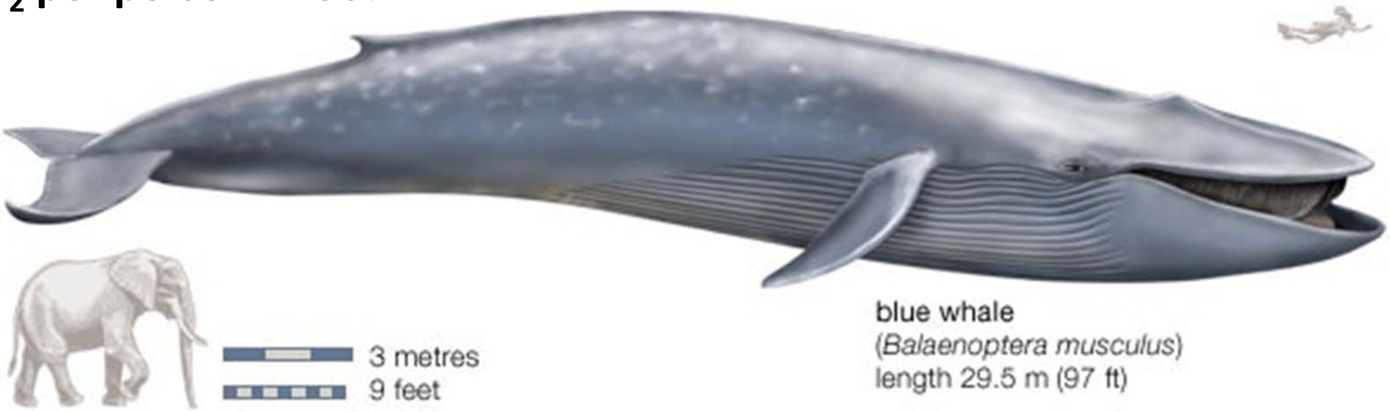
Earth • Energy • Environment Colorado School of Mines

- US population ≈ 320,000,000
- CH population ≈ 1,370,000,000
- Annual emissions per capita:
  - US ≈ 16 tons CO_2
  - CH ≈ 7 tons CO_2
- Depending on sorbent loading and performance (cycling)
  - 16 tons ➔ total 150 tons material

Just the CO_2 per person in US!



Just the sorbent + CO_2 per person in US!



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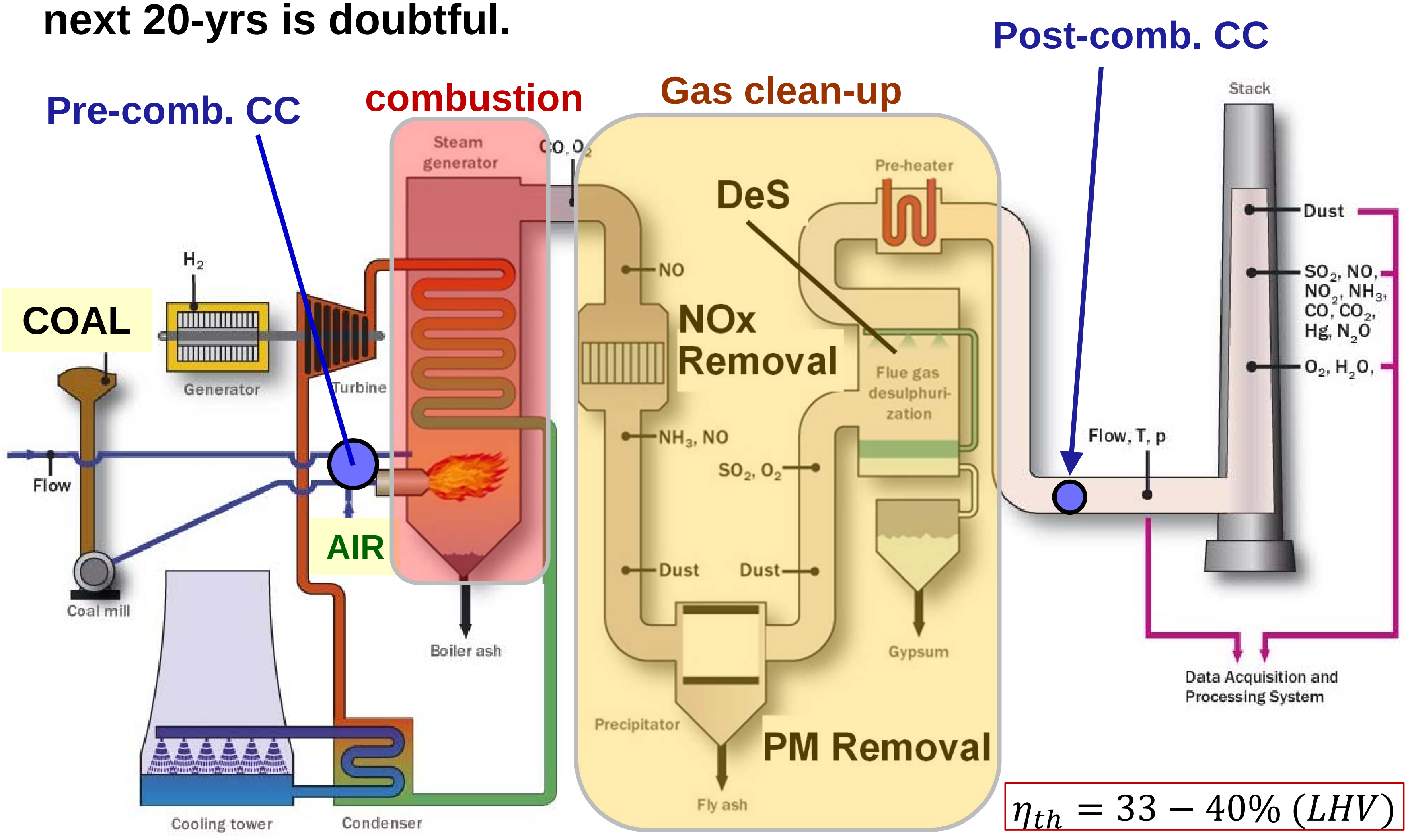
The world will need 100 carbon capture and storage (CCS) plants by 2020 and 3400 by 2050 in order to reduce greenhouse gas emissions by 50%.

That equates to building a CCS plant every three days from 2020.

-International Energy Agency

Conventional Coal-Fired Power Plant

- **Technology is down-trending significantly, but total elimination in next 20-yrs is doubtful.**

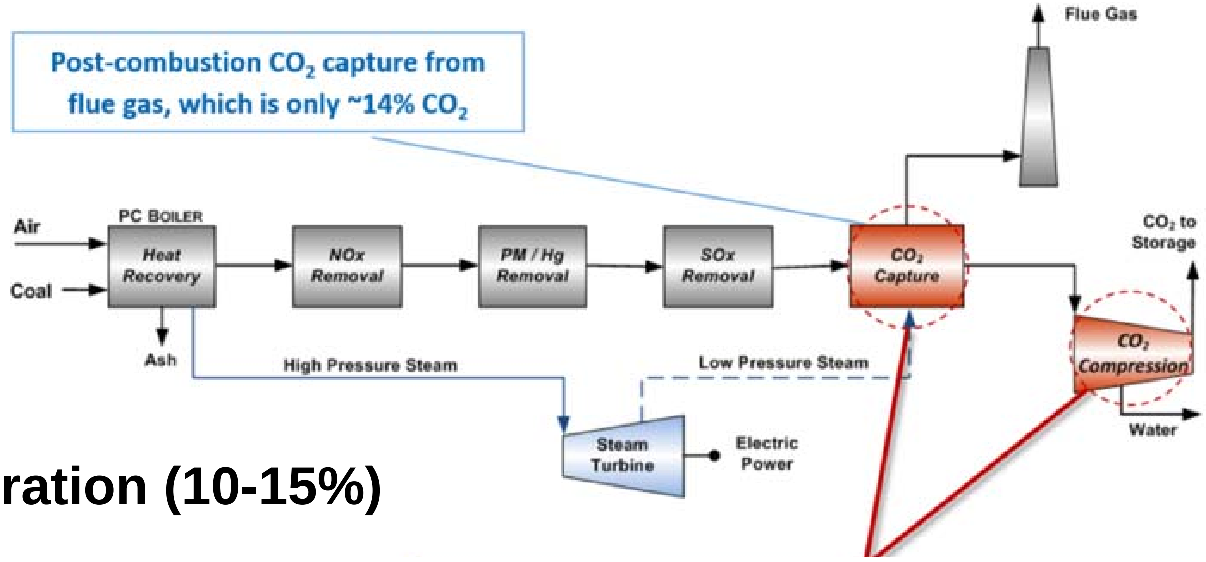


$$\eta_{th} = 33 - 40\% \ (LHV)$$

Carbon Capture (CC) Strategies:
Post-Combustion (Retrofit-end of pipe)

$$\text{Coal} + \text{Air} \rightarrow CO_2 + H_2O + N_2 + \text{Contam.} + \text{Heat}$$

