Meta-study of carbon dioxide capture technologies

Finding the signal in the noise

Canadian J of Chemical Engineering Lectureship Award Lecture

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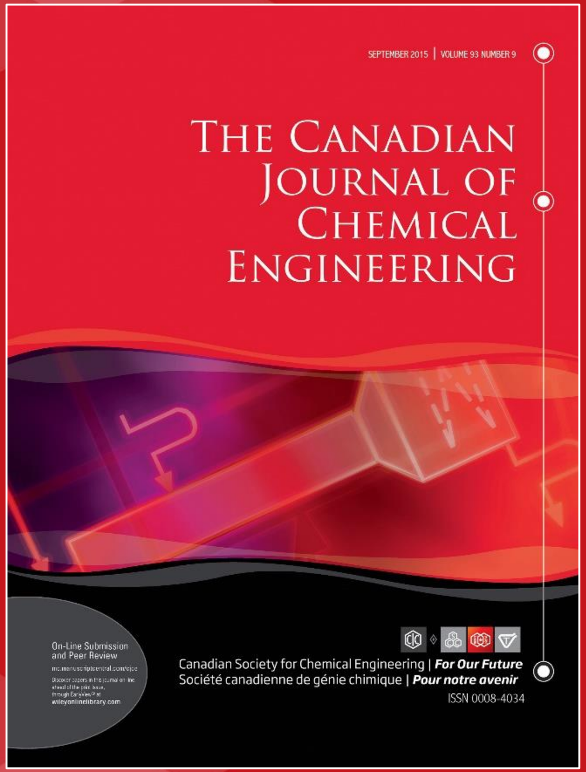

Can. J. Chem. Eng. Lectureship Award

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Presenting results from the paper:
Nease J, Adams TA II. Life Cycle Analyses of Bulk-Scale Solid Oxide Fuel Cell Power Plants and Comparisons to the Natural Gas Combined Cycle. *Canadian J Chem Eng*, 93:1349-1363 (2015).

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Presenting results from the paper:

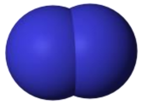
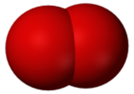
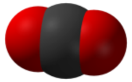
Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Comparison of CO_2 Capture Approaches for Fossil-Based Power Generation: Review and Meta-Study. *Processes* **2017,** *5*, 44.

Submit to Special Issue "**Process Systems Engineering à la Canada**" for this Conference.

Fundamental Problem of CO_2 Capture and Sequestration

- Fundamental problem: separation of CO_2 and N_2 in flue gases:
  - We need to go from dilute to high purity
- We need to go from low pressure to high pressure
- And there's an awful lot of it (~7 million ton/yr per coal power plant).

TYPICAL COAL POWER FLUE EXHAUST, 1 BAR

	Mol %	Kinetic Diameter (Images to Scale)	
N_2 (&Ar)	68%		3.6 Å
O_2	2%		3.45 Å
CO_2	13%		3.30 Å
H_2O	17%		2.7 Å

CO_2 PIPELINE LIMITS, 120 BAR

	Kinder Morgan	Sleipner
N_2 (&Ar)	<4%	3-5%
O_2	<50ppm	<50ppm
CO_2	>95%	93-96%
H_2O	<690ppm	<Saturated

Sources: NETL 2007 - Bituminous Baseline Report (see required reading). Adams & Barton, AIChE J (2010)
deVisser E., et al. Dynamis CO2 quality recommendations. Int. J. Greenhouse Gas Cont. 2008, 2, 478–484
Molecule Images from chemistry.about.com. Sizes from Angew. Chem. Int. Ed. 2010, 49, 6058 – 6082.

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Post-Combustion Solvent-Based Capture

