Gap Analysis for Modular Scale Pre-Combustion CO_2 Capture

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Carbon Capture Project Review Meeting
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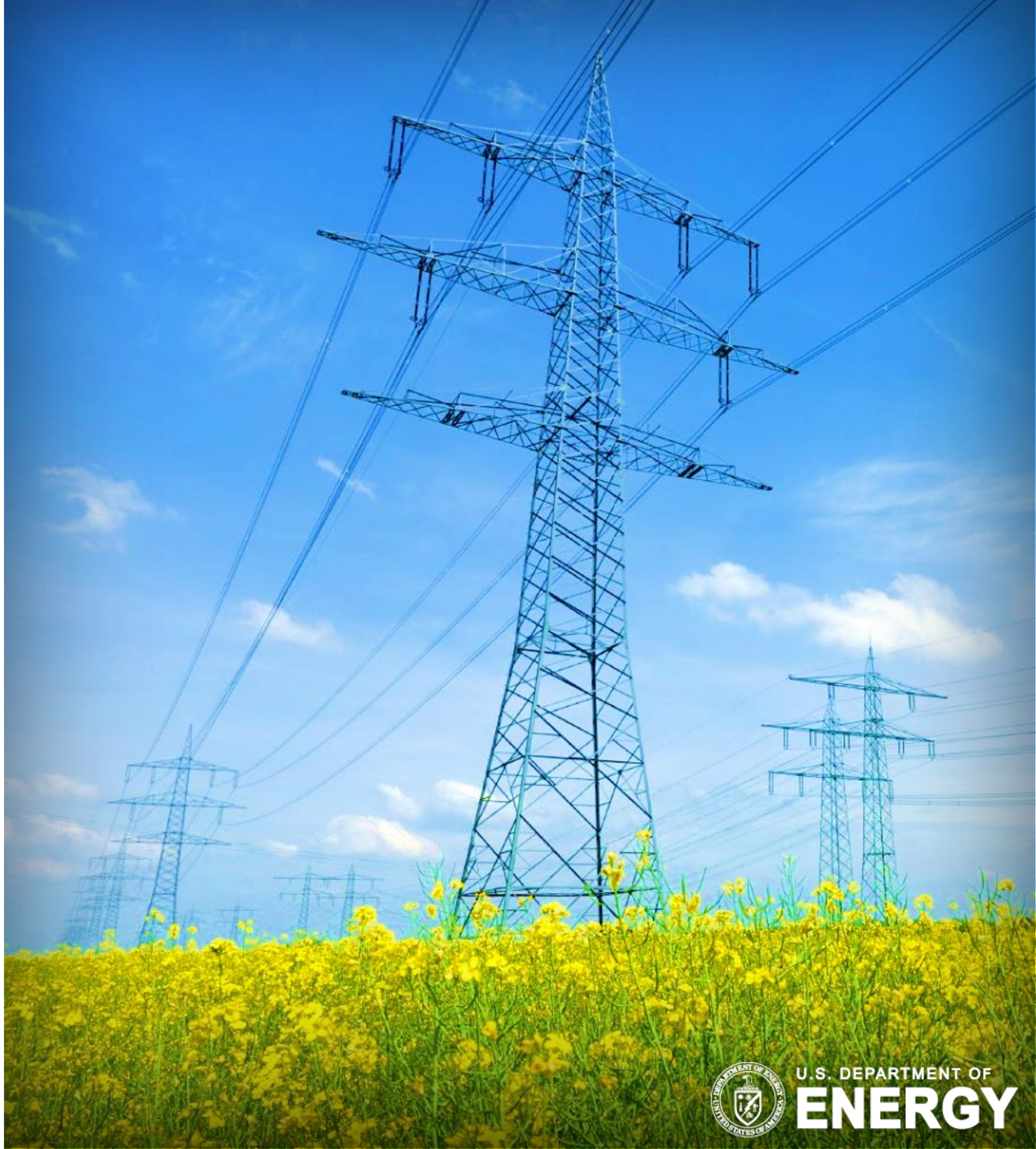
NATIONAL ENERGY TECHNOLOGY LABORATORY



