Lecture # 20

CO_2 CAPTURE and STORAGE
Mostly NG but with some Coal

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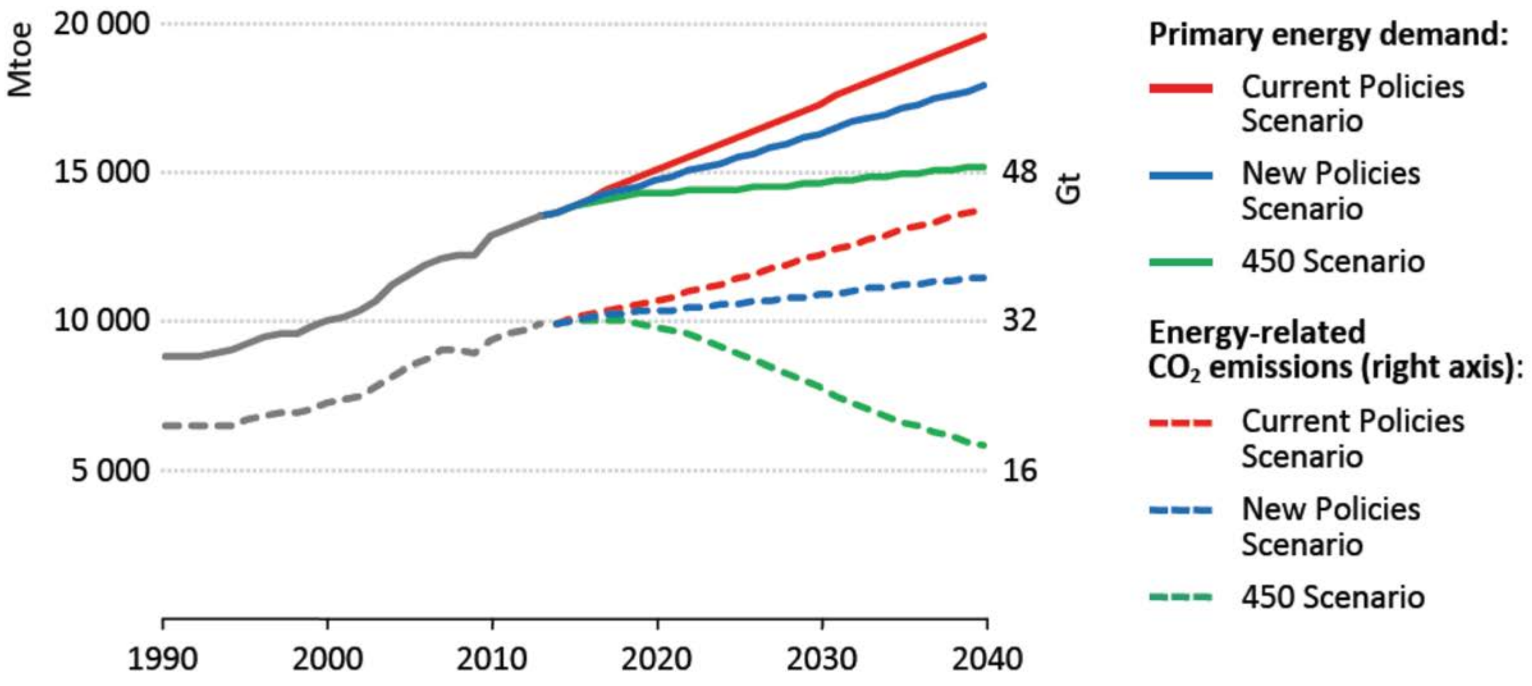
April 15, 2020

CO_2 reduction and improved efficiency
CO_2 Capture Schemes
CO_2 Capture Enabled Cycles
CO_2 Sequestration

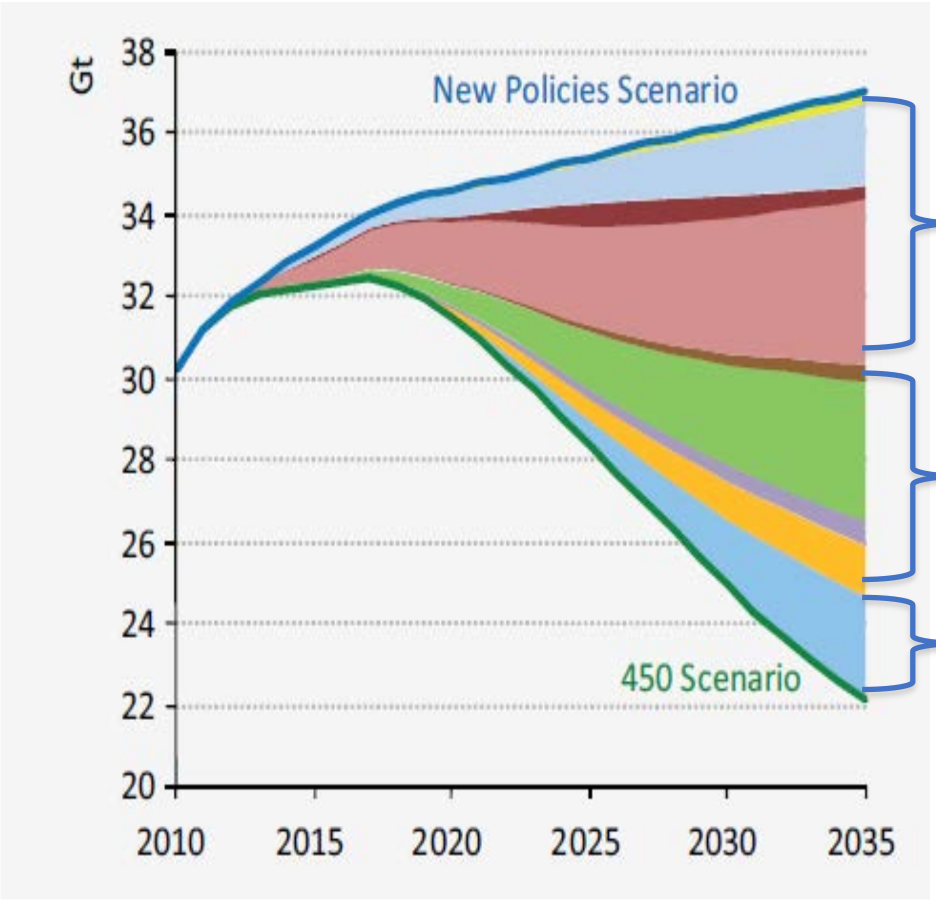
COP21



- New policies scenario: takes into account the policies and implementing measures affecting energy markets that had been adopted as of mid-2015 (as well as the energy-related components of climate pledges in the run-up to COP21)
- 450 scenario: depicts a pathway to the 2° C climate goal that can be achieved by fostering technologies that are close to becoming available at commercial scale.

Source: IEA world energy outlook 2015, P55

Energy-related CO_2 emission's reduction



1. Efficiency improvement

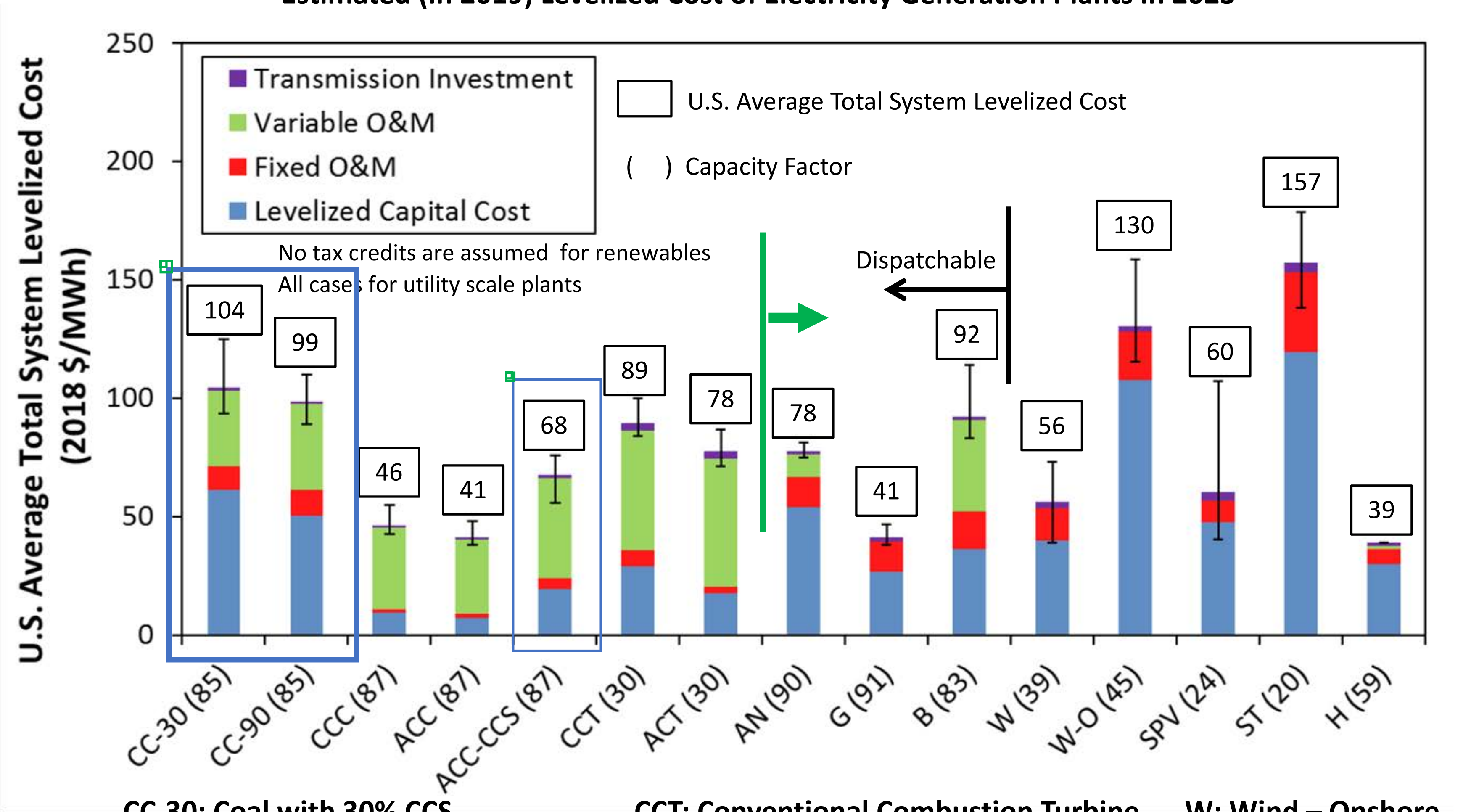
2. New and clean energy

3. CCS

CO_2 abatement	2020	2035
Activity	2%	2%
End-use efficiency	18%	13%
Power plant efficiency	3%	2%
Electricity savings	50%	27%
Fuel and technology switching in end-uses	2%	3%
Renewables	15%	23%
Biofuels	2%	4%
Nuclear	5%	8%
CCS	4%	17%
Total (Gt CO_2)	3.1	15.0

[1] IEA, *World Energy Outlook 2012*

Estimated (in 2019) Levelized Cost of Electricity Generation Plants in 2023



CC-30: Coal with 30% CCS
CC-90: Coal with 90% CCS
CCC: Conventional Combined Cycle
ACC: Advanced Combined Cycle
ACC-CCS: Advanced CC with CCS

CCT: Conventional Combustion Turbine
ACT: Advanced Combustion Turbine
AN: Advanced Nuclear
G: Geothermal
B: Biomass

W: Wind – Onshore
W-O: Wind – Offshore
SPV: Solar PV
ST: Solar Thermal
H: Hydroelectric

Image courtesy of U.S. Energy Information Administration.