NGCC Example

Gas combustion and turbines

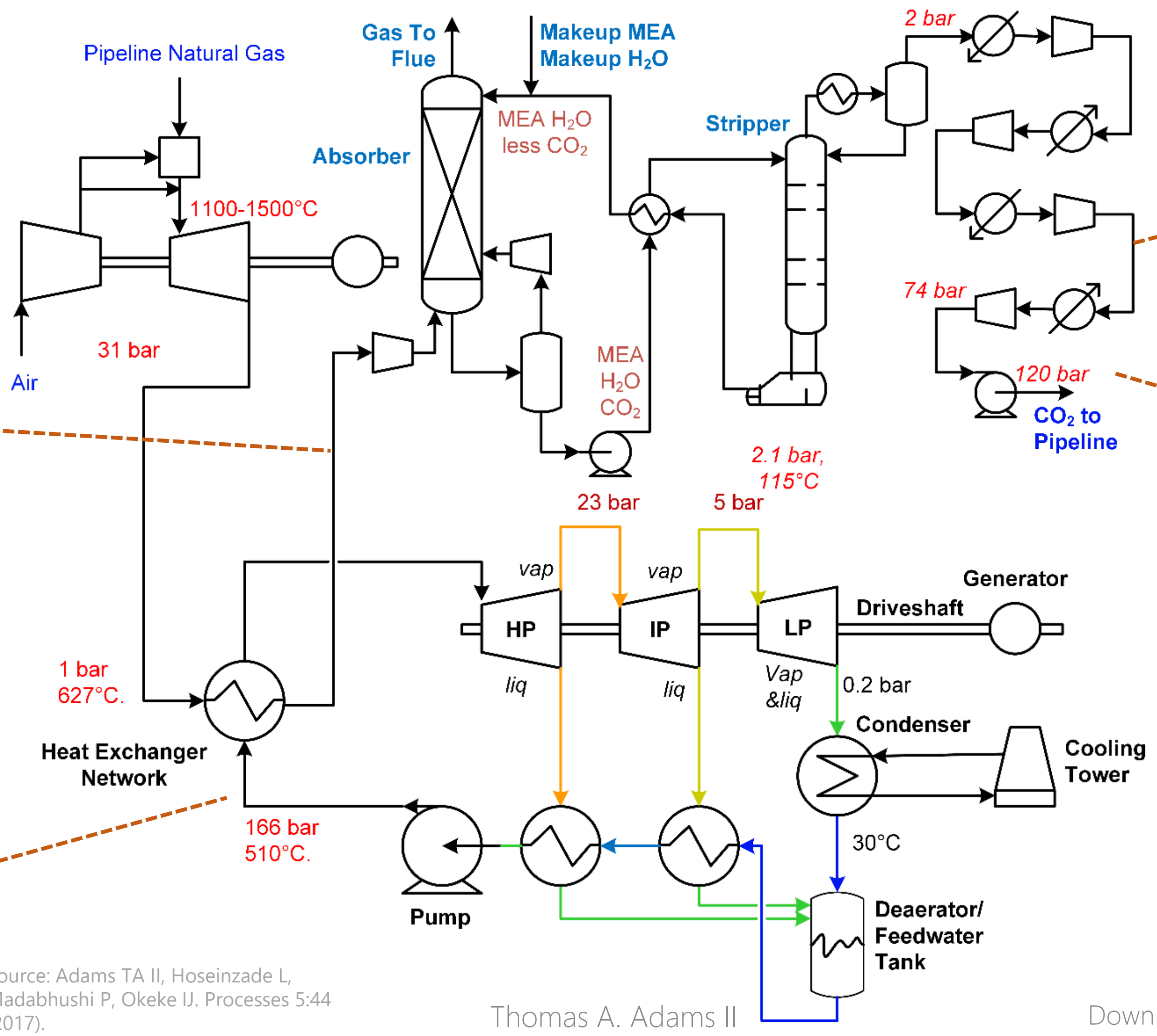
Combustion Products
(Flue Gas) after heat removal

Combined Cycle (Steam)
Secondary power source from waste heat

CO_2 Absorption
Solvent-based (this example uses MEA)

CO_2 Gas Compression
From 2 bar to the supercritical point

CO_2 Pump
Pumps supercritical CO_2 to pipeline pressures



Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

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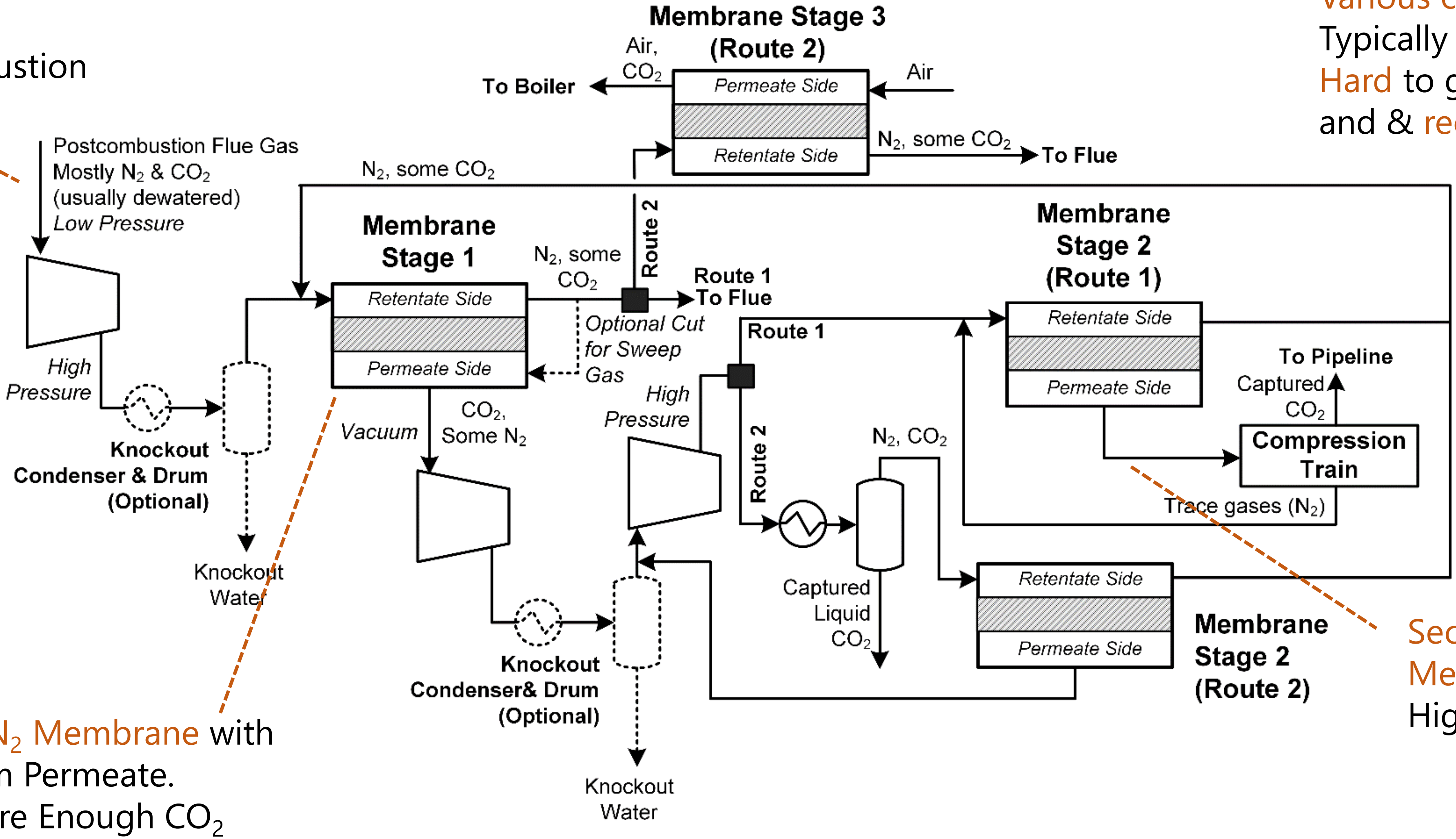
Post-Combustion Membrane-Based Capture