(Fuel)



Post-combustion CO_2 capture from flue gas, which is only ~14% CO_2

2-separation processes

Key Challenges:

- Low CO_2 concentration (10-15%)
- Contaminants
- High flue gas flow (2-3 million cfm @ 550 MW)
- Integration with steam cycle

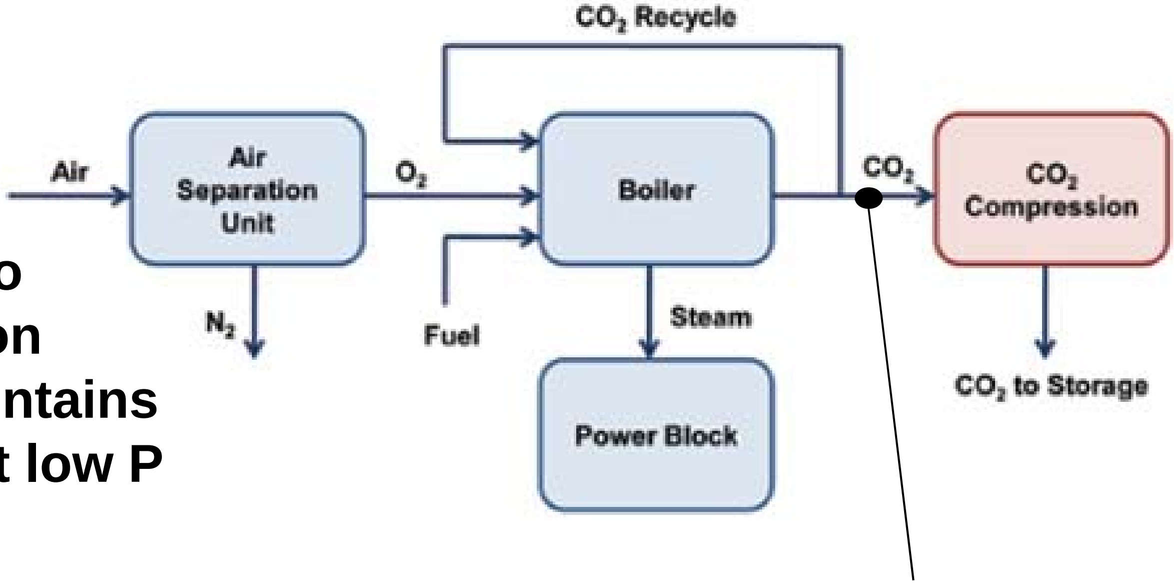
Relevant Technologies (TRL 6+):

- Chemical absorption (MDEA), Calcium looping, Solid sorbents, Polymeric membranes, Molten carbonate fuel cells

Carbon Capture (CC) Strategies:
Oxy-Combustion (Front-end Retrofit)

$$\text{Coal} + O_2 \rightarrow CO_2 + H_2O + \text{Contam.} + \text{Heat}$$

(Fuel)



Easier separation with: 50-95% CO_2
(depending on partial firing, etc.)

Method:

- **Use air separation plant to produce O_2 for combustion**
- **After cleanup, flue gas contains high CO_2 concentration at low P**

Key Challenges:

- **Cost of air separation**
- **Temperature control in boiler**
- **Boiler design/retrofit**

Relevant Technologies (TRL 6+):

- Solid **ad**sorbents, High temperature chemical looping, Ionic transport membranes

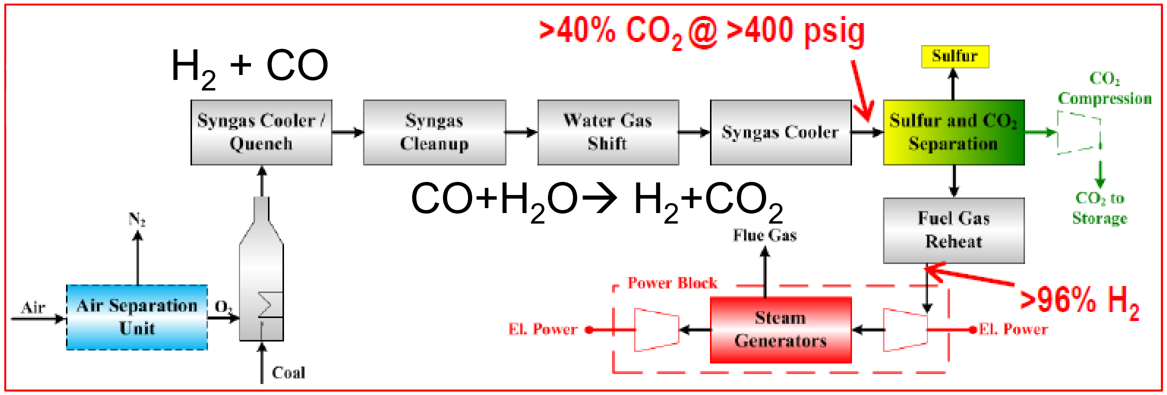
Carbon Capture (CC) Strategies:
Pre-Combustion (System-wide change)

$$\text{Coal} + O_2 + H_2O \rightarrow CO/CO_2 + H_2/H_2O + \text{Contam.}$$

(Fuel)

Method:

- Gasifier to make syngas
- Water-gas shift to convert CO to H_2/CO_2
- Separate the CO_2 and H_2



Key Challenges:

- **Process complexity and cost**
- **Additional process requirements** (ASU, WGS, thermal integration, *H_2 turbine*)
- **Systems Integration**

Efficiency penalties

- NGCC 7-11% (Selexol, Rectisol, membranes) for 85-94% CC

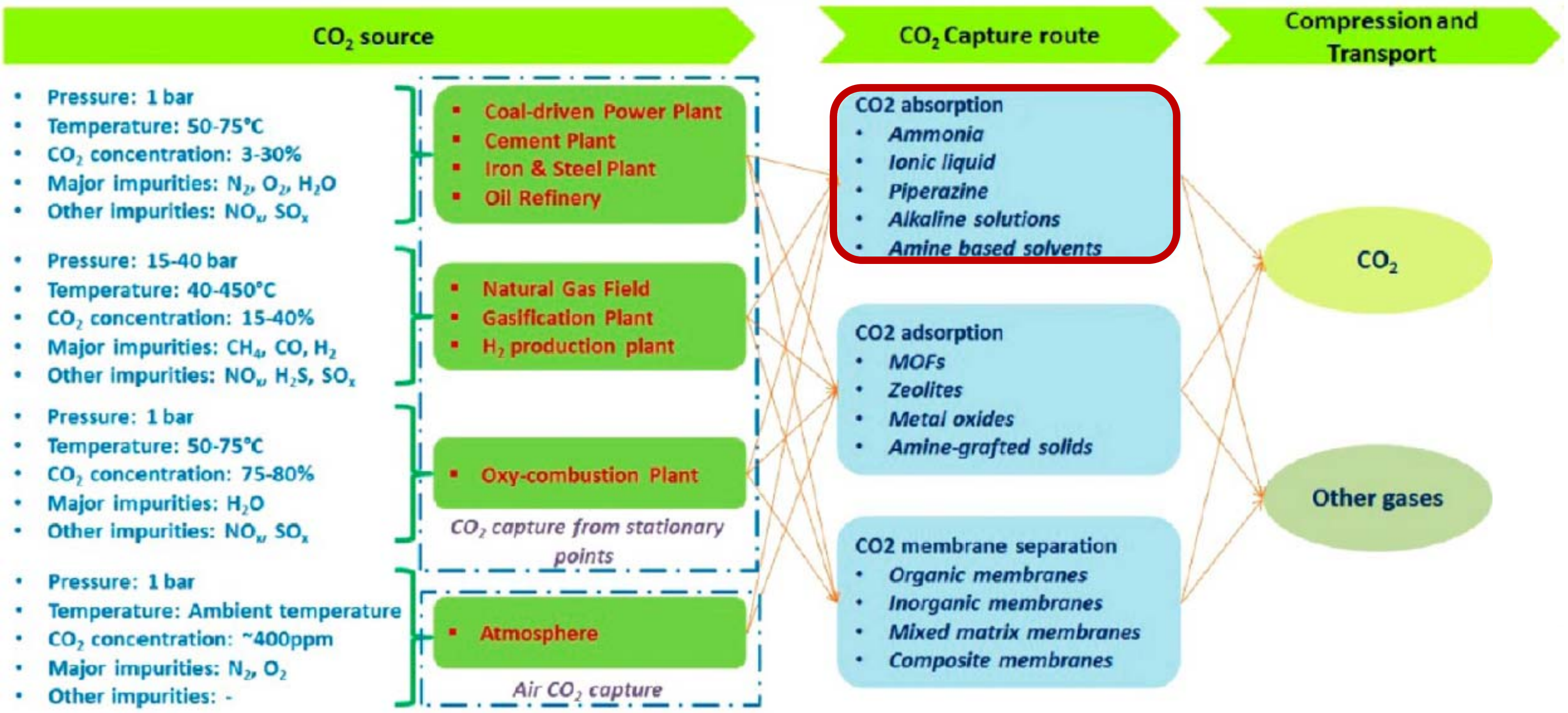
Relevant Technologies (TRL 6+):