Source: U.S. Energy Information Administration, Annual Energy Outlook 2019, Feb 2019.

Proposed CO_2 emissions Regulations on Coal and NG

Coal plant at 35% efficiency, 1 mole CO_2/mole of coal. Take 32 MJ/kg as coal heating value, plant produces (0.35 x 32 x 12 / 44) = 3.05 MJe/kgCO_2
or ~ 1,180 kg CO_2/MWhe. (proposed 1100 lb/MWhe)

NG plant at 55% efficiency, 1 mole CO_2/mole CH_4, with 45 MJ/kg NG heating value, generates (0.55 x 45 x 16 / 44) = 9 MJe/kgCO_2
or ~ 400 kgCO_2/MWhe. (proposed 1000 lb/MWhe)

Coal can not meet these without CCS ..

Petra Nova!

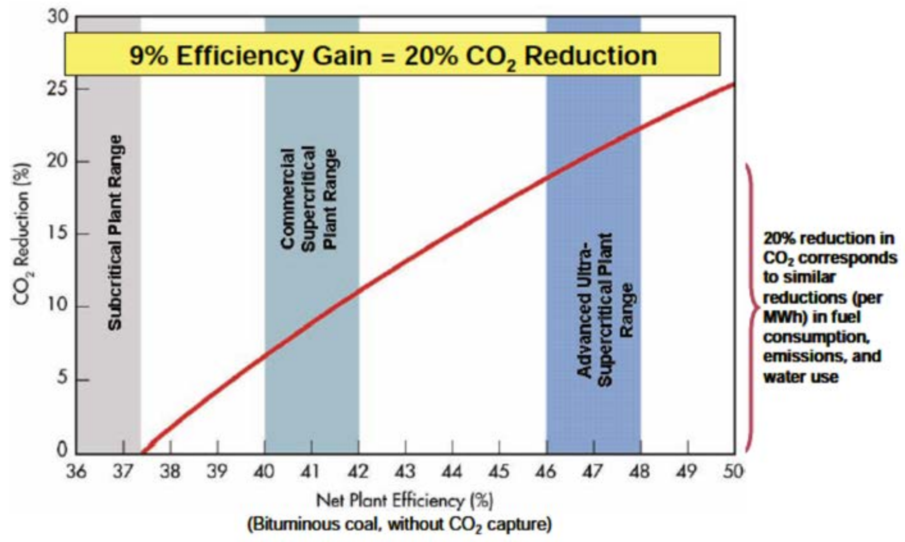


Figure 1-4
High-Efficiency Advanced Pulverized Coal Power Plants Substantially Reduce Fuel Costs and CO_2 and Other Emissions[8]

Efficiency improvements reduce CO_2 emissions, with limits

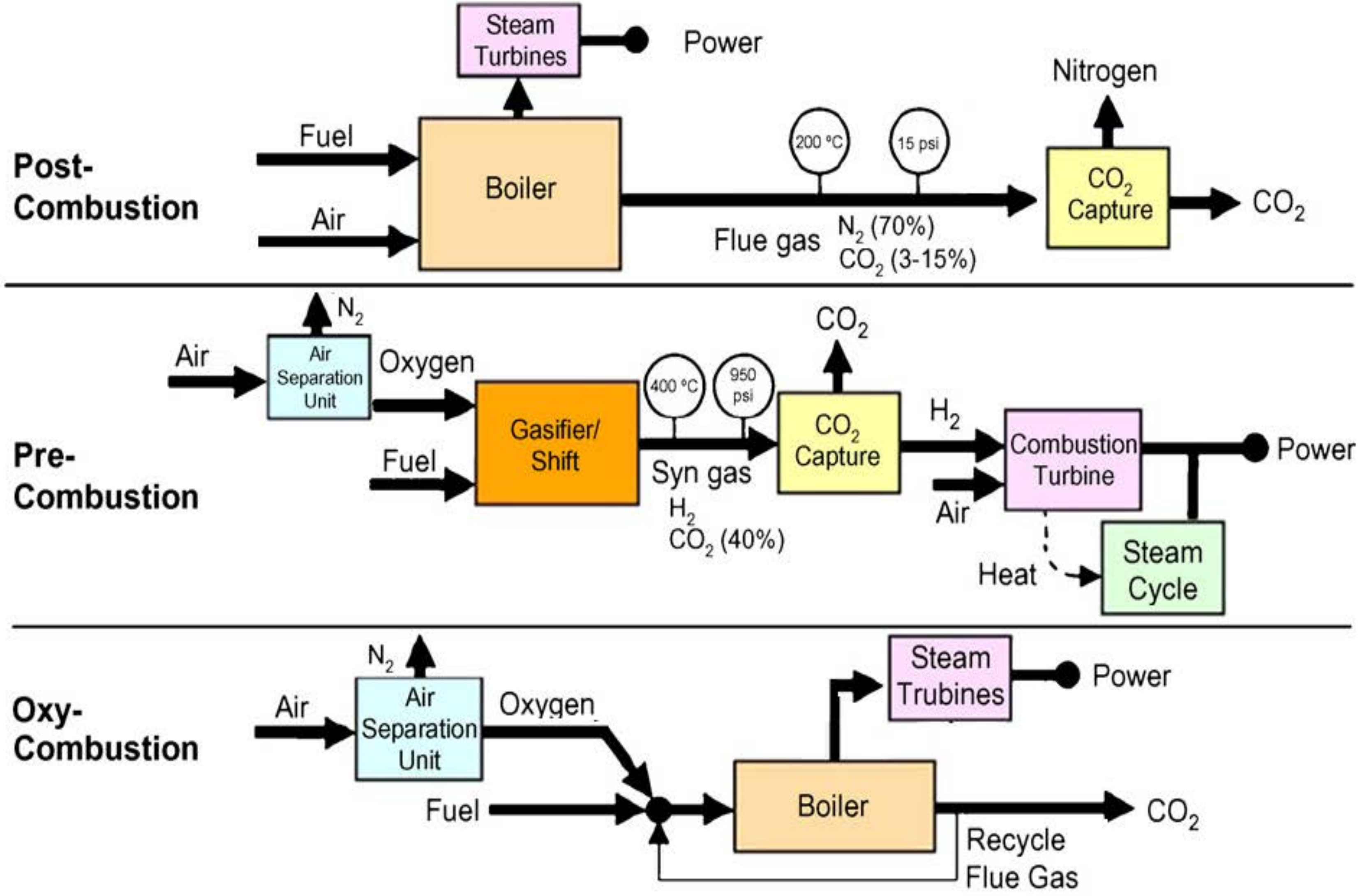
Advanced Coal Power Systems with CO2 Capture …, EPRI Report, 1016877, Sept 2008

Approaches for CO_2 capture
(shown for coal used in steam cycle plants)