Flue Gas from Upstream Combustion

Various configurations
Typically 2 or 3 stages
Hard to get both purity and & recovery



Second CO_2 / N_2 Membrane
Higher Purity CO_2

CO_2 / N_2 Membrane with Vacuum Permeate.
Not Pure Enough CO_2

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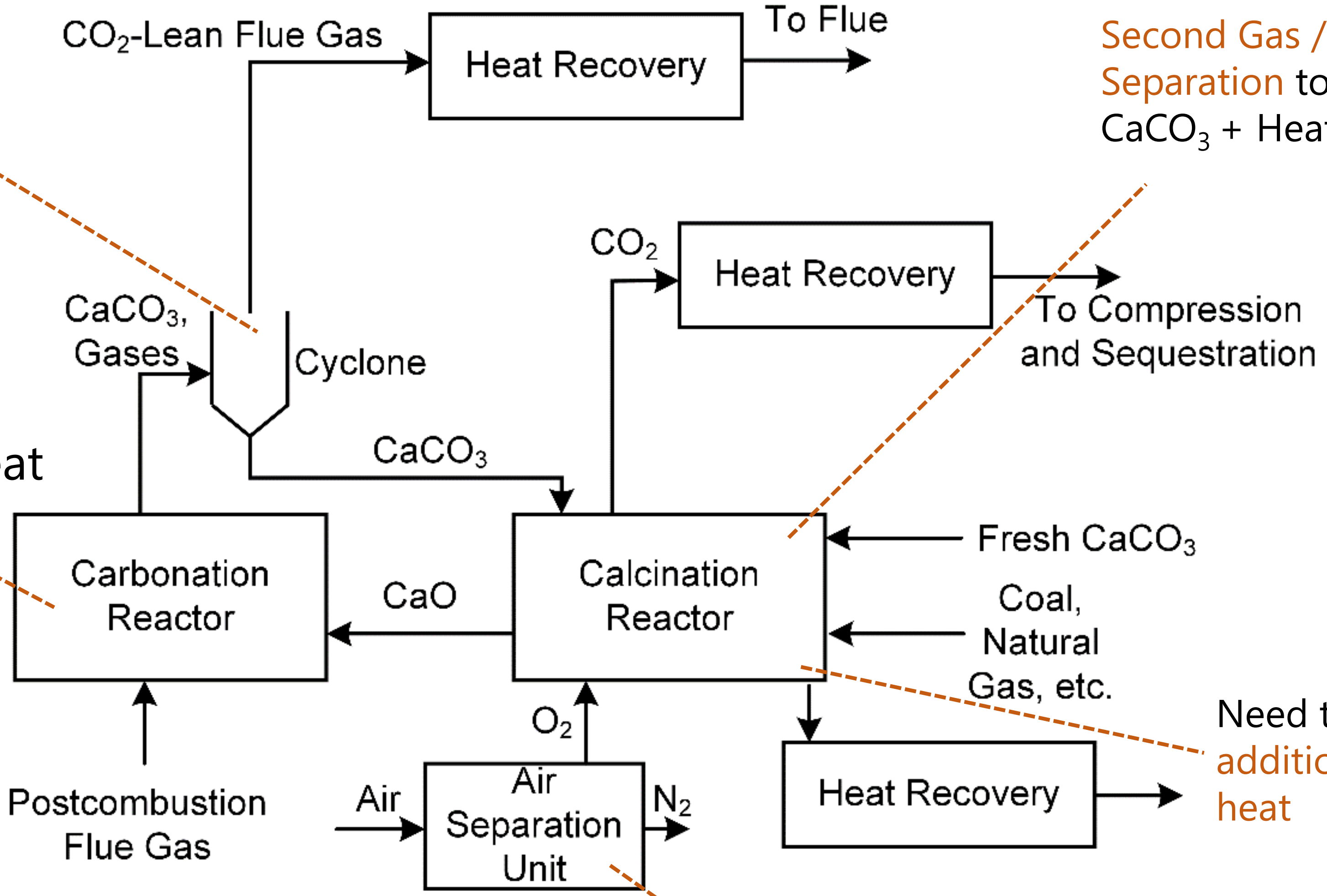
Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

Post-Combustion Solid-Based Capture

Solid Calcium Carbonate
Cycloned from rest of flue gases

$$CaO + CO_2 \rightarrow CaCO_3 + Heat$$



Second Gas / Solid Separation to release CO_2.
$CaCO_3 + Heat \rightarrow CaO + CO_2$

Need to burn additional fuel for heat

Need High Purity Oxygen to prevent N_2 injection

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Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