➢ Physical solvents (Rectisol, Selexol, Purisol), Solid sorbents

Adapted from: R. Gupta, Sustainable power production, ASME ES 2016

There are many CC technologies under development and many commercial already

- The capture route depends, in part, on the CO_2 source
- **Ab**sorption, **Ad**sorption, and Membrane Separations are the primary ***technology*** classifications



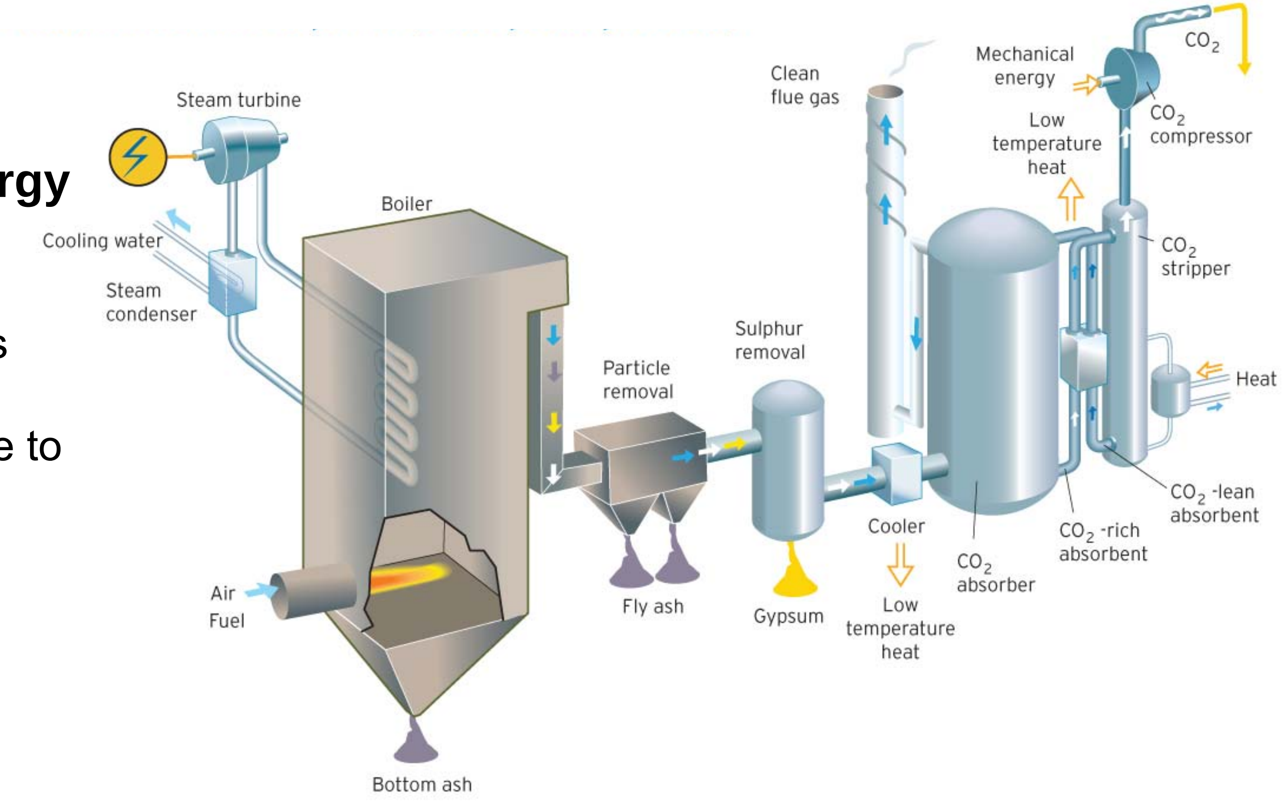
Yuan and Eden, *Ind. Eng. Chem. Res.* 2016, 55, 3383−3419

Post-Combustion CC technology features both highest TRL and most R&D activity

- Most mature P-C technology is absorption via monoethanolamines
- Commercially available tech dominated by solvent-based processes

Drivers:

- **High thermal req’mts**
  (steam for regen of solvent)
- **Parasitic electrical energy**
  (compression of CO2)
- **High capital costs**
  - Extremely large process equipment
  - Expensive materials due to corrosion resistance
  - Evaporative losses and wastewater treatment
  - Large plant footprint