Separate CO_2 from CO_2+N_2

Separate CO_2 from CO_2+H_2

Separate O_2 from O_2+N_2



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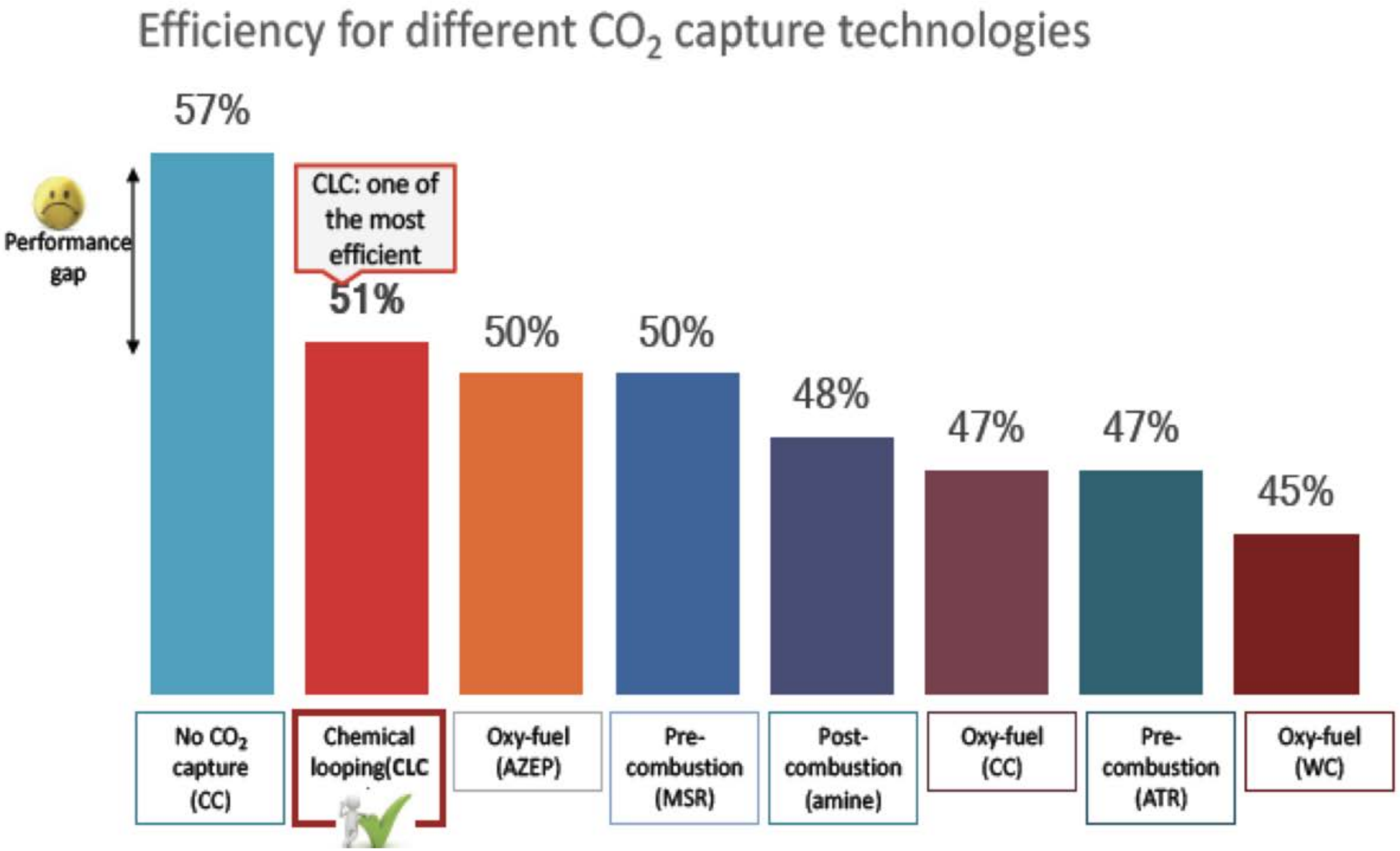
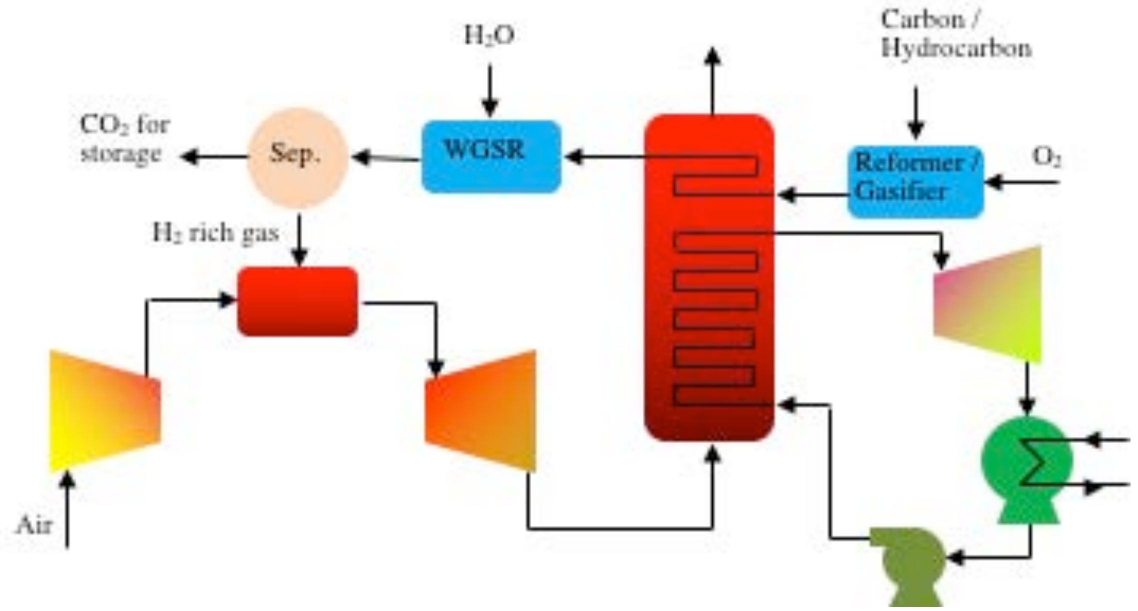
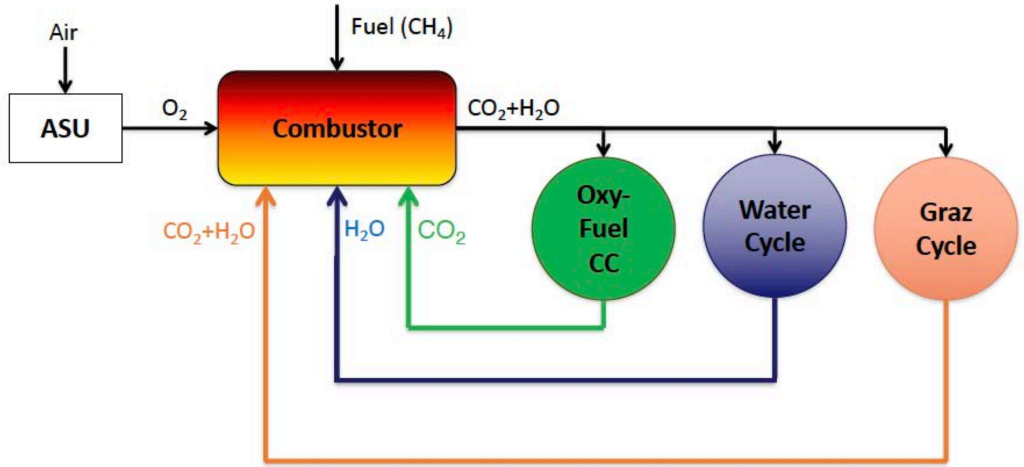
System level analysis for NG (ASPEN BASED ANALYSIS)



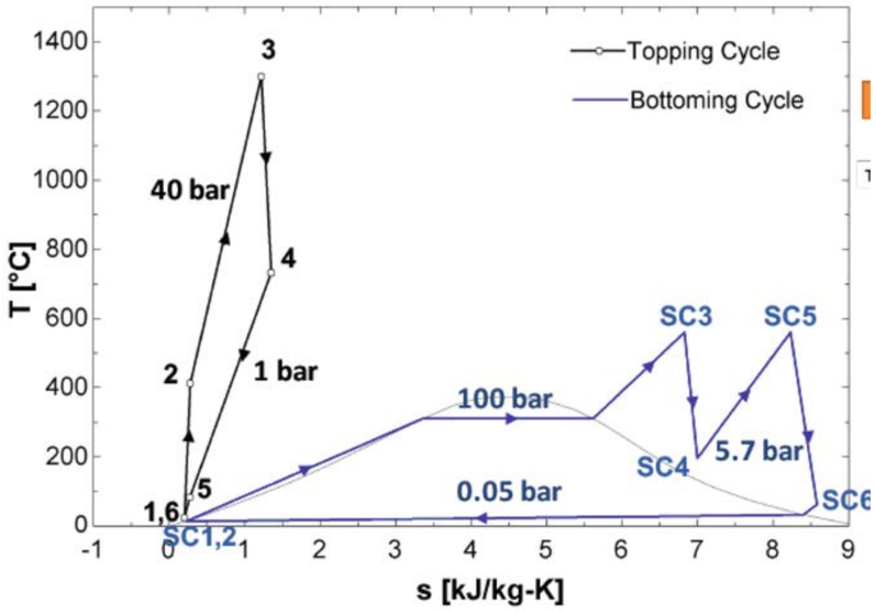
NG OXY-COMBUSTION CAPTURE SCHEME





Oxyfuel combustion. An air separation unit is used. Estimated efficiency penalty for syngas and NG are 5-12% points and 6-9% points, respectively. This amounts to increasing the fuel use by 24-27 % and 22-28 %. Broken line for a PC plant.

NG Oxy-combustion Combined cycle



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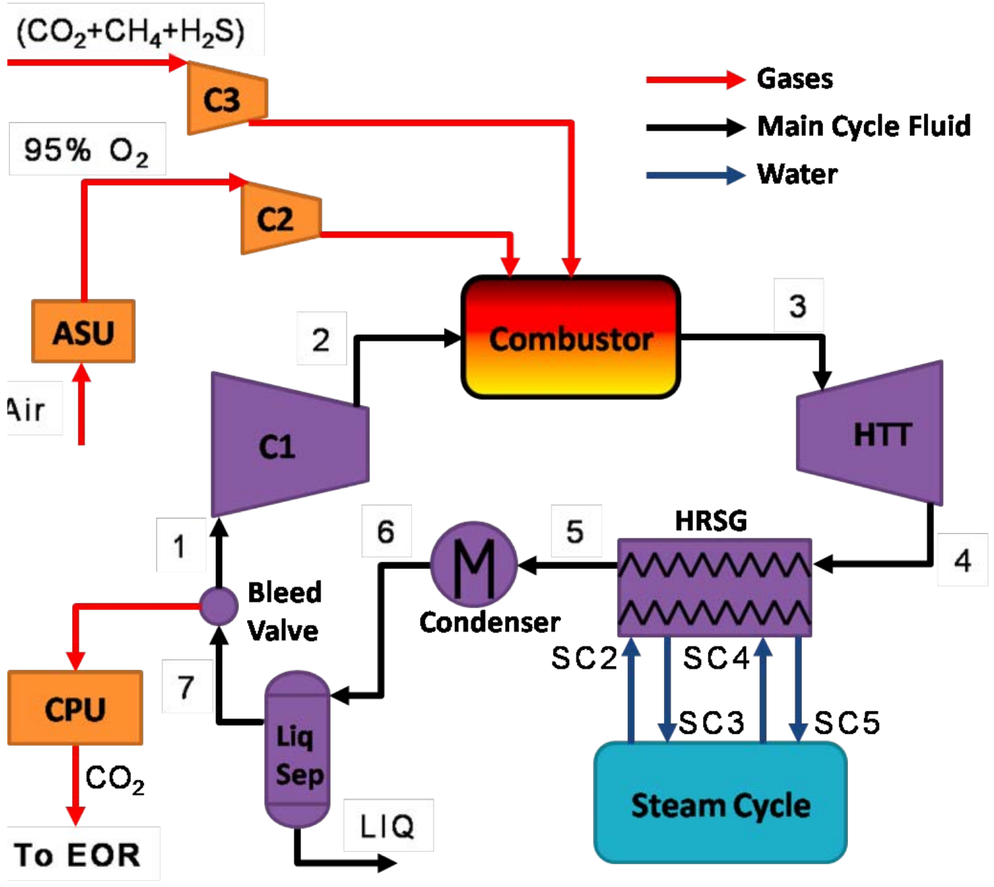

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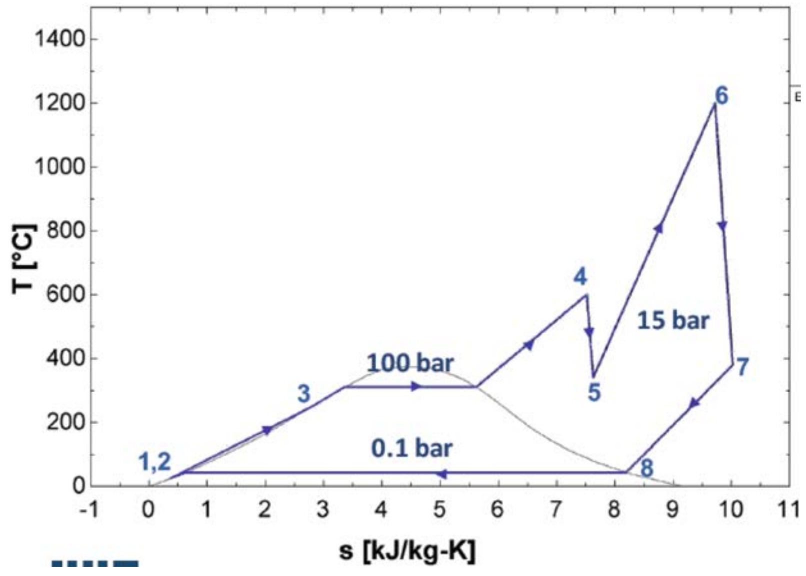
- Working Fluid: Mainly CO_2 (78%)
- CO_2 is recycled back to the combustor in order to moderate temperatures (93%)
- Net Efficiency: **45.9%**
- 100 MW_e SCOC-CC demonstration plant, partnership of Siemens , Nebb Engineering, SINTEF & Lund University.

Chakroun, N. W. and Ghoniem, A.F., *Int. J. Greenhouse Control*, 36 (2015) 1-12.
Chakroun, N.W. and Ghoniem, A.F., *Int. J. Greenhouse Control*, 41 (2015) 163-173.