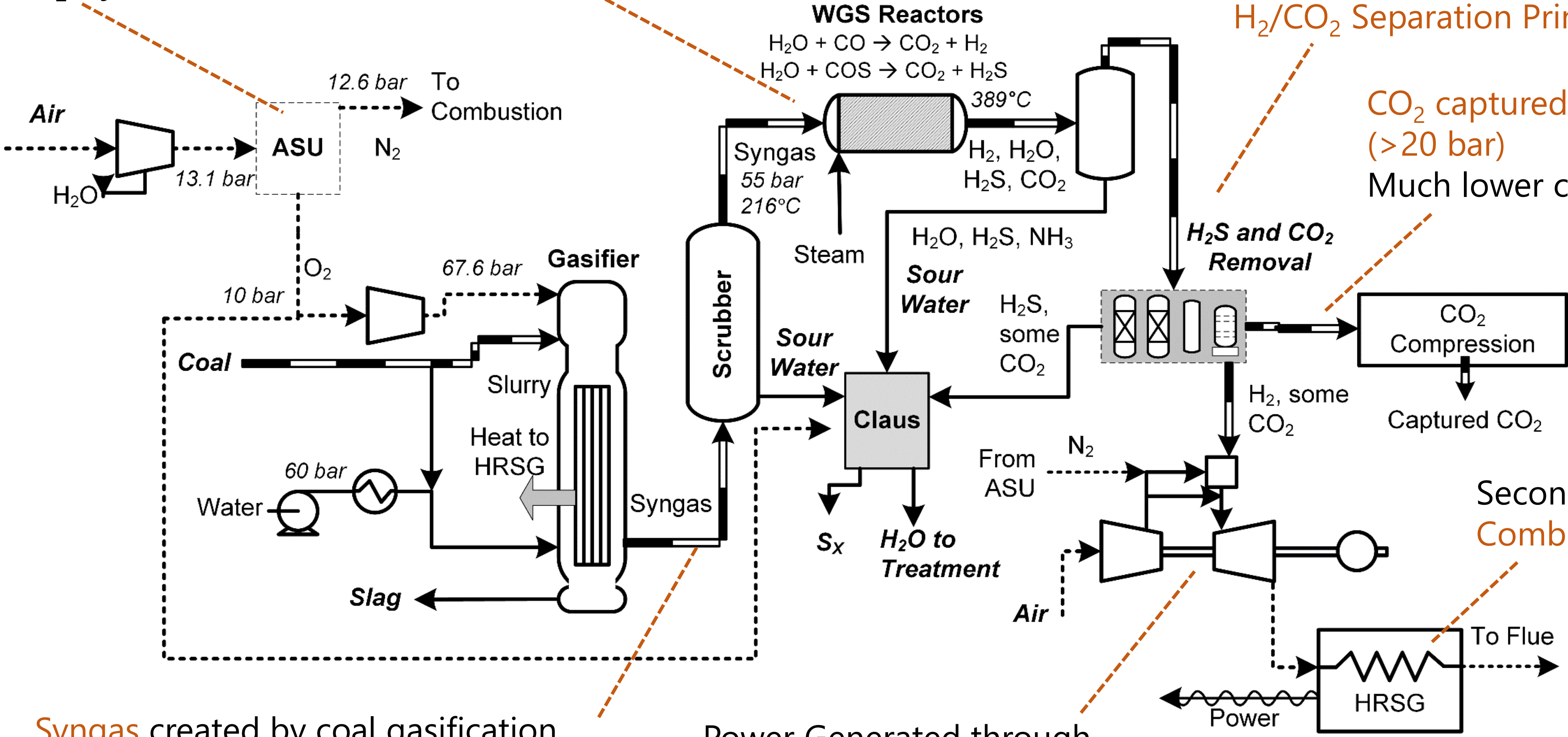
Pre-Combustion Solvent-Based Capture (IGCC)

Need High Purity Oxygen to prevent N_2 injection

Water Gas Shift moves chemical potential to H_2

Selexol or Rectisol Solvents
Capture H_2S and CO_2 in separate stages
H_2/CO_2 Separation Principle

CO_2 captured at higher pressures (>20 bar)
Much lower compression costs



Secondary Power from Combined Cycle (Steam)

Syngas created by coal gasification.

Power Generated through Gas Combustion Turbine

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Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