U.S. DEPARTMENT OF ENERGY

Transformational Carbon Capture FWP Task 14

- **Task 14:** Modular CO_2 Capture Processes for Integration with Modular Scale Gasification Technologies.
- **Task Objective:** To assess the potential of integrating small-scale modular pre-combustion CO_2 capture technologies with small-scale modular coal gasification technologies.
- **Outcomes:** Report that includes a literature review, thermodynamic modelling and economical screening of modular scale pre-combustion carbon capture technologies.

The **Gap Analysis Report** can be used to guide future R&D of pre-combustion CO_2 capture to ensure alignment with future gasification processes and applications.

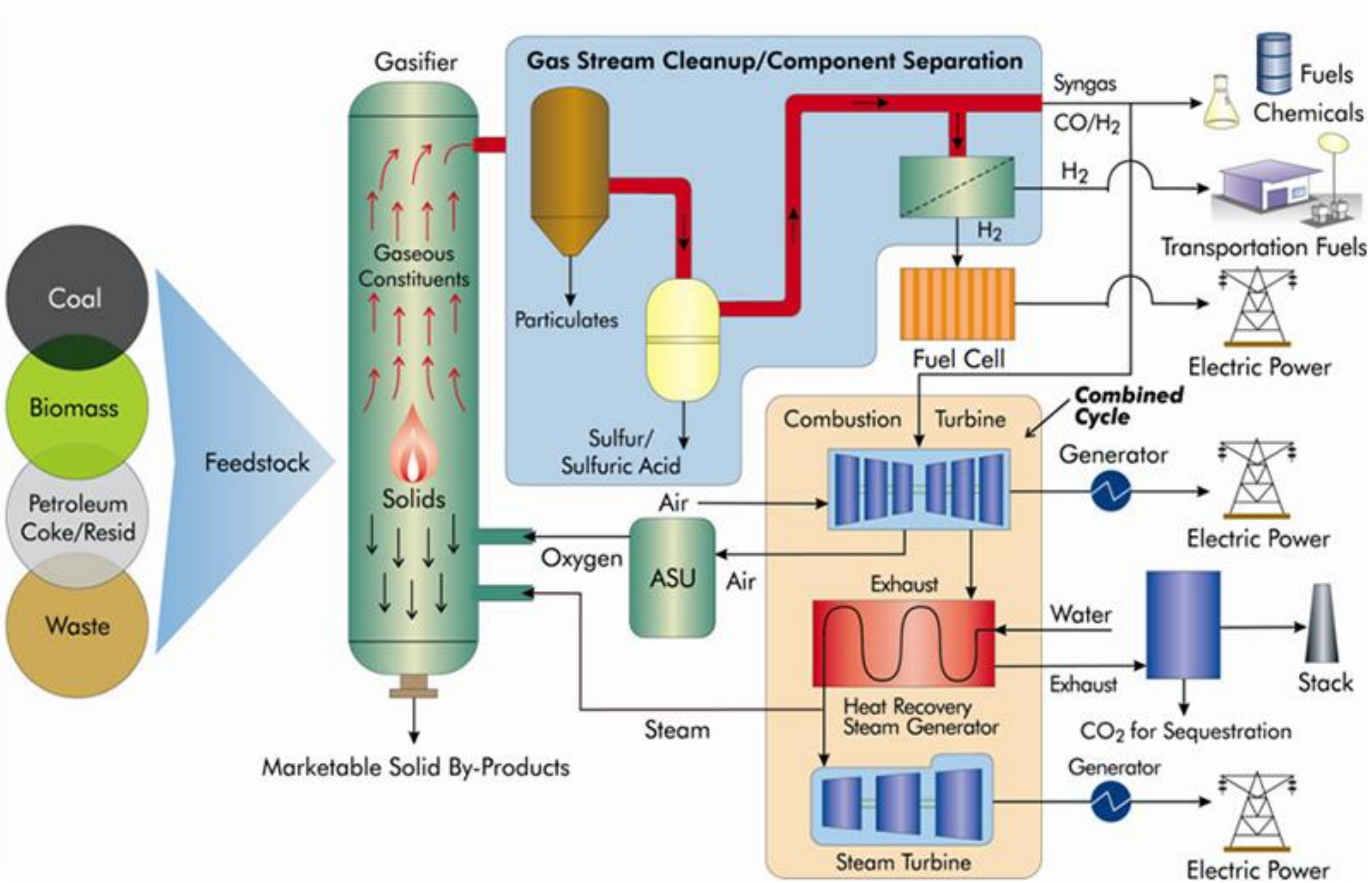


Image from: https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/intro-to-gasification

From large scale…

Duke Energy IGCC power plant

2 x GE gasifiers

Images from: https://boilermakers.org/news/headlines/duke-completes-worlds-largest-igcc-plant
https://www.modernpowersystems.com/features/featuregasifier-projects-and-igcc-the-big-picture-4188432/
https://www.zeton.com/industries/gas-to-liquids-synfuels/

From large scale… To modular scale…

Duke Energy IGCC power plant

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Transportation of modular plant (from Zeton website)