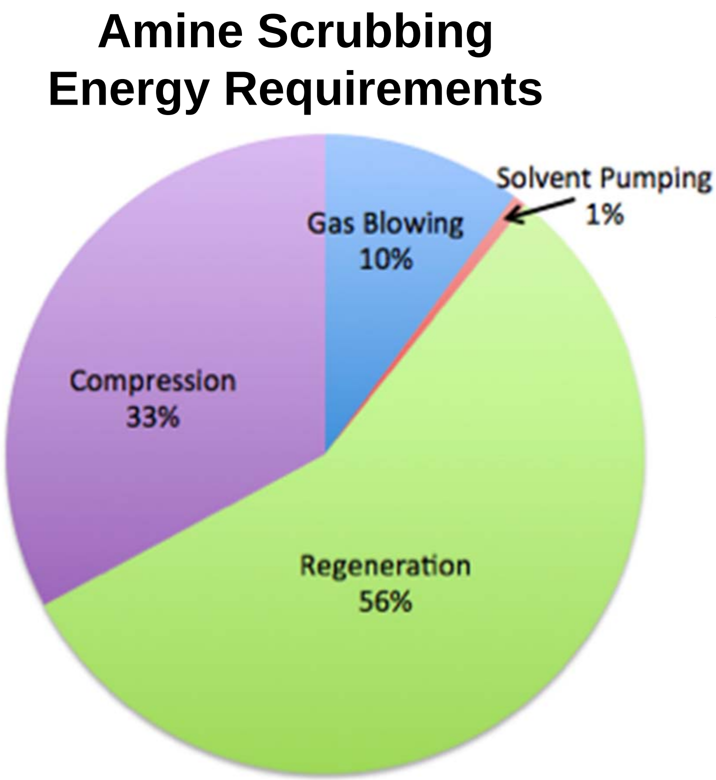


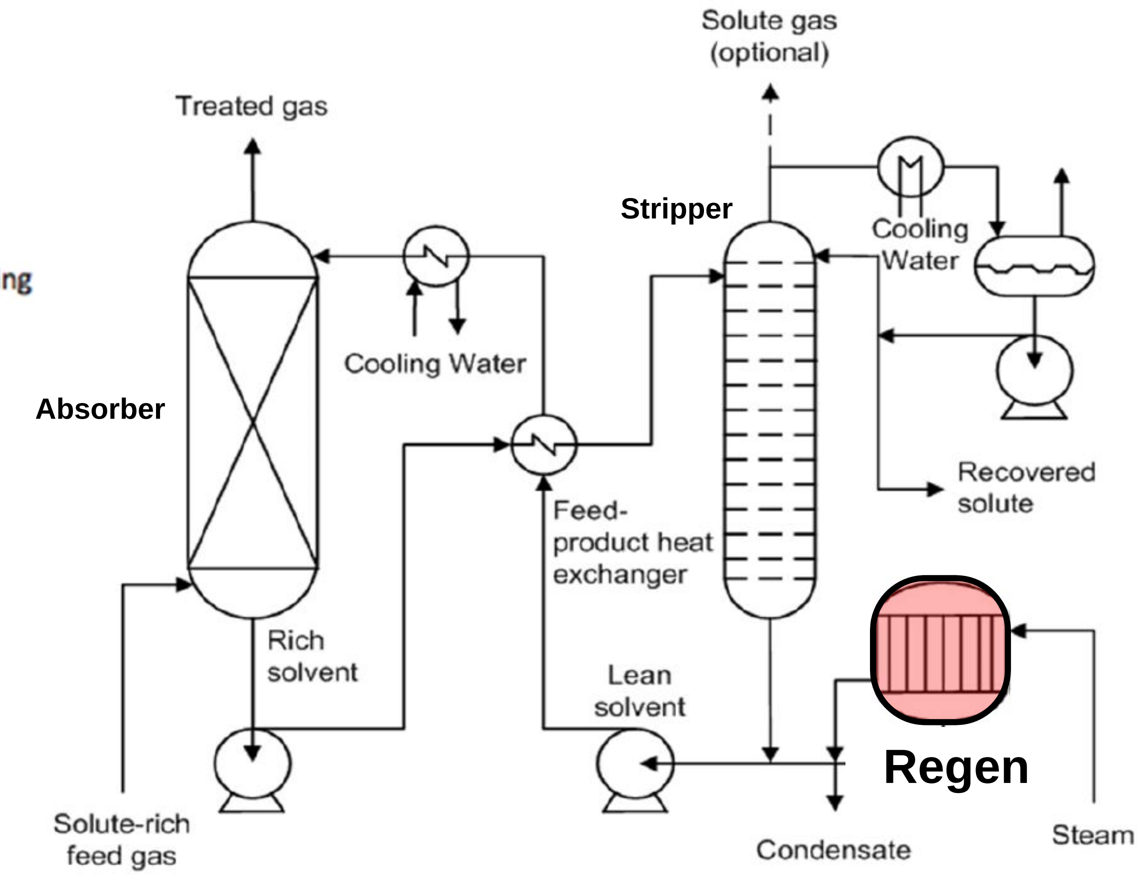
Result:

- **Increase in COE > 65%**
- **Reduction in Efficiency ~10%**
- **Cost of Avoided CO_2 > $60/ton**

Amine scrubbing absorption is state-of-the-art for point-source CO_2 capture

- In absorber: CO_2 dissolves into liquid solvent, reacts w/ binding agent in liquid
- In stripper: process is reversed
- **Solvent regeneration dominates energy requirements**





Wilcox, *Carbon Capture*, Springer, 2012

Advances in solvent-absorption lie in solvent improvement

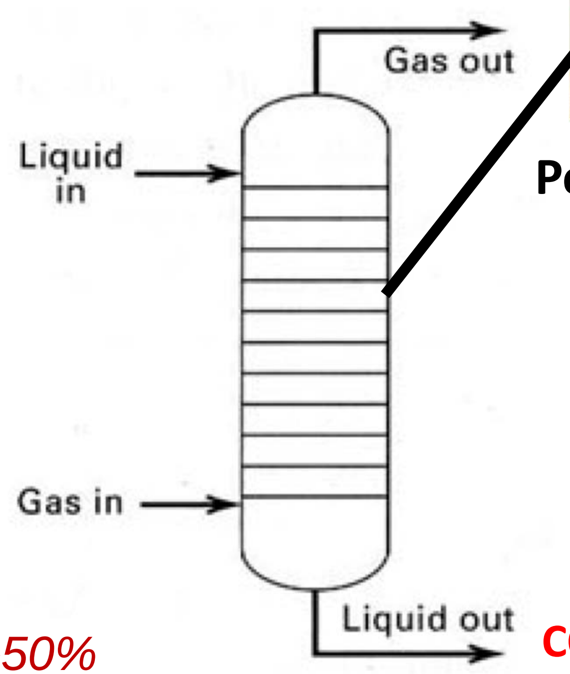
- **Desirable solvent properties:**
  - High CO2 capacity
  - Fast kinetics
  - Low volatility & viscosity
  - Relatively high density
  - Nontoxic, nonflammable, and noncorrosive
  - High thermal stability
  - Resistance to oxidation
- **Advanced R&D Focus:**
  - Blended Amines
  - Liquid-Solid Sorbents
    - Carbonates
    - Ammonia

➢ *Reduce Regen Duty by 30-50%*

Gas to Liquid Flux

$$J_{\mathrm{L,CO_2}} = c_{\mathrm{i}} k_{\mathrm{L}} E$$

“CO_2-free” gas out

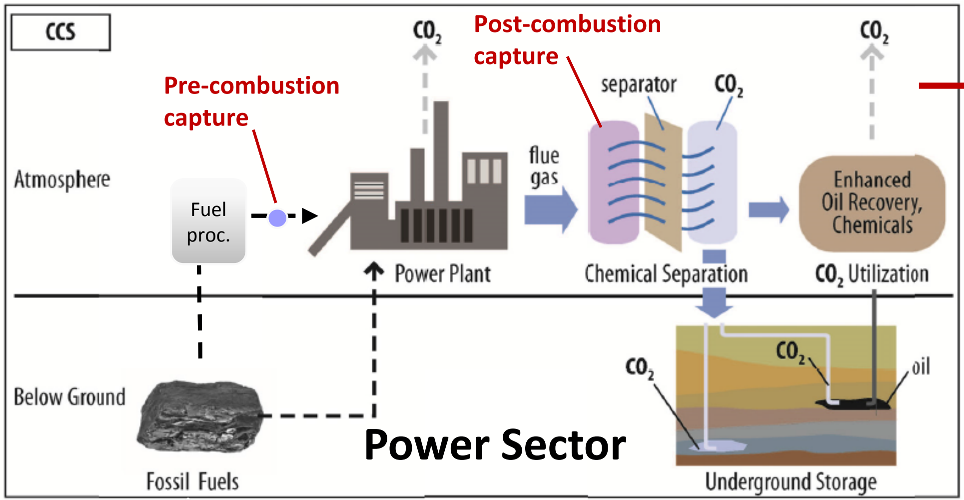


CO_2-loaded solvent out

Petra Nova – 1.4 Mt CO_2/year
115 Meters Tall Absorber

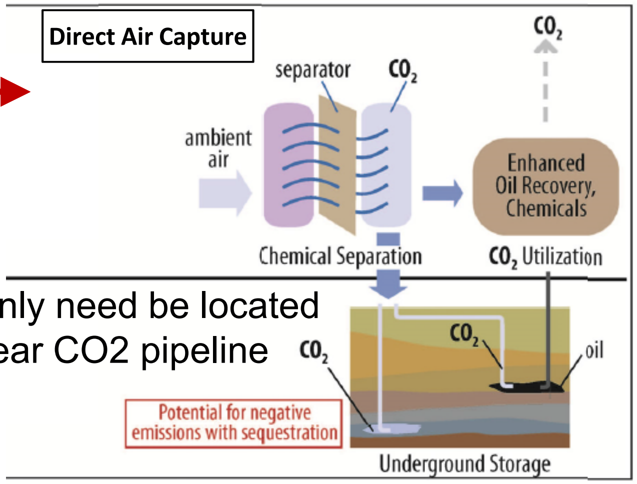
Adapted from: Wilcox, *Carbon Capture*, Springer, 2012

Carbon negative emissions via DAC and BECCS may be attractive for capturing difficult / past emissions