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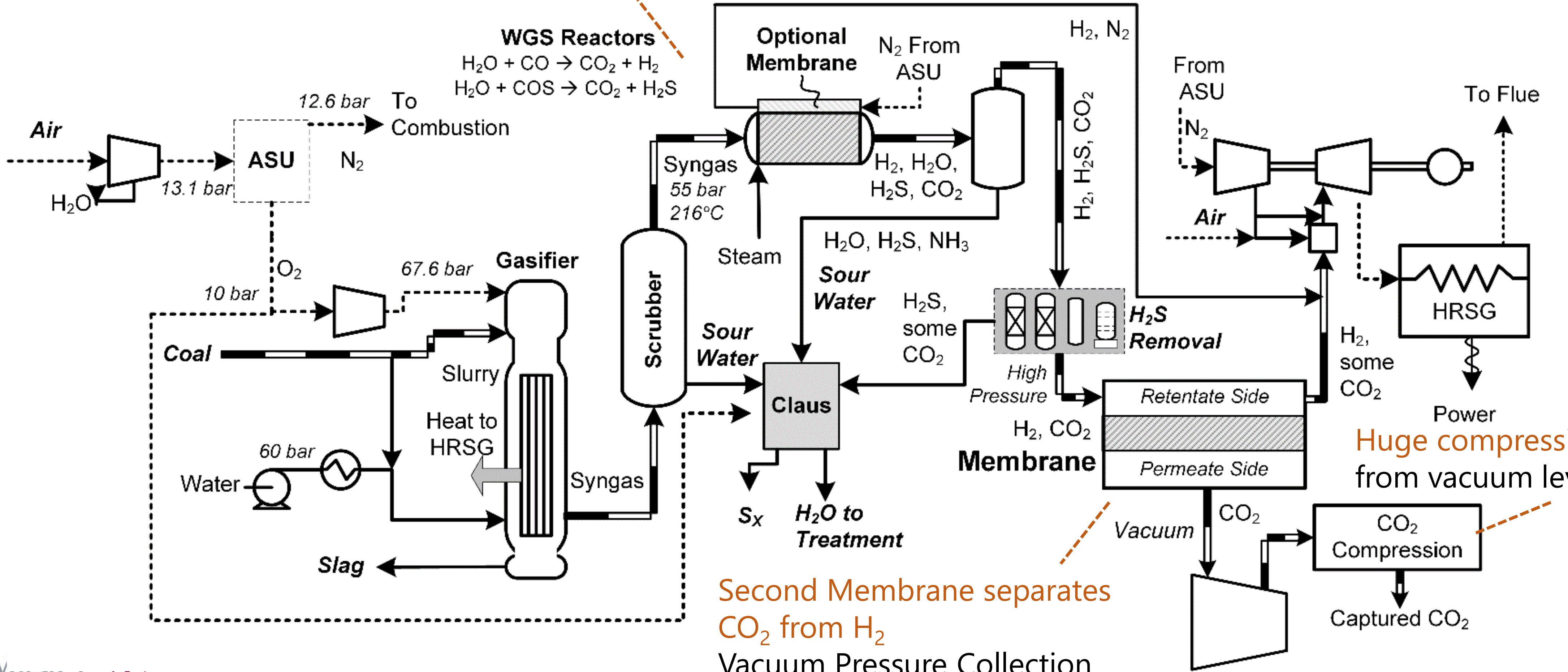
Pre-Combustion Membrane-Based Capture