NG Oxy-Combustion Water cycle



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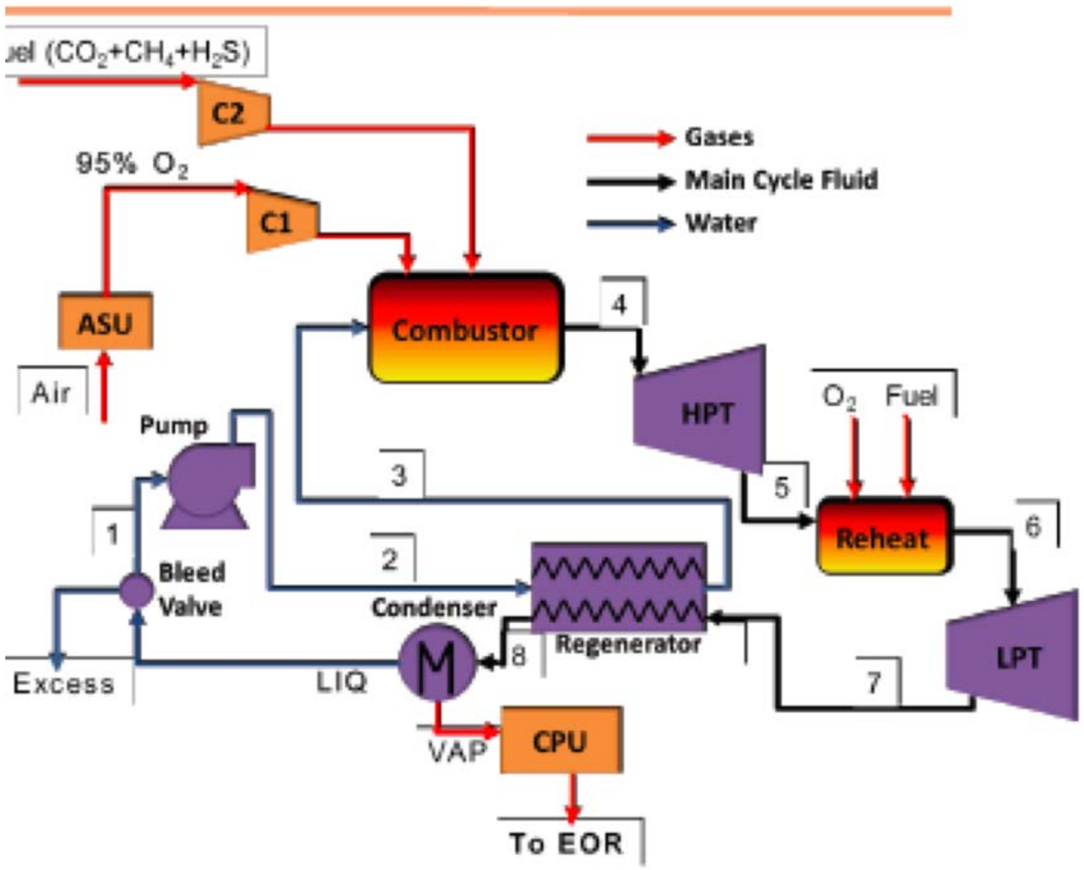

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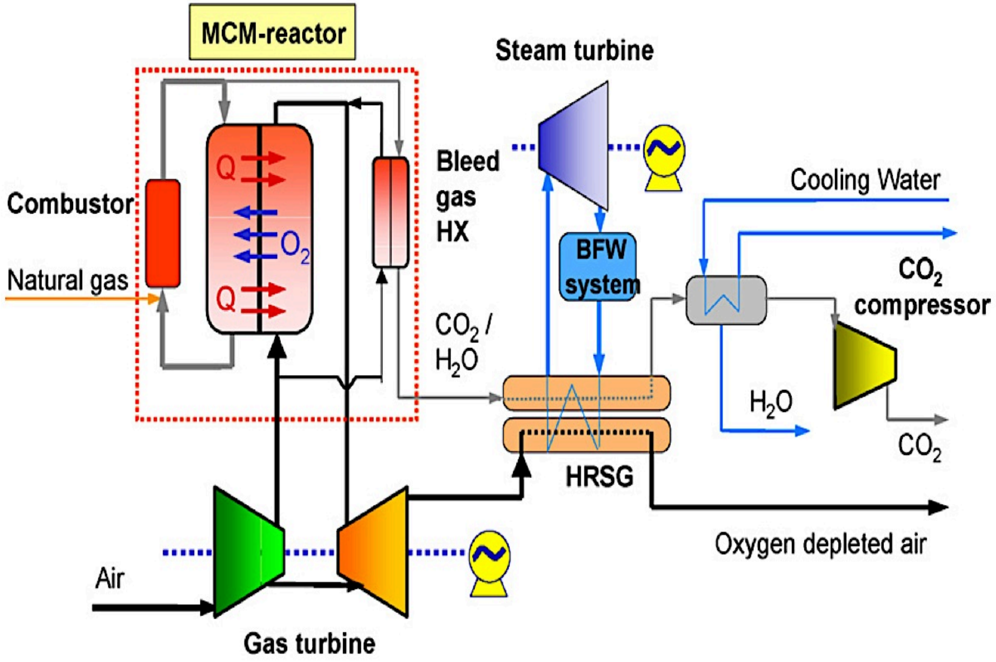
- Working Fluid: Mainly H_2O (94%)
- **Liquid** water is recycled to the combustor to moderate temperatures (83%)
- Net Efficiency: **41.4%**
- This cycle has been implemented since 2005 by Clean Energy Systems (CES) in a 5MW test plant in Kimberlina, CA (world's first zero emission power plant)

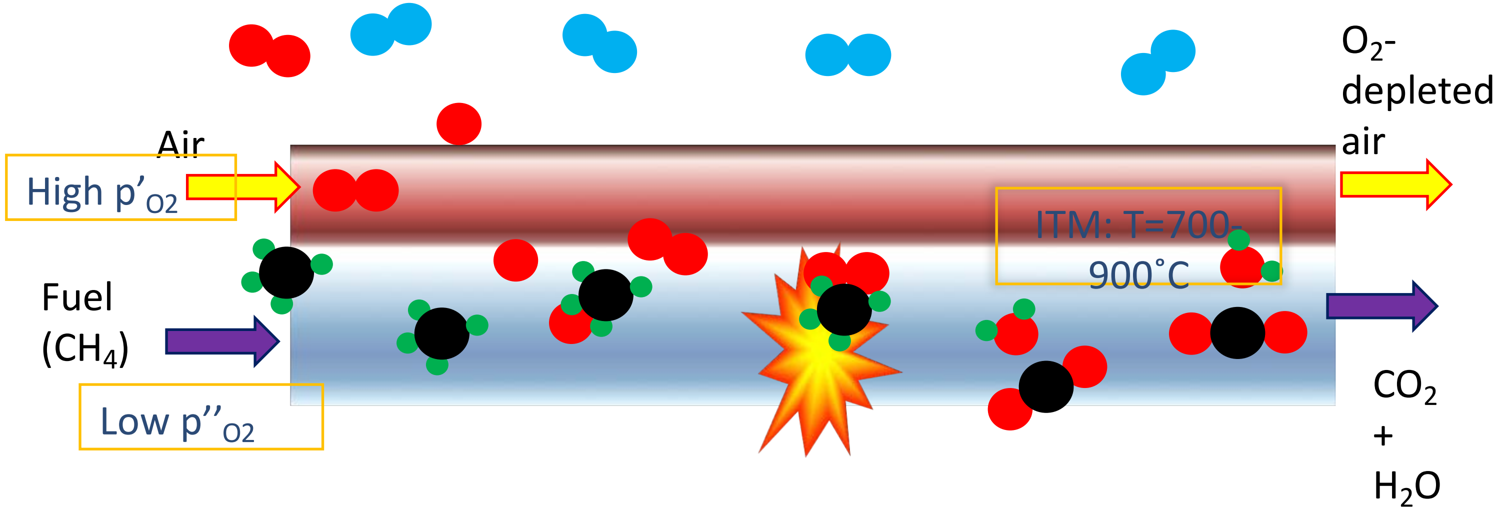
Oxygen Penalty

		SCOCC-CC	Water Cycle	Graz Cycle
Working Fluid Composition (% vol.)		13%	94%	
Operating P (bar)			100	
Efficiency Ranges			40-49%	
Cycle Power Breakdown (% heat input)	Turbine		62%	
	Compressors, Pumps		2.2%	
	ASU		9.1%	
	CO_2 Compression		6.1%	
Turbine Technologies		➢ New designs of current gas turbine machinery needed, due to unusual working fluid (CO_2 &H_2O) and high T's	➢ Steam turbine technologies available for HPT and LPT, from CES, for this cycle up to certain temperatures	➢ Needs development of advanced turbine technology, for HTT, due to unusual working fluid (H_2O & CO_2) & high T's
Cycle Implementation		➢ Cycle not been implemented in real life but layout of cycle is similar to CC's so modifications may be practical ➢ A new oxy-fuel power plant w/ supercritical CO_2 cycle is being developed by NET Power and a test plant should be completed by 2015	➢ Cycle has been built and implemented in real-life by CES at the Kimberlina Power Plant	➢ Cycle not been implemented yet b/c of complexity & unusual working fluid makes it economically unviable (so far) & needs new turbo-machinery design

MIEC MEMBRANES (ITM) FOR GAS SEPARATION AND FOR OXY-COMBUSTION

DOE's cycle, non reactive MSU





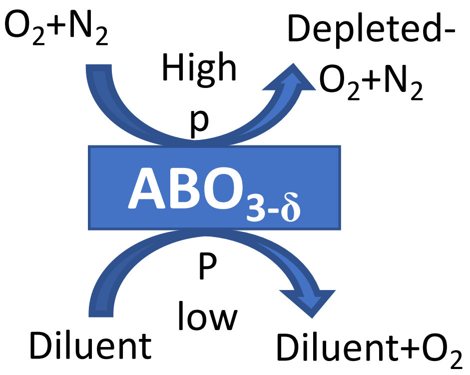
$$J_{O_2} = \frac{\frac{k_r}{k_f}\left(P_{O_2,sweep}^{-0.5} - P_{O_2,feed}^{-0.5}\right)}{R_{interface}^{feed} + R_{bulk} + R_{interface}^{sweep}}$$

- At intermediate T and high Δp_{O2}, ITMs produces high purity O_2 at reduced energy penalty
- Use <u>reactive sweep gas</u> to maintain low p''_{O2} and perform air separation and oxy-combustion in same unt

Hong, J., Kirchen, P. and Ghoniem, JMS, 2012, 407, Combust Flame 2013, 160.
Kirchen, Hong and Ghoniem, PCI, 2013, 34, 3463.