Power Sector

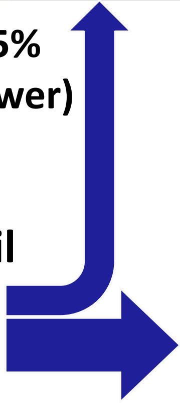
atmosphere



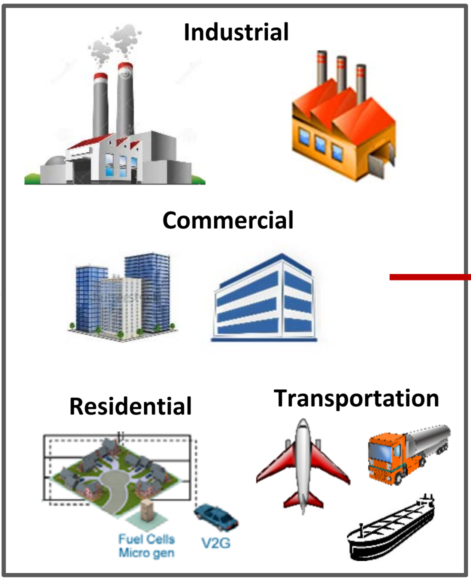
Only need be located near CO2 pipeline

- 3 companies WW
- 150-600 $/t, several demos

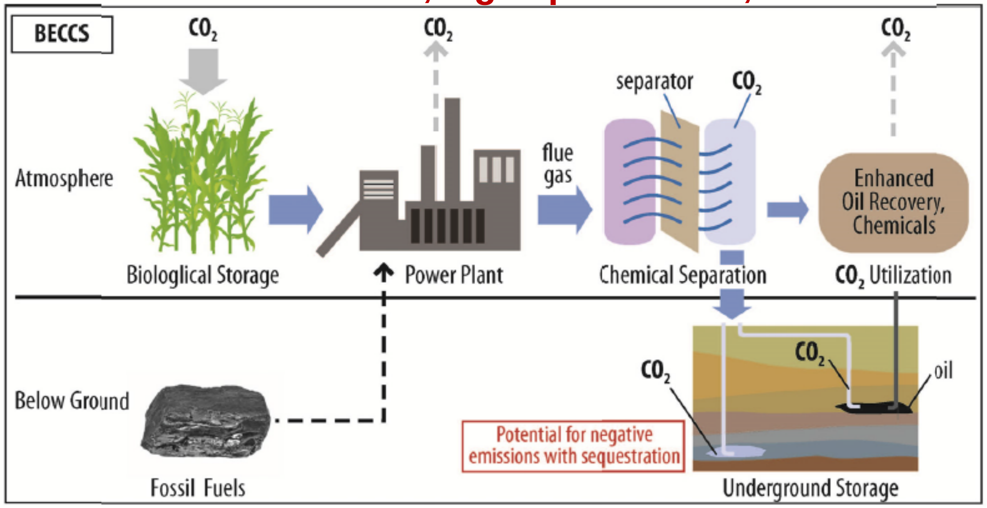
Greenhouses, algae production, etc.



Other point sources



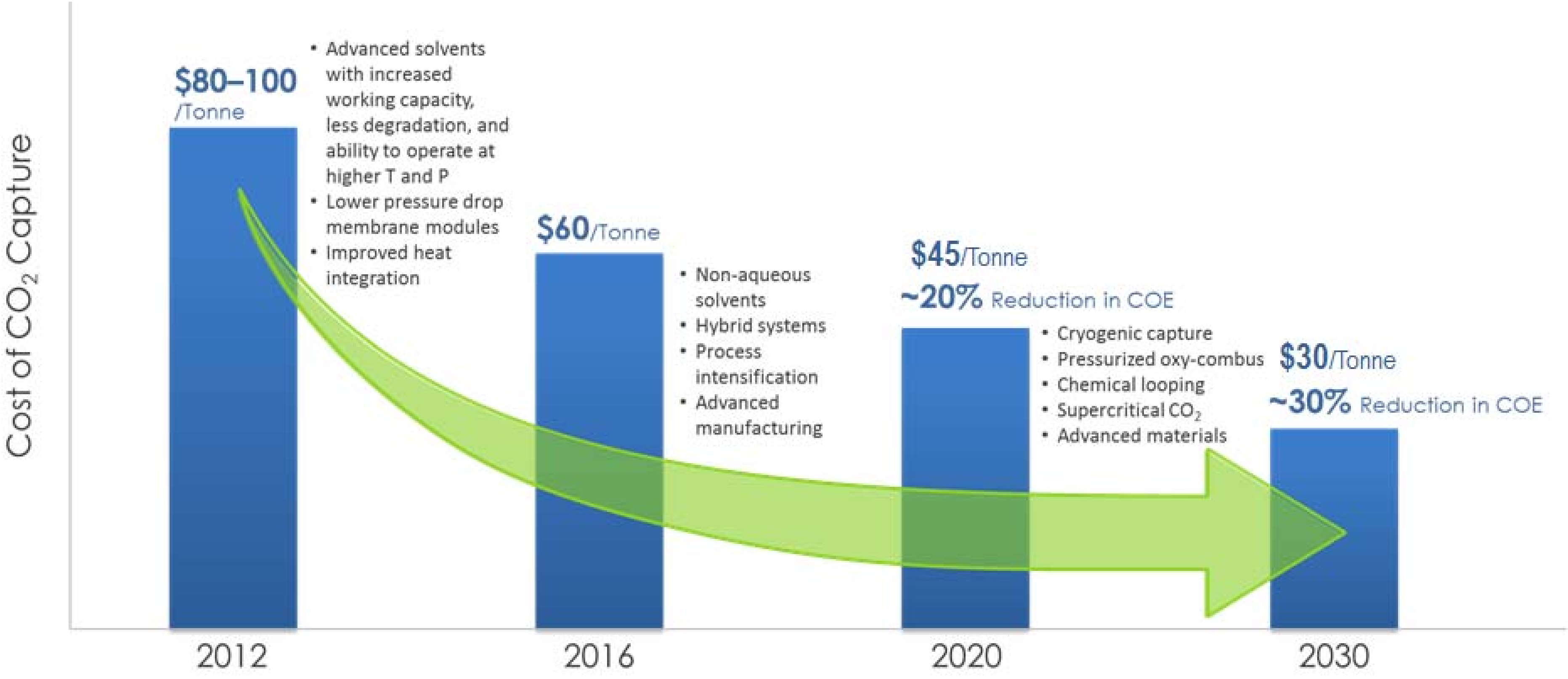
CO_2



Figures adapted from: NAS, Climate Intervention, (2015)

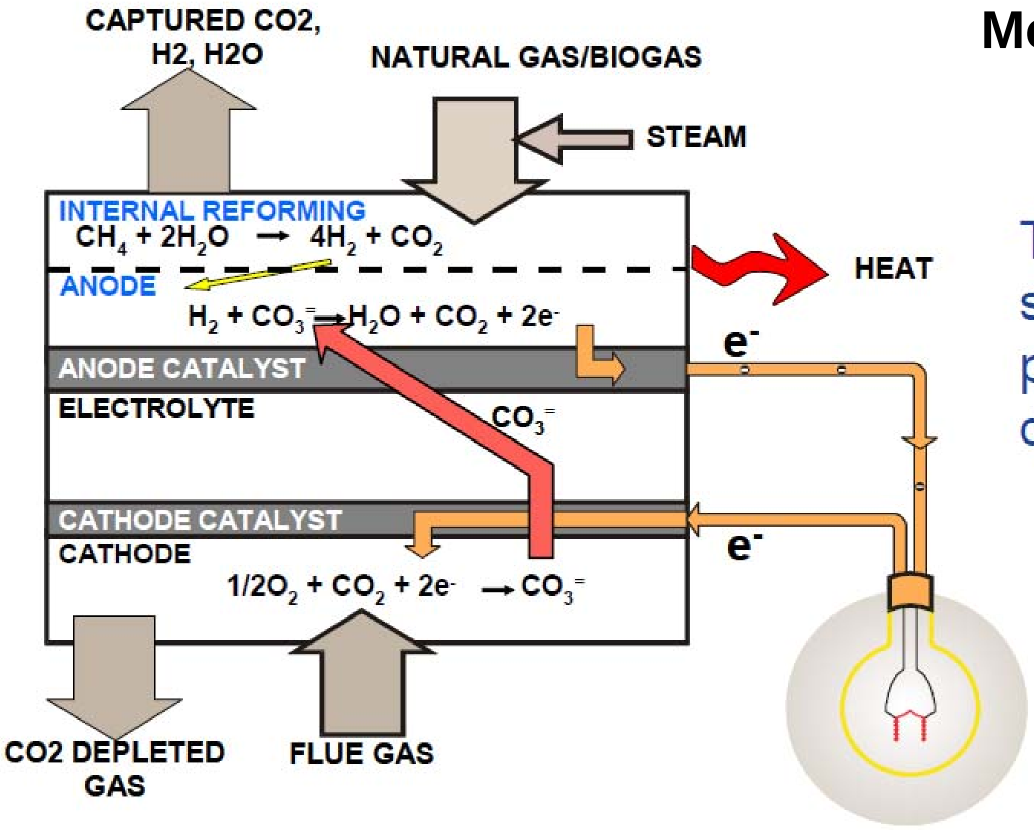
DOE targets for advancement in CC for power generation