Membrane-enhanced WGS removes H_2 as produced

Shifts equilibrium to toward higher conversion

Increases CO2 concentration for later



Huge compression costs from vacuum levels

Second Membrane separates CO_2 from H_2

Vacuum Pressure Collection

Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

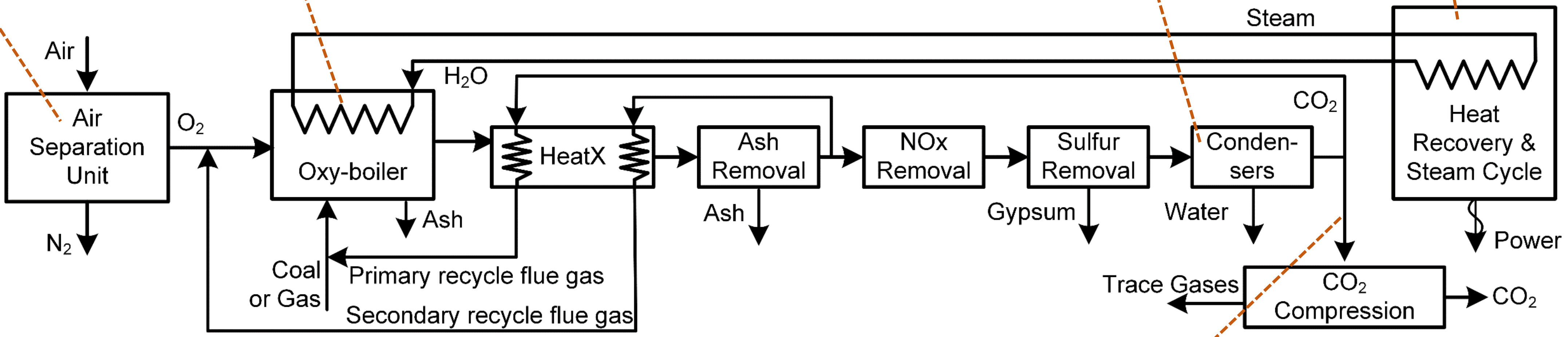
Oxyfuel Combustion

Fuel combusted in N2-free flame
Diluted with CO_2 for thermal management

Very Large ASU

CO_2/H_2O Separation
via water condensation

Power Produced through
Steam Cycles



CO2 captured at
atmospheric pressure

Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

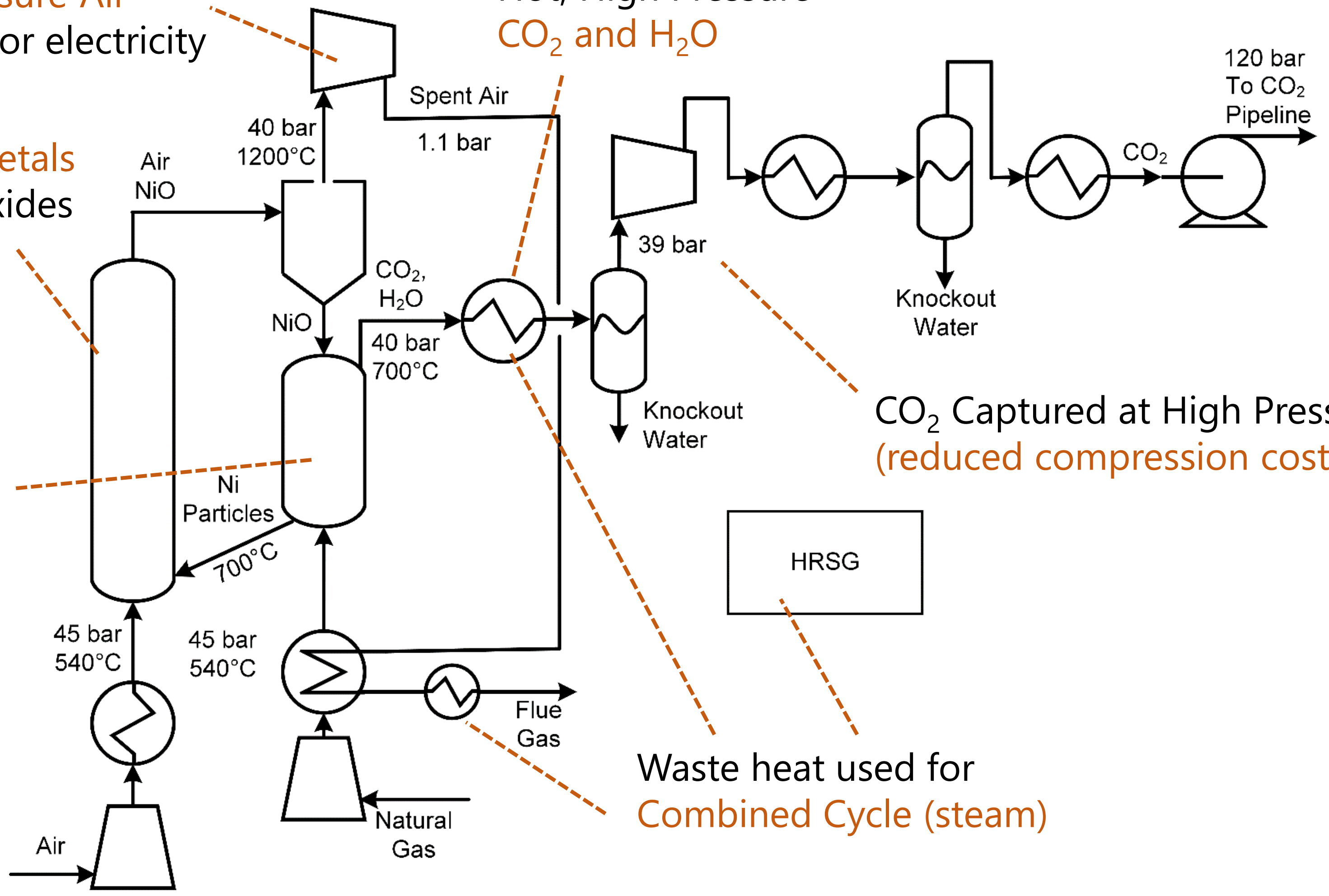
Chemical Looping Combustion

Hot, High Pressure Air
Spins turbine for electricity

Hot, High Pressure
CO_2 and H_2O

Air reacts with reduced metals
Creates heat and metal oxides
O_2 + Me → MeO + Heat

Fuel combusts using
metal oxides instead of air
MeO + CH_4 + Heat→
H_2O + CO_2 + Me

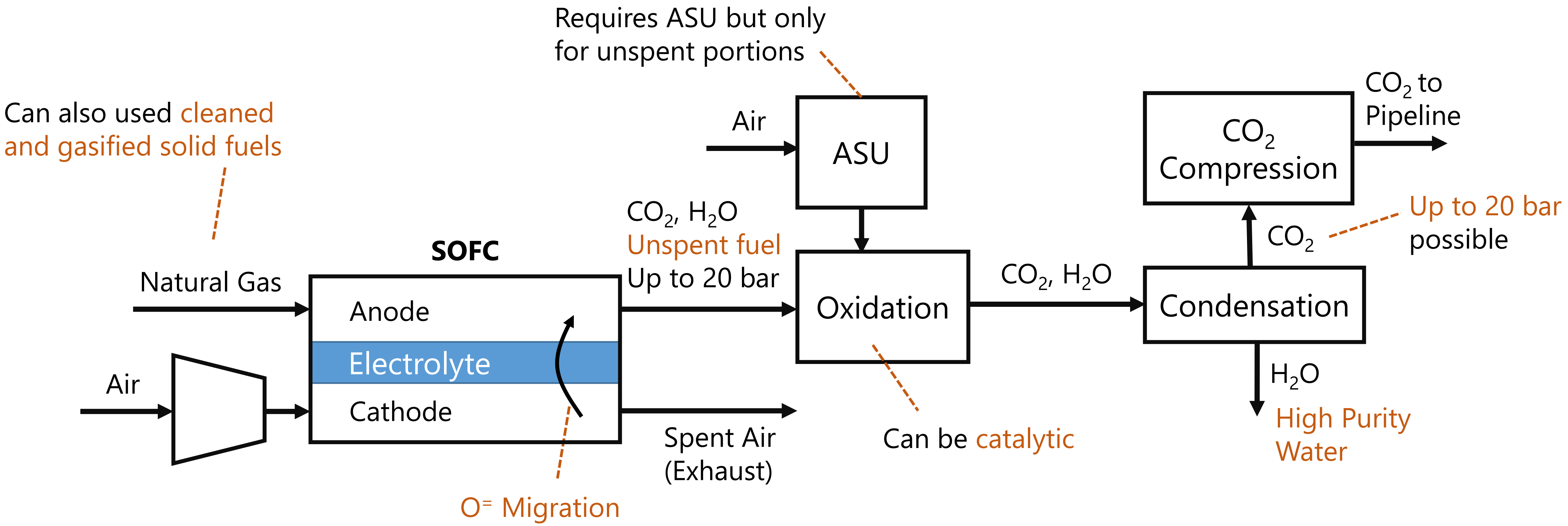


CO_2 Captured at High Pressure
(reduced compression costs)

Waste heat used for
Combined Cycle (steam)

Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

Solid Oxide Fuel Cell (SOFC) Process



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Recap

Type	Separation Problem	ASU Requirements	CO_2 Capture Pressure	Example Applications
Solvent-based Post-Combustion	CO_2/N_2	—	1 bar	Pulverized Coal, NGCC
Membrane-Based Post-Combustion	CO_2/N_2	—	Vacuum	Pulverized Coal, NGCC
Solid-Based Post-Combustion	CO_2/N_2	Low	1 bar	Pulverized Coal, NGCC
Solvent-Based Pre-Combustion	CO_2/H_2	Medium	10-50 bar	IGCC, pre-reforming NGCC
Membrane-Based Pre-Combustion	CO_2/H_2	Medium	Vacuum	IGCC, pre-reforming NGCC
Oxyfuels	CO_2/H_2O	High	1 bar	Gasified Coal/Nat Gas
Chemical Looping	CO_2/H_2O	—	10-50 bar	Gasified Coal/Nat Gas
Solid Oxide Fuel Cells	CO_2/H_2O	Low	1-20 bar	Gasified Coal/Nat Gas

Key Problems

- No systematic comparison between processes
- Everyone claims their own process is the best when compared against some other
- Wide variation in assumptions, strategies and ideas.

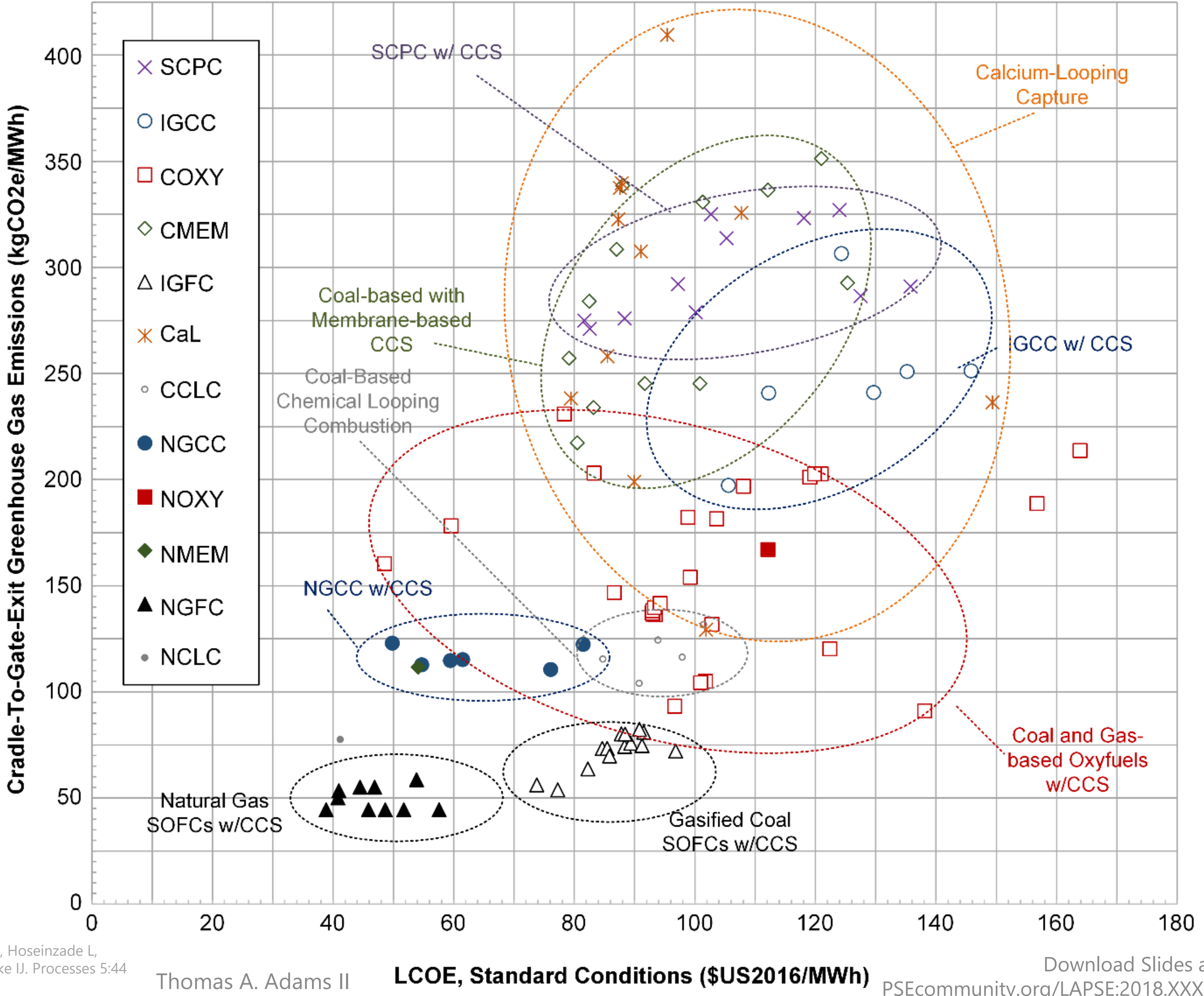
- Solution: Meta-Study of ~100 published data points on those 8 processes.
- Convert to a standard basis of comparison

Standards

- Size: 550 MW net, plant gate
  - Nonfuel costs scaled with power law method p=0.9
- Time & Place: 1Q2016 USA
  - Time: North American Plant Cost Index
  - Place: Purchasing Power Parity Index
- Fuel
  - US Bituminous Coal #6 2016 Avg Price
  - US Conventional Average Gas Mix 2016 Avg Price
- Captured CO_2 at plant gate
  - Pressure: >115 bar
  - Purity: >95 mol%
  - Capture Rate: 90-100%
- LCA: Cradle to Gate GHG
  - Consistent NOx production where neglected in original
  - Standardize cradle-to-plant-entrance life cycle impacts
- CCA: Cost of CO_2 Avoided
  - Same standard plant without CCS
  - SCPC and NGCC US baseline std's