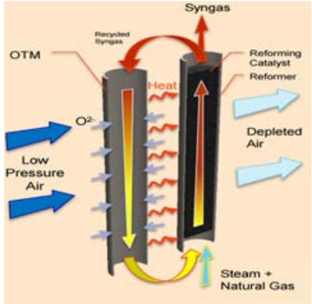
ITM based ASU (MSRU)/Syngas Production

- Large penalty in ASU technology
  - Cryogenic: 0.36 $kWh_{el}/m^3\ STP\ O_2$
  - Small PSA ~ 0.9 $kWh_{el}/m^3\ STP\ O_2$
- Ion Transport Membranes (ITM):
  - ❑Oxygen purity: near 100%
  - ❑O_2 separation/reaction combined in a single unit
  - ❑Energy ~ 0.2 $kWh_{el}/m^3\ STP\ O_2$ (Fraunhofer IKTS)



ITM stacks by Air Products

In our Labs, we have fabricating some of the best performing pervoskite membranes (LCF, LSCF, BZF, LSCo, LSCrCo, including biphasic and bilayer, novel morphology, etc. for different applications)

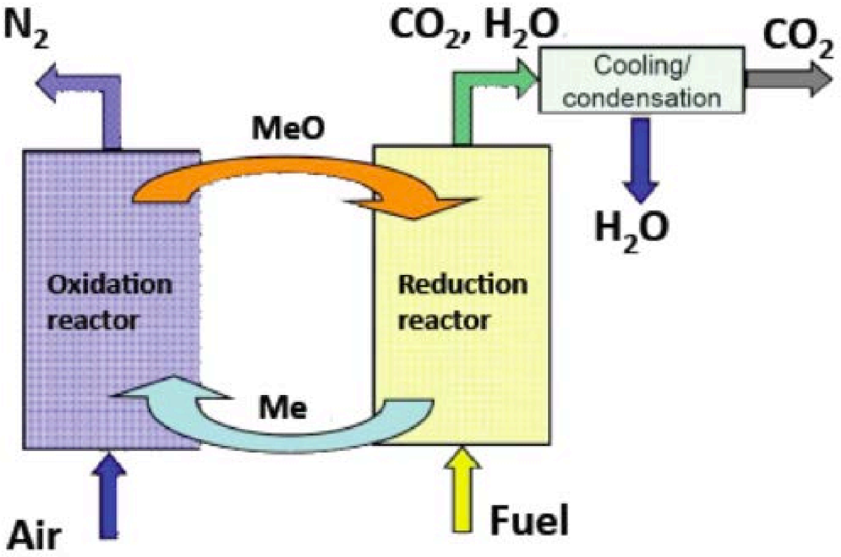


OTM Syngas module by Praxair

Fraunhofer Institute, $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$, uses tubular membranes, heat recovery to achieve 0.14 kWh/kg_O_2

Hunt, Dimitrakopoulos,. Ghoniem, J Membrane Science 489 (2015) 248–257.
Hunt, Dimitrakopoulos,. Kirchen, Ghoniem, J Membrane Science 468 (2014) 62–72

Chemical Looping for Oxy-combustion

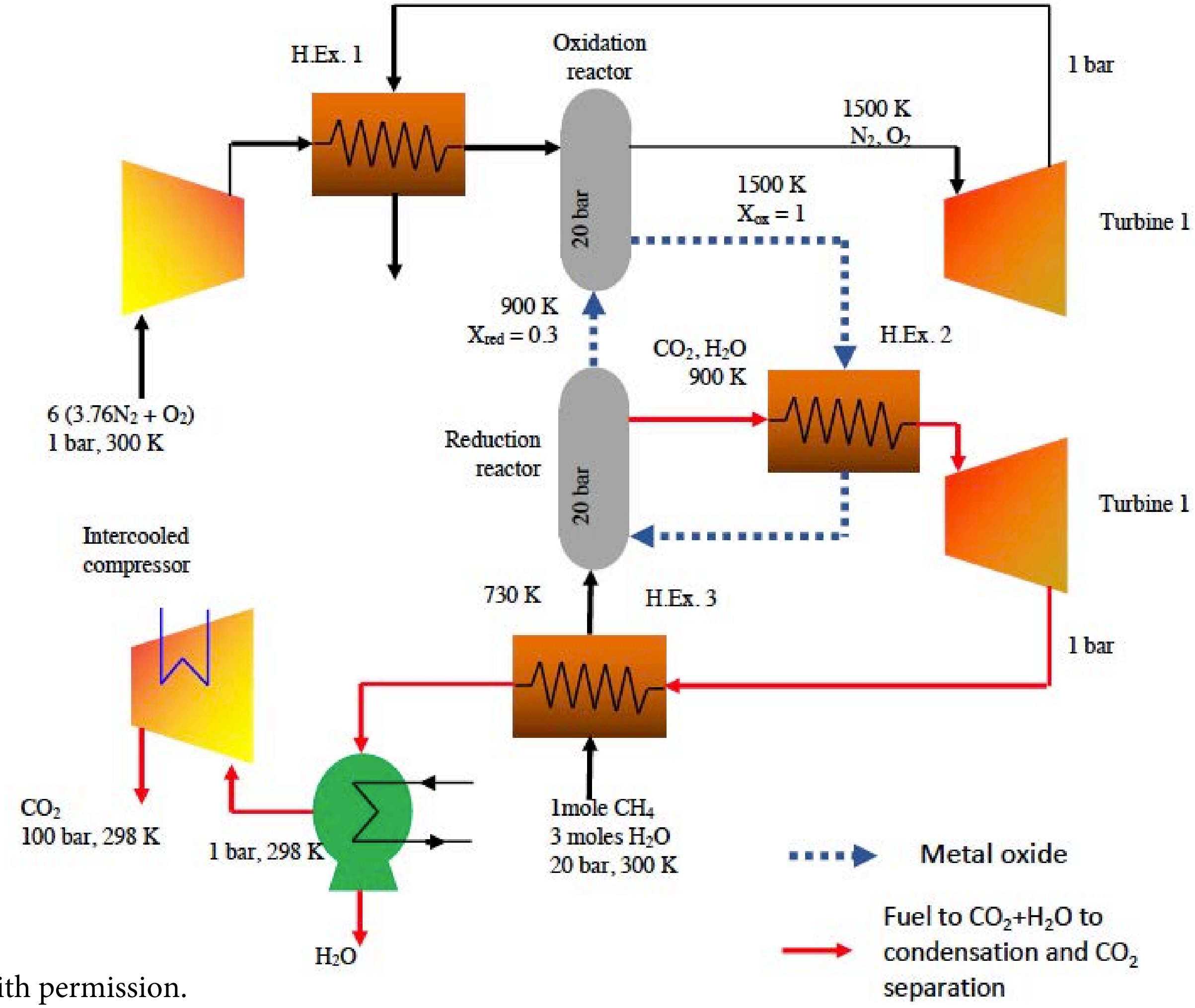


Reduction:

$$4MeO + CH_4 \rightarrow 4Me + CO_2 + 2H_2O$$

Oxidation:

$$Me + 1/2O_2 \rightarrow MeO$$



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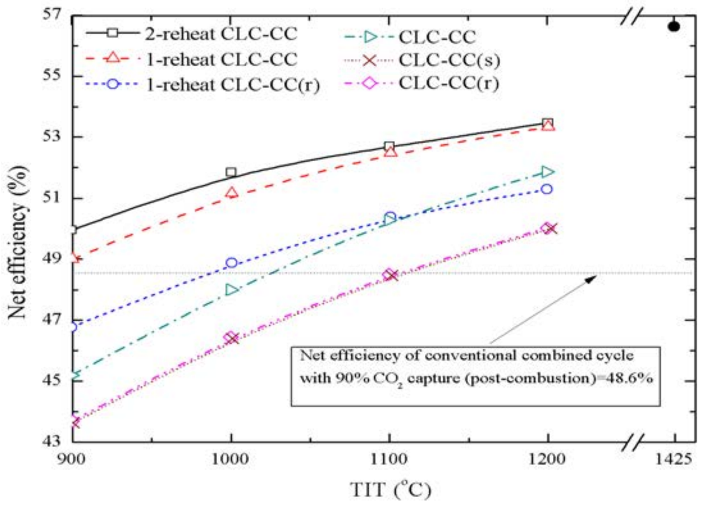
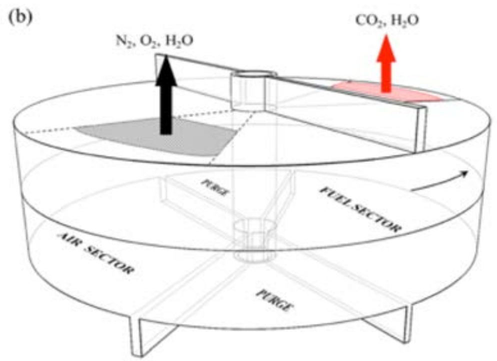
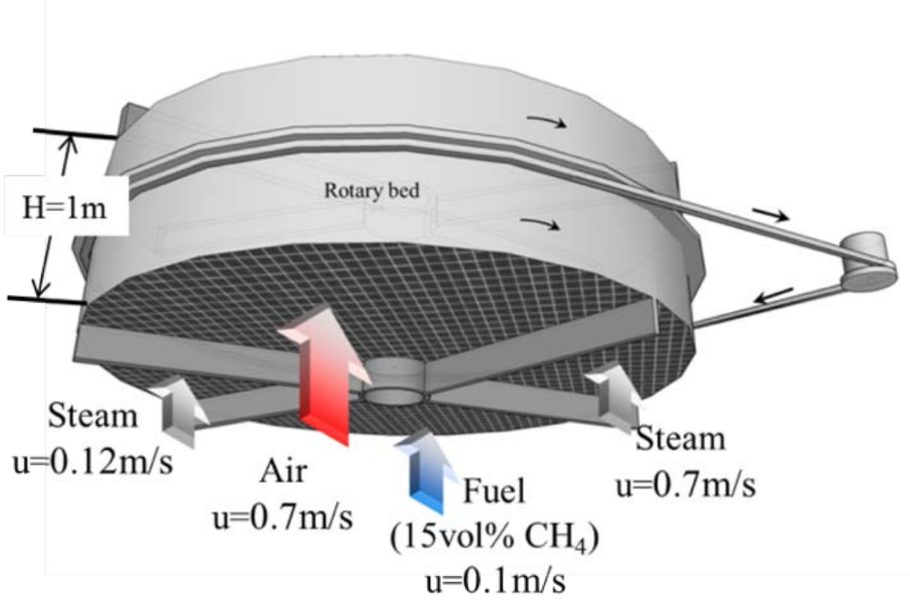
CHEMICAL LOOPING COMBUSTION USING OXYGEN METAL CARRIERS IN REDOX REACTIONS AND AN ISOTHERMAL ROTARY REACTOR