- However, note many projects being executed for industrial applications



J. Litynski, U.S. DOE Office of Fossil Energy (2017)

Advanced CC Technologies – Hybrid Solution
Electrochemical Membrane & Power Gen



Molten Carbonate Fuel Cells

The driving force for CO_2 separation is electrochemical potential, not pressure differential across the membrane

Net Results ⇨

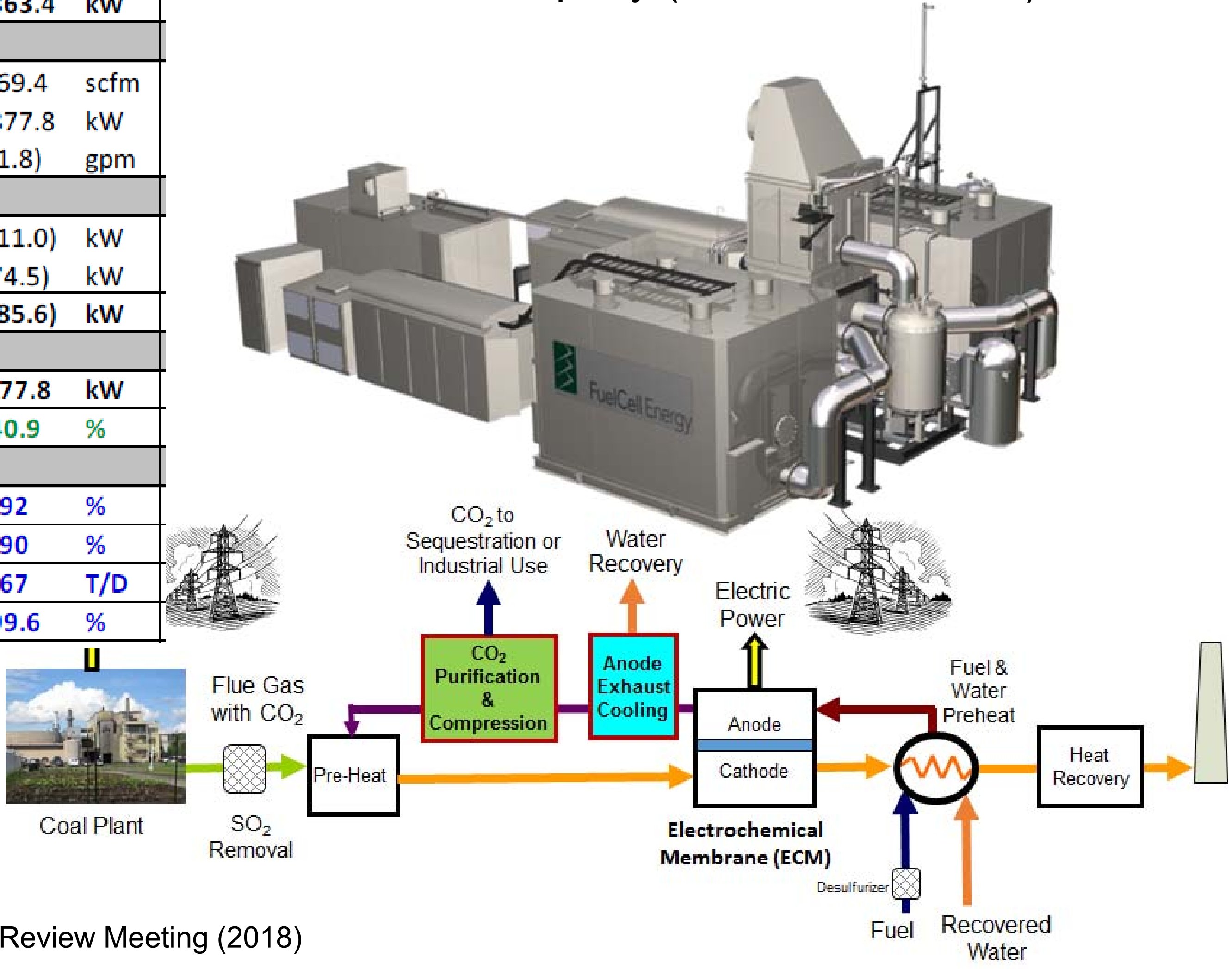
- Simultaneous Power Production and CO_2 Separation from Flue Gas of an Existing Facility
- Excess Process Water Byproduct
- Complete Selectivity towards CO_2 as Compared to N_2

H. Ghezel-Ayagh, NETL CC Project Review Meeting (2018)

Re-application of commercial fuel cell technology for CC and additional power gen

Operating Mode	90% Capture Coal-Derived FG	
MCFC Gross Power, DC	1863.4	kW
Energy & Water Input		
Natural Gas Fuel Flow	169.4	scfm
Fuel Energy (LHV)	2877.8	kW
Water Consumed/(Produced)	(1.8)	gpm
Consumed Power		
AC Power Consumption	(611.0)	kW
Inverter Loss	(74.5)	kW
Total Parasitic Power Consumption	(685.6)	kW
Net Generation & Efficiency		
CEPACS Plant Net AC Output	1177.8	kW
Electrical Efficiency (LHV)	40.9	%
Carbon Capture		
Total Carbon Capture, %	92	%
Carbon Capture from FG, %	90	%
Total CO_2 Captured, Tons per Day	67	T/D
CO_2 Purity	99.6	%

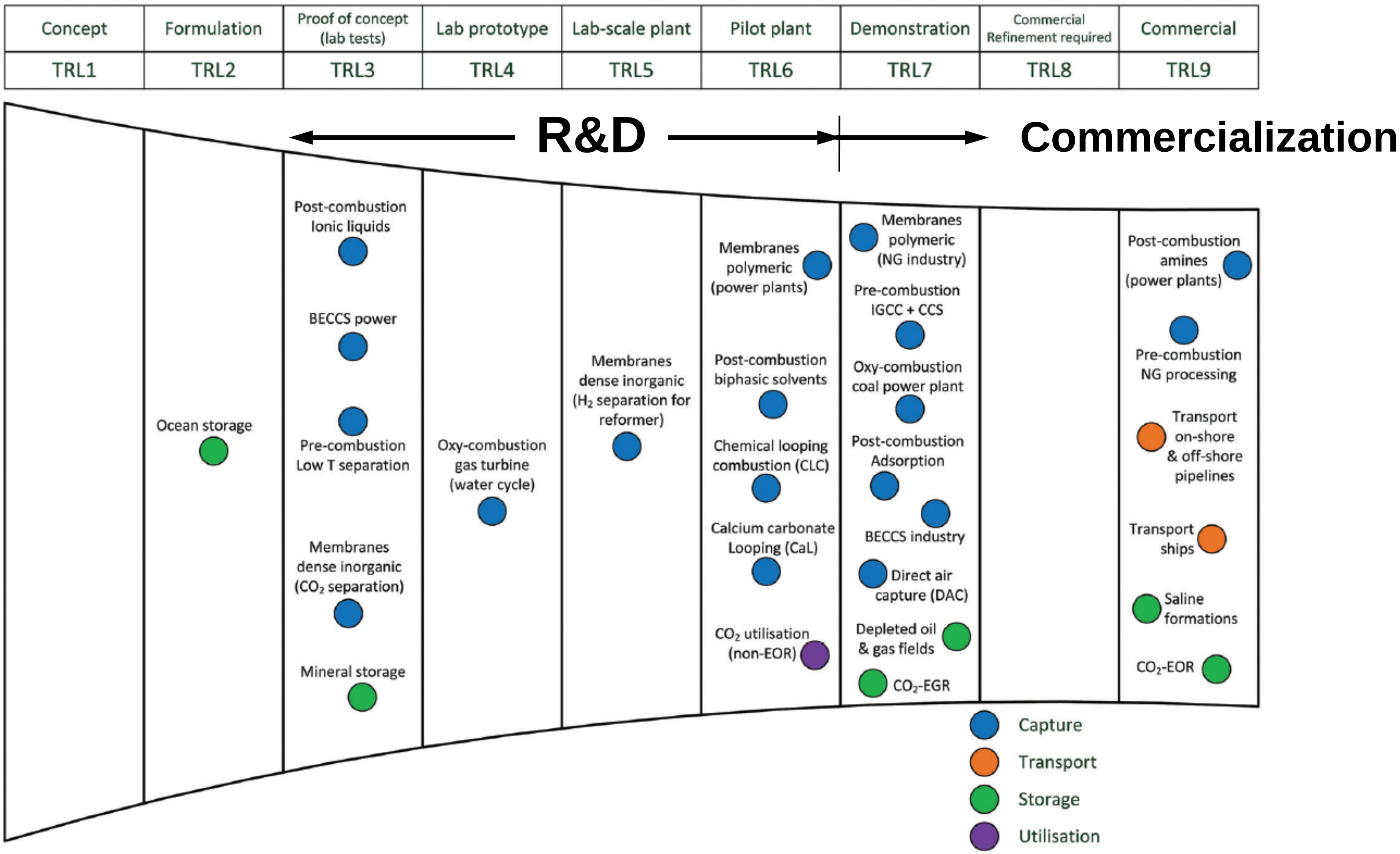
Fuel Cell Energy in partnership with AECOM and Southern Company ($30M DOE NETL)



H. Ghezel-Ayagh, NETL CC Project Review Meeting (2018)

WHAT CC TECHNOLOGIES ARE READY TO PROVIDE A SOLUTION ?