Overall

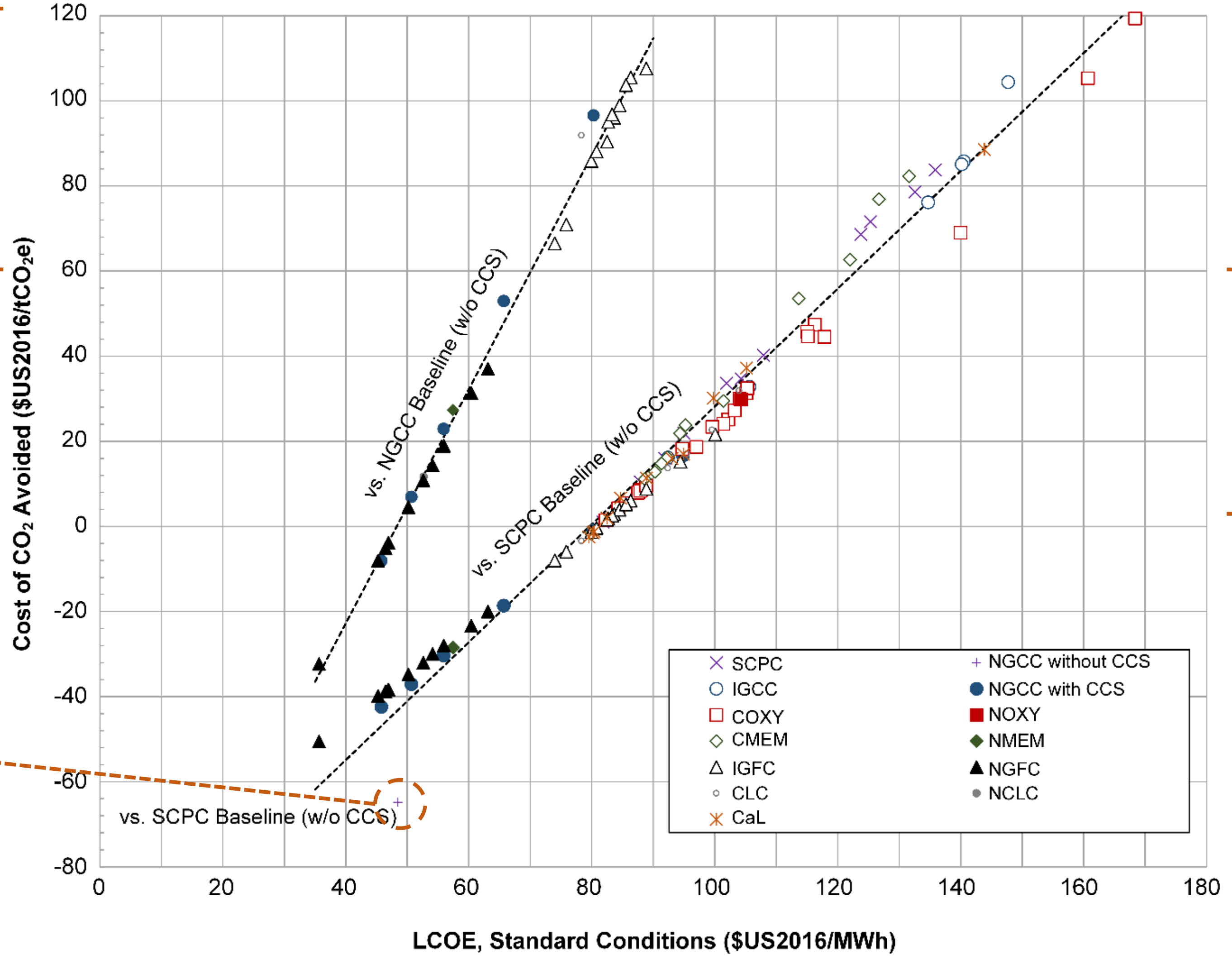
- SOFC clear winner for coal and gas
- NGCC w/CCS excellent near term solution
- No point in using membranes!
- Oxyfuels / CLC good coal intermediate step



Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

Cost of CO_2 Avoided

High CCA Means
Probably better to use NGCC w/o CCS



Sweet Spot:
The best of post-combustion solvent systems are the only mature technology to be competitive.
Rest requires CO2/H2O style power gen.

Negative CCA means:
Gas is so cheap in North America, there is no point to using coal at all.

Special Point:
Switching from coal to gas w/o CCS
No point to new coal at all in North America!

Source: Adams TA II, Hoseinzade L, Madabhushi P, Okeke IJ. Processes 5:44 (2017).

Conclusions

- No point to building new coal
  - (as long as gas prices stay low)
  - IGCC cannot compete with SCPC
  - Calcium Looping unlikely to either
- Membranes not so promising
  - Coal: Only fictional membranes could compete with solvents at the system level
  - Gas: At best competes with solvent directly, maturity / lifetime issues aside.
- SOFC is best way to use coal
  - (Could be better than gas in Asian context. Asian study needed!)

FINAL RECOMMENDATIONS

- Near Term: Use NGCC with CCS
  - Closest thing we have to commercial
- Long Term: Use SOFCs with CCS
  - Needs research and investment now
  - Best fossil fuel approach possible
  - Translates well in foreign situations