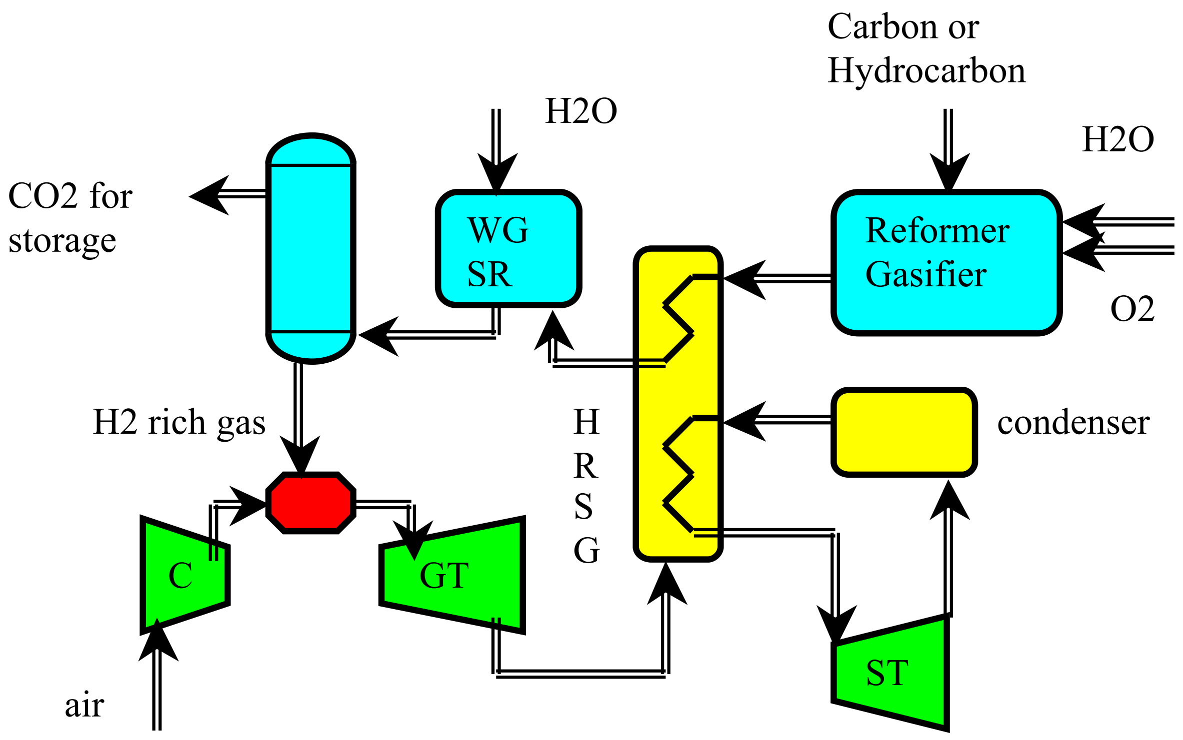
Comparison of multi-stage combined cycle designs. The solid circle on the top right-hand corner is for the combined cycle without CCS. CLC-CC with no reheat, 1 or 2 reheat. CLC-CC(r) is the CLC combined cycle with FR flue gas recuperation (no reheat and a single reheat); CLC-CC(s) is the CLC combined cycle with FR flue gas powering a bottom steam cycle. The TIT plays a very important role in determining the efficiency





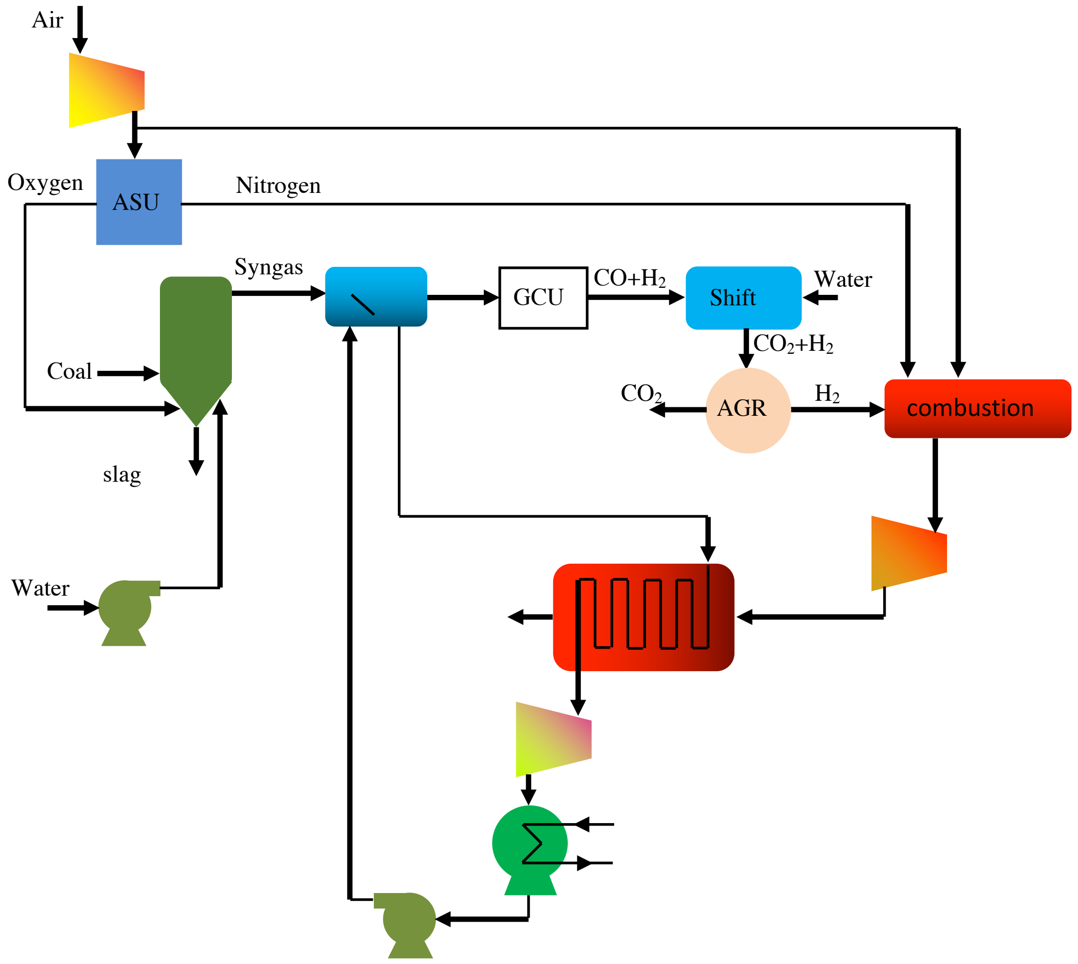
Zhao, Z.L., Chen, T.J., and Ghoniem, A.F., Energy & Fuels, 2013.

PRE-COMBUSTION CO_2 CAPTURE, NGCC or IGCC

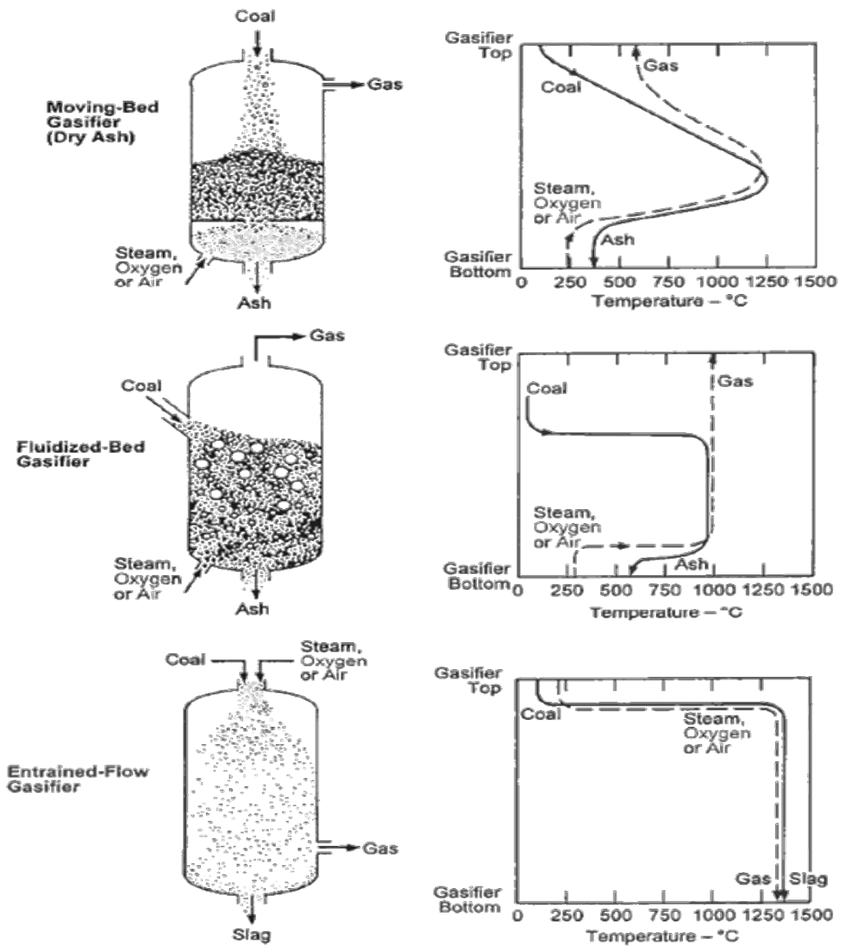


CO2 pre-combustion capture. Reformed fuel is shifted and CO_2. Estimated efficiency penalty for syngas and NG are 7-13% points and 4-11% points, respectively. Given current efficiencies of coal and NG plants, this amounts to increasing the fuel use by 14-25 % and 16-28 %, respectively.