Technology Readiness Levels of various CO_2 capture technologies



Concept	Formulation	Proof of concept (lab tests)	Lab prototype	Lab-scale plant	Pilot plant	Demonstration	Commercial Refinement required	Commercial
TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9

Bui et al., *Energy Environ. Sci.*, 2018, **11**,1062

Only 2 Power Plant CCS demonstration projects are operational

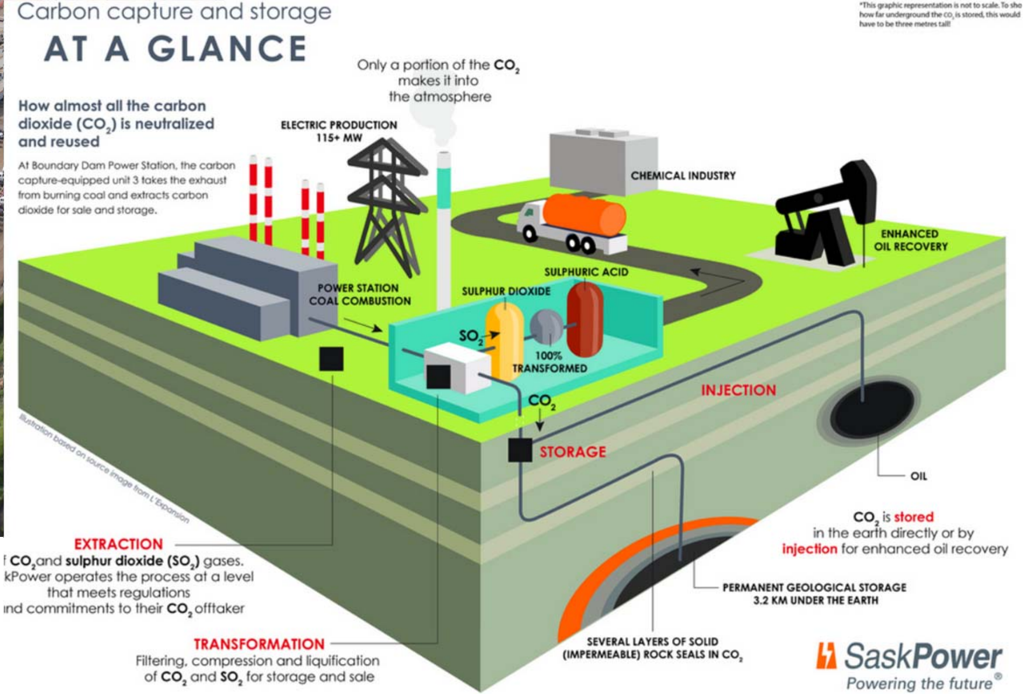
Project	**Boundary Dam**	**Kemper**	**Petra Nova**
Location	Saskatchewan, Canada	Mississippi, USA	Texas, USA
Start date	Oct 2014	Jan 2017 (?)	Dec 29, 2016
Size (MW)	115 (net)	582 (net)	240 (gross)
Size (Mt CO_2/yr)	1.3	3.0	1.4
New/Retrofit	Retrofit	New	Retrofit
Plant Type	PC	**IGCC (NGCC)**	PC
Steam Source	Steam Turbines	---	NG Cogeneration Plant
Solvent	Shell Cansolv	Selexol/TRIG	MHI KS-1
Initial Cost Estimate	$1.1 billion	$2.4 billion	$1 billion
Actual Cost (est)	$1.5 billion	$7.5 billion	$1 billion

HALTED

Boundary Dam
World’s first CCS Power Plant

Colorado School of Mines

110 MW Power Plant in Canada near border of North Dakota



Carbon capture and storage

AT A GLANCE

How almost all the carbon dioxide (CO_2) is neutralized and reused

At Boundary Dam Power Station, the carbon capture-equipped unit 3 takes the exhaust from burning coal and extracts carbon dioxide for sale and storage.

*This graphic representation is not to scale. To sho how far underground the CO_2 is stored, this would have to be three metres tall!

Only a portion of the CO_2 makes it into the atmosphere

EXTRACTION

f CO_2 and sulphur dioxide (SO_2) gases. kPower operates the process at a level that meets regulations ınd commitments to their CO_2 offtaker

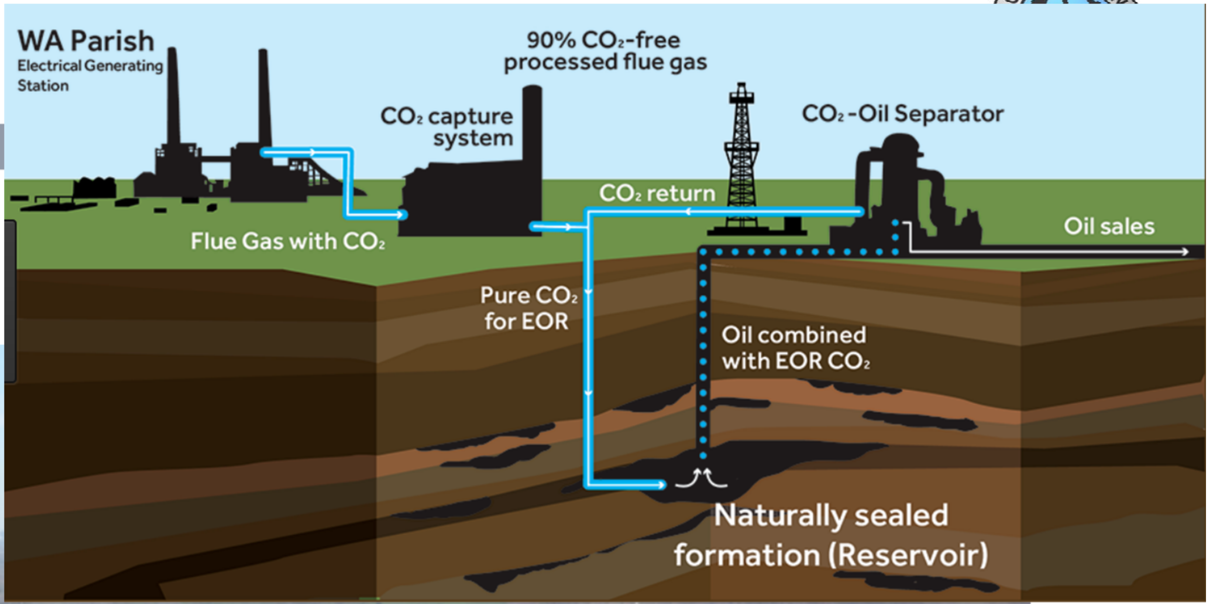
TRANSFORMATION

Filtering, compression and liquification of CO_2 and SO_2 for storage and sale

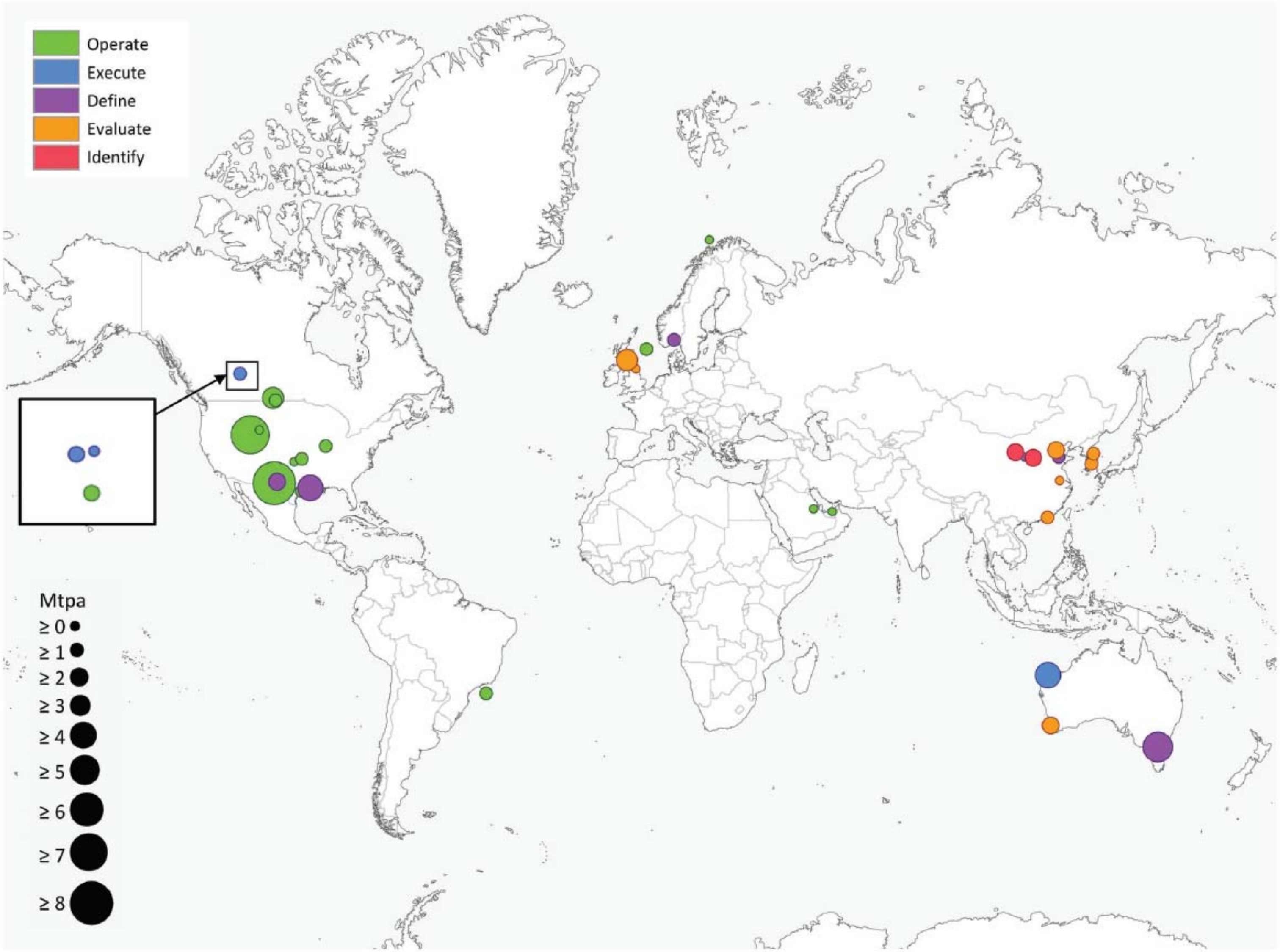
CO_2 is stored in the earth directly or by injection for enhanced oil recovery

Petra Nova -Houston, TX

240 MW Power Plant



Most large-scale CCS demonstrations are in the U.S. and are dominated by EOR applications



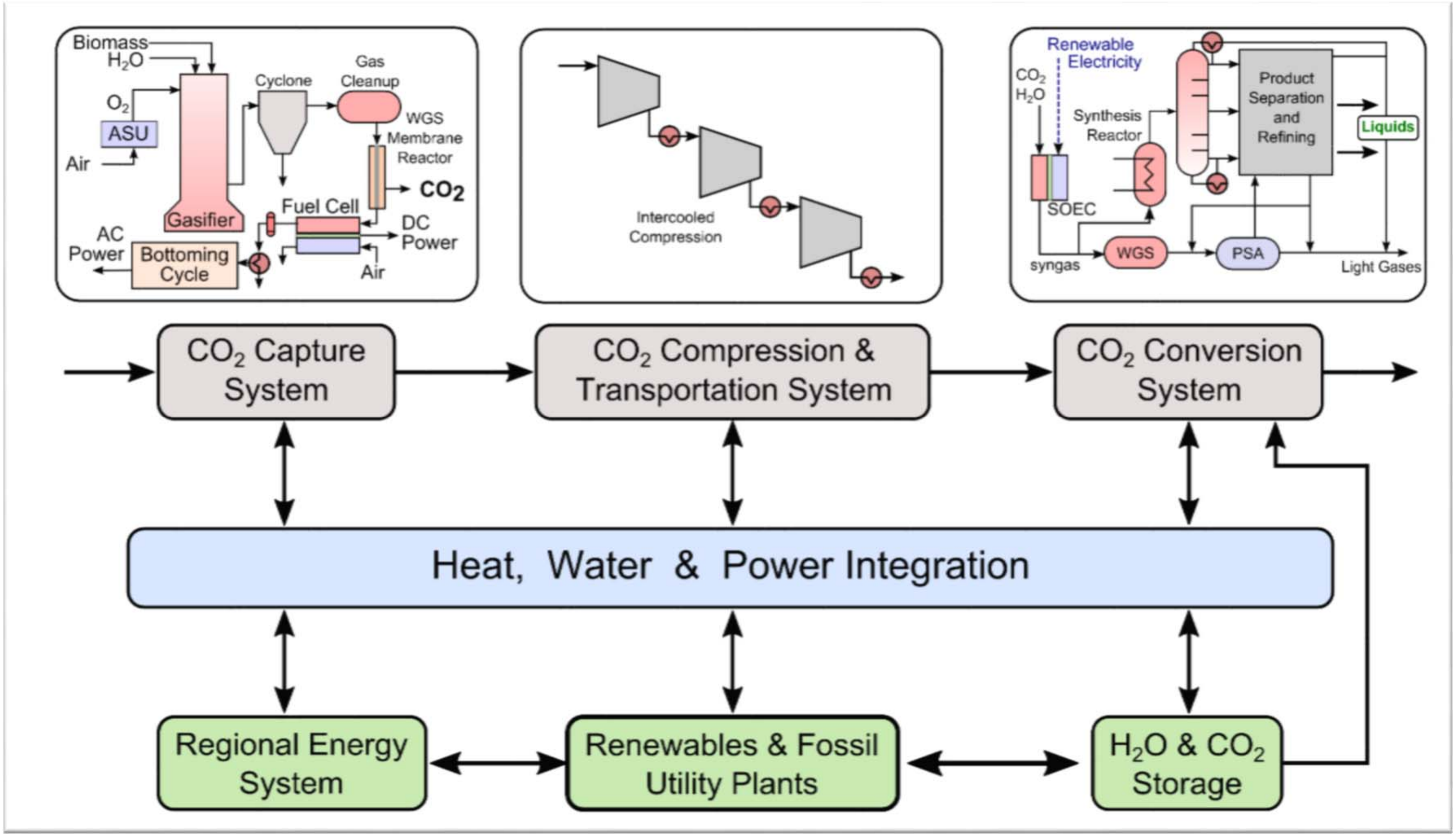
Bui et al., *Energy Environ. Sci.*, 2018, **11**,1062

Final thoughts from a Systems Integration Perspective

- **Huge focus on power generation studies & tech development, yet vast majority of operational CCS projects are in industrial sector**
- **Realizing deep decarbonization goals requires solution sets that vary depending on resource mix** (wind/solar [CSP, PV], geothermal, biomass, gas-CCS, nuclear)
- **Few CC technologies address past emissions (DAC, BECCS)**
- **Firming capacity of technologies may be important for grid-integration → Dispatch/Storage considerations…**
  - Post-combustion such as amine regeneration, could be ***scheduled*** at times of excess power enabling output to be boosted when required.
  - Pre-combustion or oxy-fuel capture, an oxygen buffer would allow the air separation unit to run independently of generation to maximize revenue/cost effectiveness (e.g., operate ASU during off-peak hours)
- **Energy planning and Infrastructure transitions are needed**
  - Energy conservation, carbon management, water, power

Integration of CO_2 capture, conversion, & storage with energy & water systems

Eventually, infrastructure redesign/expansion and energy planning will need to be dealt with



CO_2 Capture System

CO_2 Compression & Transportation System

CO_2 Conversion System

Heat, Water & Power Integration

Regional Energy System

Renewables & Fossil Utility Plants

H_2O & CO_2 Storage

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- Raghubir Gupta (Susteon, Inc.)