Integrated Gasification Combined Cycle Coal Plants



Gasifier Types and the exit gas temperature



Fixed Bed
30-60 minutes

Fluidized Bed
1-10 minute

Entrained flow
0.1 s
Most common in IGCC

GCU: Gas Cleanup Unit
AGR: Acid Gas Removal to separate CO2

TEMPA ELECTRIC POLK IGCC POWER PLANT

250 MW, 35.3 % efficiency, 2500 TPD coal,
200 TPD sulfuric acid, built 1996, $600M

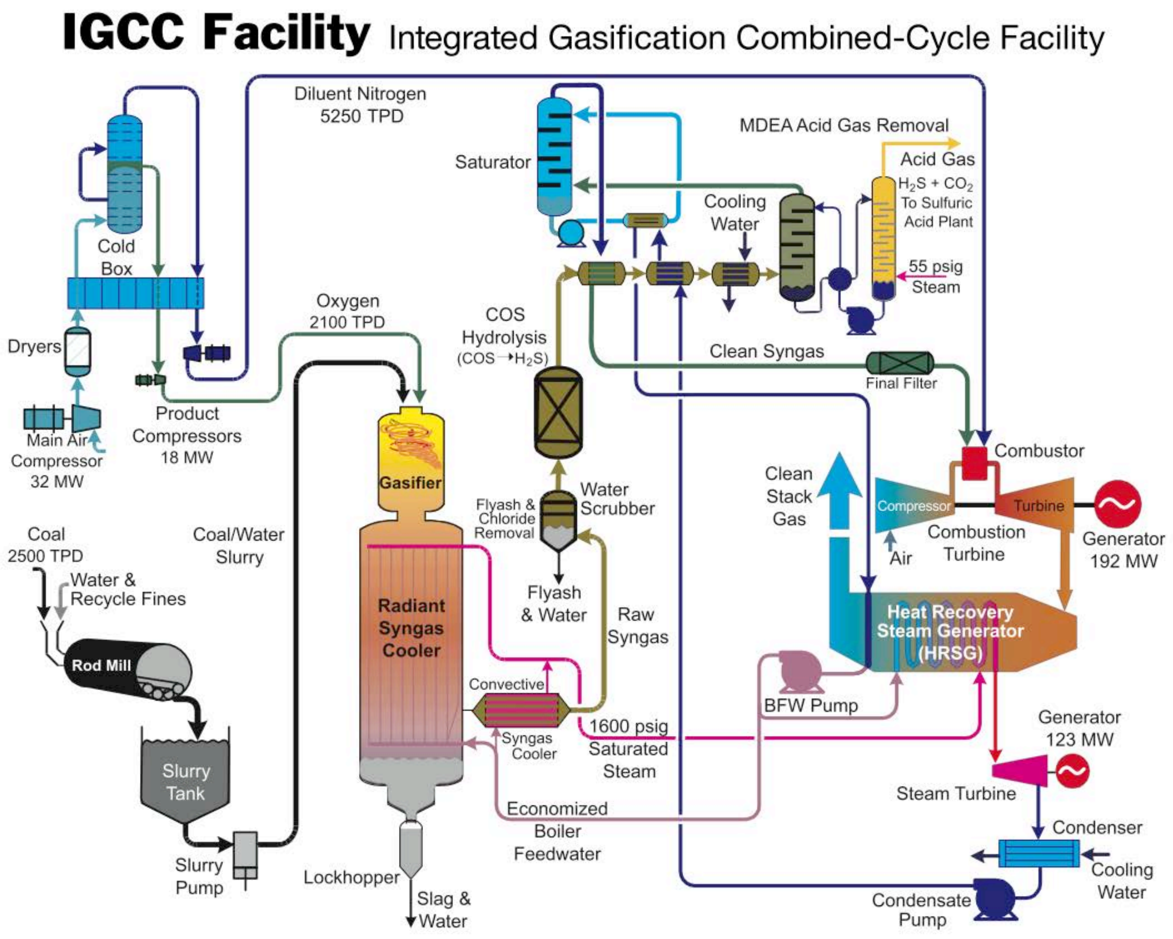


Image courtesy of DOE.

Why add oxygen in gasification ???

steam gasification: $C + H_2O \rightarrow CO + H_2$

is endothermic $\Delta\hat{h}_r = 118$ MJ/kgmol C (1)

partial oxidation: $C + \frac{1}{2}O_2 \rightarrow CO$

is exothermic $\Delta\hat{h}_r = -123$ MJ/kgmol C (2)

Add (1)+(2) makes the gasification nearly autothermal:

$$2C + \frac{1}{2}O_2 + H_2O \rightarrow 2CO + H_2$$

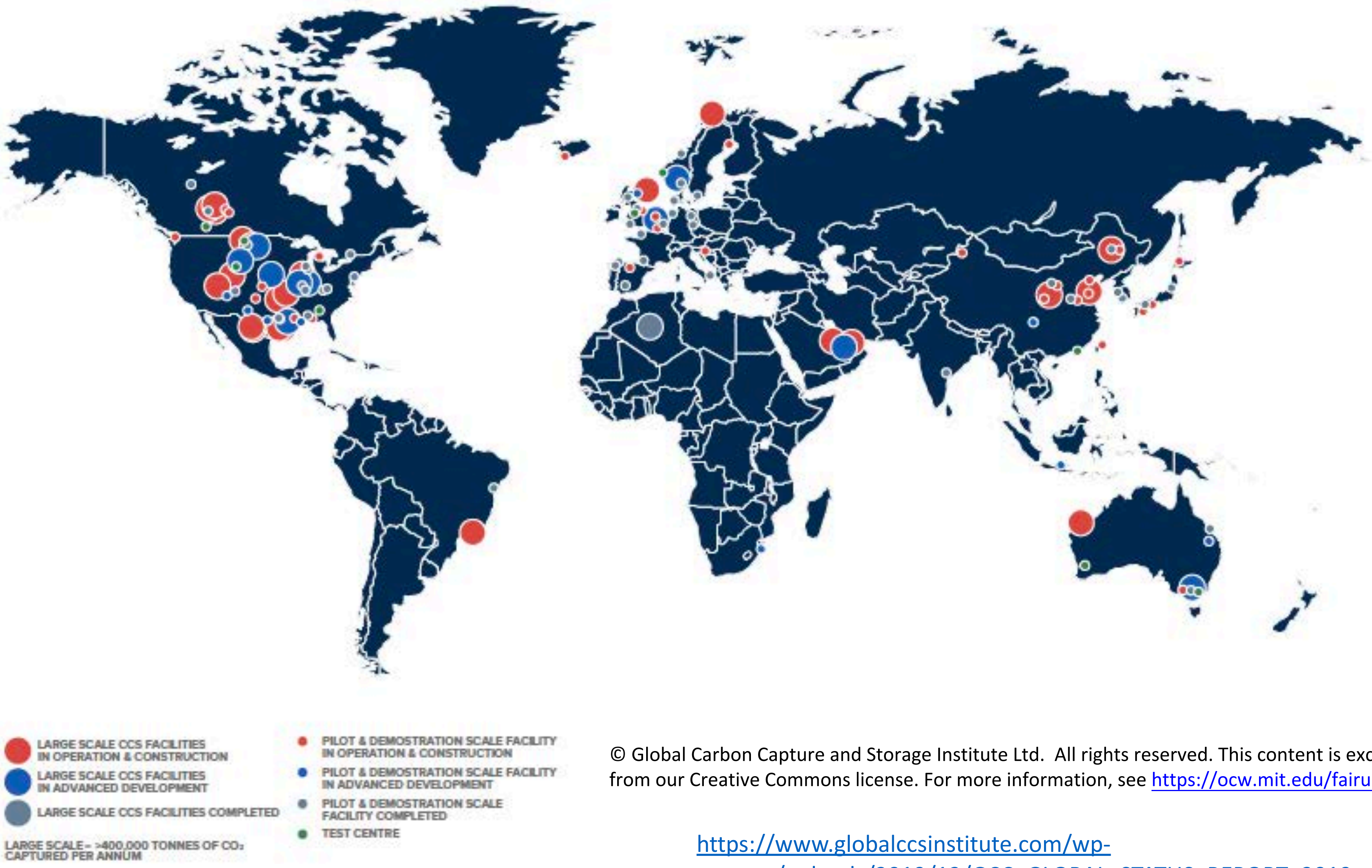
$\Delta\hat{h}_r = -5$ MJ/2 kgmol C

$\Rightarrow$ cold gas efficiency:

chemical energy in syngas/chemical energy in coal is ~100%

(practical values are lower becasue of heat losses)

GLOBAL CCS FACILITIES UPDATE



https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf

FIGURE 2 CURRENT CCS FACILITIES AROUND THE WORLD[1]

LARGE SCALE CCS FACILITIES IN OPERATION

NO.	TITLE	STATUS	COUNTRY	OPERATION DATE	INDUSTRY	CAPTURE CAPACITY (Mtpa)	CAPTURE TYPE	STORAGE TYPE
1	GORGON CARBON DIOXIDE INJECTION	Operating	Australia	2019	Natural Gas Processing	3.4 - 4.0	Industrial separation	Dedicated Geological Storage
2	JILIN OIL FIELD CO_2-EOR	Operating	China	2018	Natural Gas Processing	0.6	Industrial separation	Enhanced Oil Recovery
3	ILLINOIS INDUSTRIAL CARBON CAPTURE AND STORAGE	Operating	United States of America	2017	Ethanol Production	1	Industrial separation	Dedicated Geological Storage
4	PETRA NOVA CARBON CAPTURE	Operating	United States of America	2017	Power Generation	1.4	Post-combustion capture	Enhanced Oil Recovery
5	ABU DHABI CCS (PHASE 1 BEING EMIRATES STEEL INDUSTRIES)	Operating	United Arab Emirates	2016	Iron and Steel Production	0.8	Industrial separation	Enhanced Oil Recovery
6	QUEST	Operating	Canada	2015	Hydrogen Production for Oil Refining	1	Industrial separation	Dedicated Geological Storage
7	UTHMANIYAH CO_2-EOR DEMONSTRATION	Operating	Saudi Arabia	2015	Natural Gas Processing	0.8	Industrial separation	Enhanced Oil Recovery
8	BOUNDARY DAM CCS	Operating	Canada	2014	Power Generation	1	Post-combustion capture	Enhanced Oil Recovery
9	PETROBRAS SANTOS BASIN PRE-SALT OIL FIELD CCS	Operating	Brazil	2013	Natural Gas Processing	3	Industrial separation	Enhanced Oil Recovery
10	COFFEYVILLE GASIFICATION PLANT	Operating	United States of America	2013	Fertiliser Production	1	Industrial separation	Enhanced Oil Recovery
11	AIR PRODUCTS STEAM METHANE REFORMER	Operating	United States of America	2013	Hydrogen Production for Oil Refining	1	Industrial separation	Enhanced Oil Recovery
12	LOST CABIN GAS PLANT	Operating	United States of America	2013	Natural Gas Processing	0.9	Industrial separation	Enhanced Oil Recovery
13	CENTURY PLANT	Operating	United States of America	2010	Natural Gas Processing	8.4	Industrial separation	Enhanced Oil Recovery
14	SNØHVIT CO_2 STORAGE	Operating	Norway	2008	Natural Gas Processing	0.7	Industrial separation	Dedicated Geological Storage
15	GREAT PLAINS SYNFUELS PLANT AND WEYBURN-MIDALE	Operating	United States of America	2000	Synthetic Natural Gas	3	Industrial separation	Enhanced Oil Recovery
16	SLEIPNER CO_2 STORAGE	Operating	Norway	1996	Natural Gas Processing	1	Industrial separation	Dedicated Geological Storage
17	SHUTE CREEK GAS PROCESSING PLANT	Operating	United States of America	1986	Natural Gas Processing	7	Industrial separation	Enhanced Oil Recovery
18	ENID FERTILISER	Operating	United States of America	1982	Fertiliser Production	0.7	Industrial separation	Enhanced Oil Recovery
19	TERRELL NATURAL GAS PROCESSING PLANT (FORMERLY VAL VERDE NATURAL GAS PLANTS)	Operating	United States of America	1972	Natural Gas Processing	0.4 - 0.5	Industrial separation	Enhanced Oil Recovery

LARGE SCALE CCS FACILITIES IN CONSTRUCTION, ADVANCED AND EARLY DEVELOPMENT

NO.	TITLE	STATUS	COUNTRY	OPERATION DATE	INDUSTRY	CAPTURE CAPACITY (Mtpa)	CAPTURE TYPE	STORAGE TYPE
20	ALBERTA CARBON TRUNK LINE ("ACTL") WITH NORTH WEST REDWATER PARTNERSHIP'S STURGEON REFINERY CO_2 STREAM	In Construction	Canada	2020	Hydrogen Production for Oil Refining	1.2 - 1.4	Industrial separation	Enhanced Oil Recovery
21	ALBERTA CARBON TRUNK LINE ("ACTL") WITH AGRIUM CO_2 STREAM	In Construction	Canada	2020	Fertiliser Production	0.3 - 0.6	Industrial separation	Enhanced Oil Recovery
22	SINOPEC QILU PETROCHEMICAL CCS	In Construction	China	2020	Chemical Production	0.40	Industrial separation	Enhanced Oil Recovery
23	YANCHANG INTEGRATED CARBON CAPTURE AND STORAGE DEMONSTRATION	In Construction	China	2020 - 2021	Chemical Production	0.41	Industrial separation	Enhanced Oil Recovery
24	WABASH CO_2 SEQUESTRATION	Advanced development	United States of America	2022	Fertiliser production	1.5-1.75	Industrial separation	Dedicated Geological Storage
25	PORT OF ROTTERDAM CCUS BACKBONE INITIATIVE (PORTHOS)	Advanced development	Netherlands	2023	Various	2.0 - 5.0	Various	Dedicated Geological Storage
26	NORWAY FULL CHAIN CCS	Advanced development	Norway	2023-2024	Cement production and waste-to-energy	0.80	Various	Dedicated Geological Storage
27	LAKE CHARLES METHANOL	Advanced development	United States of America	2024	Chemical production	4.20	Industrial separation	Enhanced oil recovery
28	ABU DHABI CCS PHASE 2 - NATURAL GAS PROCESSING PLANT	Advanced development	United Arab Emirates	2025	Natural gas processing	1.9 - 2.3	Industrial separation	Enhanced Oil Recovery
29	DRY FORK INTEGRATED COMMERCIAL CCS	Advanced development	United States of America	2025	Power generation	3.00	Post-combustion capture	Dedicated Geological Storage or Enhanced Oil Recovery
30	CARBONSAFE ILLINOIS – MACON COUNTY	Advanced development	United States of America	2025	Power generation and ethanol production	2.0 - 5.0	Post-combustion capture and industrial separation	Dedicated Geological Storage and Enhanced Oil Recovery
31	PROJECT TUNDRA	Advanced development	United States of America	2025 - 2026	Power generation	3.1 - 3.6	Post-combustion capture	Dedicated Geological Storage or Enhanced Oil Recovery
32	INTEGRATED MID-CONTINENT STACKED CARBON STORAGE HUB	Advanced development	United States of America	2025 - 2035	Ethanol production, power generation and/or refinery	1.90	Various	Dedicated Geological Storage and Enhanced Oil Recovery
33	CARBONNET	Advanced development	Australia	2020's	Under evaluation	3.00	Under Evaluation	Dedicated Geological Storage
34	OXY AND WHITE ENERGY ETHANOL EOR FACILITY	Early development	United States of America	2021	Ethanol production	0.6-0.7	Industrial separation	Enhanced Oil Recovery
35	SINOPEC EASTERN CHINA CCS	Early development	China	2021	Fertiliser production	0.50	Industrial separation	Enhanced oil recovery
36	HYDROGEN 2 MAGNUM (H2M)	Early development	Netherlands	2024	Power Generation	2.00	Under Evaluation	Dedicated Geological Storage

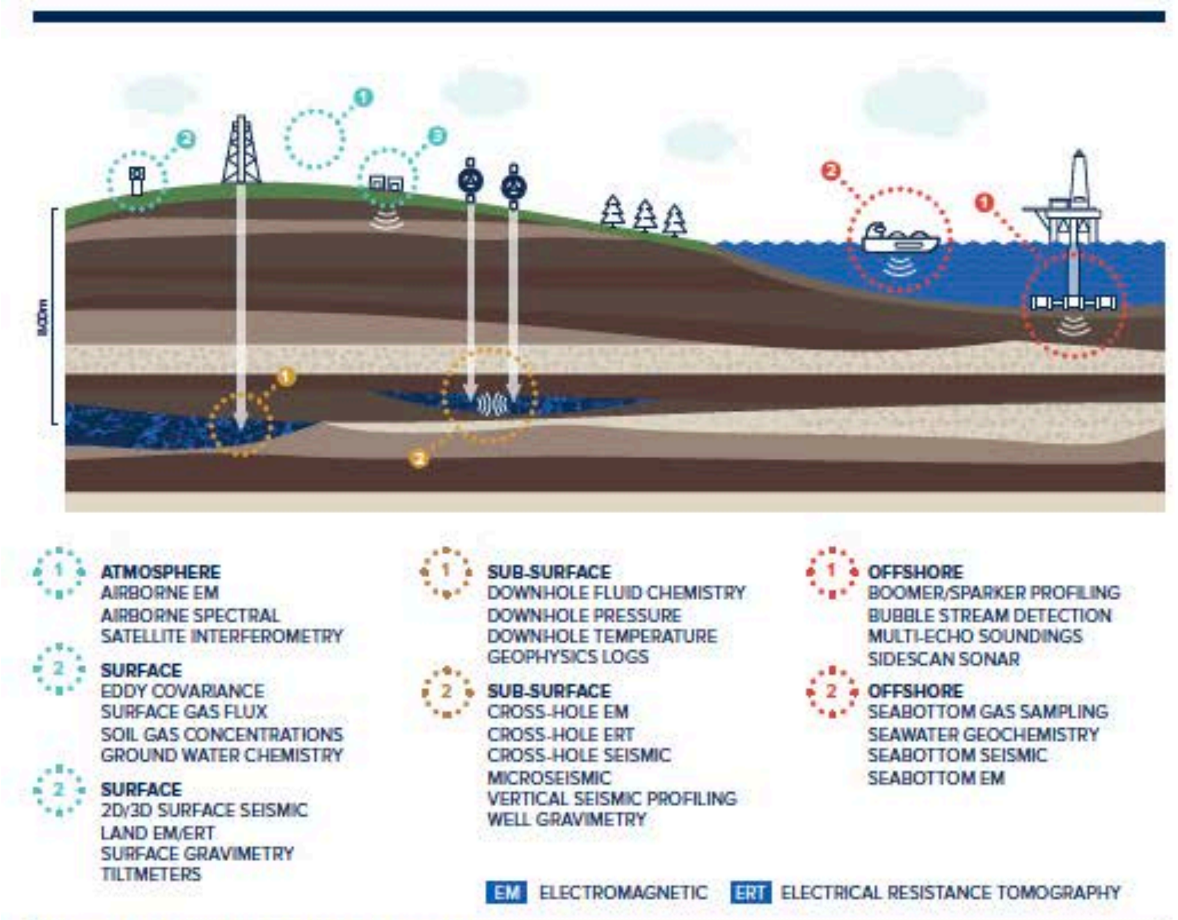


FIGURE 11 A SCHEMATIC OF SELECT MONITORING TECHNOLOGIES AVAILABLE FOR CO_2 STORAGE FACILITIES

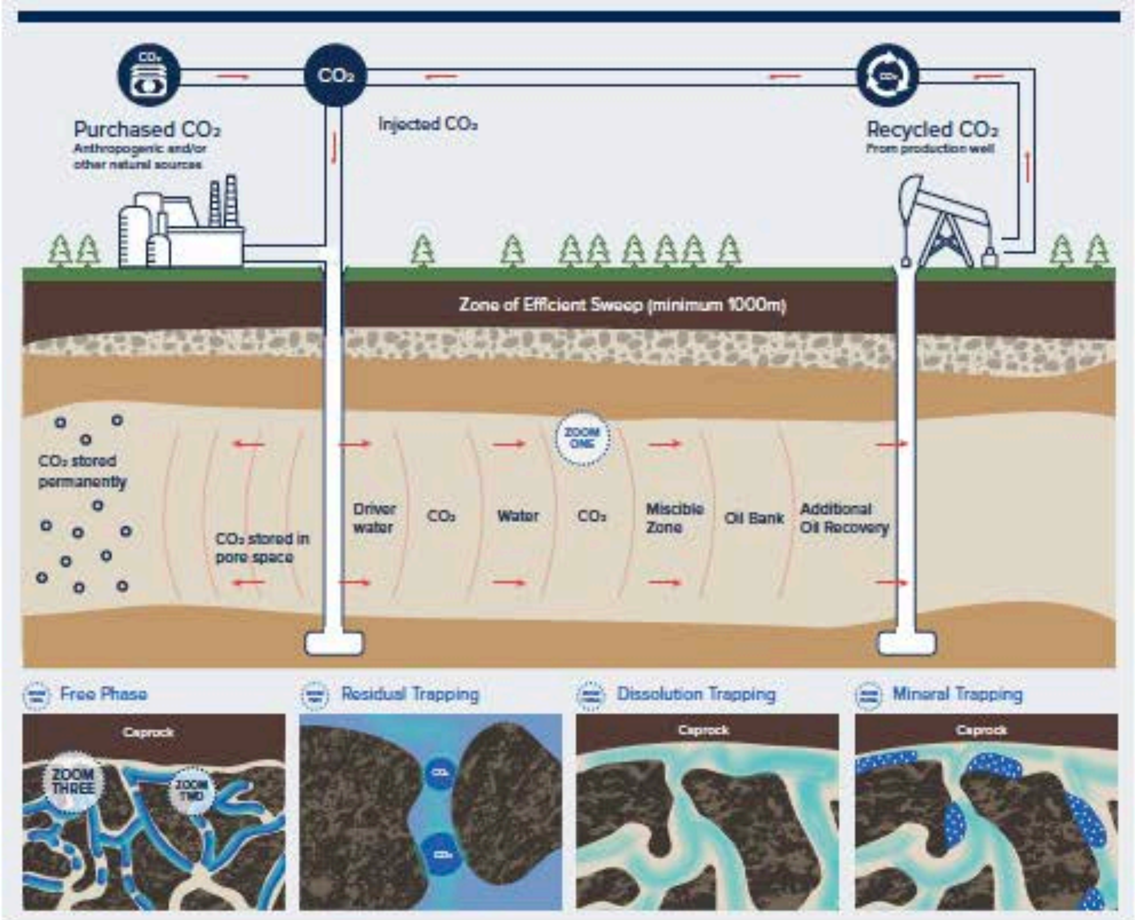


FIGURE 12 SCHEMATIC OF CO_2 EOR AND CO_2 TRAPPING MECHANISMS

https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf

Oil recovery is under:
Field pressure (primary): 15%
Water floods (secondary): 30 %
CO2 flood (tertiary): 15%

Chemical scrubbing of CO_2 from flue gases has already been demonstrated.

During 82-86, an aqueous solution of MEA was used in: Lubbock Power plant, Texas, NG was fired in a 50 MW plant, producing near 1000 t/d of CO_2 , and in a coal-steam generator in Carlsbad NM producing 113 t/d. In both cases, CO_2 was used for enhanced oil recovery (EOR) in nearby fields.

1991, CO_2 scrubbing using 15-20% MEA solutions in the 300 MW Shady Point Combined Heat and Power Plant in Oklahoma has been producing nearly 400 t/d CO_2, which is used in the food industry and in EOR.

A similar operation is done in a Botswana plant burning coal.

Norway Sleipner Vest gas field separates CO_2 from the recovered natural gas to reduce CO_2 concentration in the produced gas from 95% to 2.5%. The separated CO_2 is then injected back into a 250 m deep aquifer located 800 m below the ocean surface.