Modular manufacturing plants (from Zeton website)

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Literature Review & Gap Analysis Report

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1 - Review of modular gasification systems

- Gasification Market - electricity generation (IGCC) and other syngas applications
- Gasification Technology - current options and future trends
- Syngas properties and syngas processing requirements

2 - Review of CO_2 capture technologies for modular gasification systems

- Solvent, membrane, sorbent, hybrid, integrated processes
- What will encourage successful implementation of modular scale pre-combustion carbon capture technology?

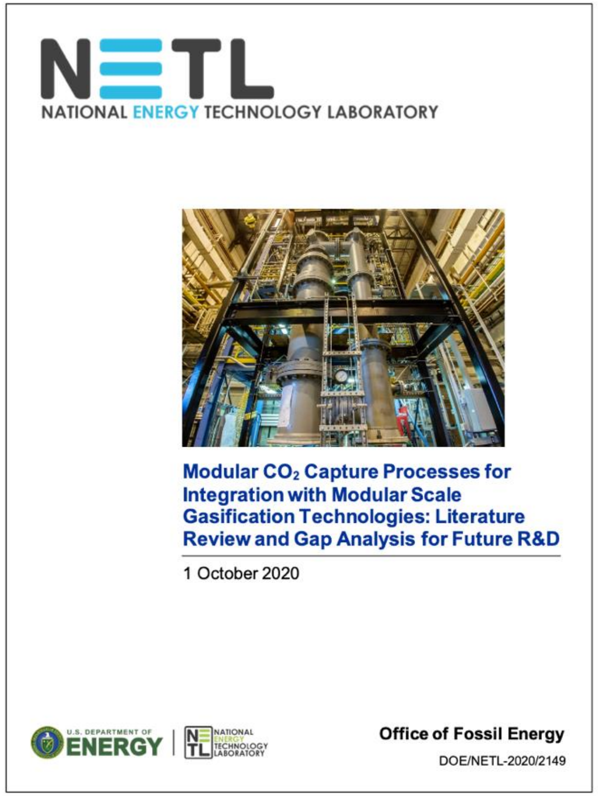
3 – Efficiency screening of carbon capture technologies for modular gasification systems

- Energy-only analyses to assess thermodynamic efficiency of promising capture technologies

4 – Preliminary cost assessments for selected CO_2 capture technologies

- Economic screening of baseline capture process at full scale and modular scale
- Economic screening of other capture technologies at modular scale

5 – Recommendations for integration of CO_2 capture technologies with modular gasification applications

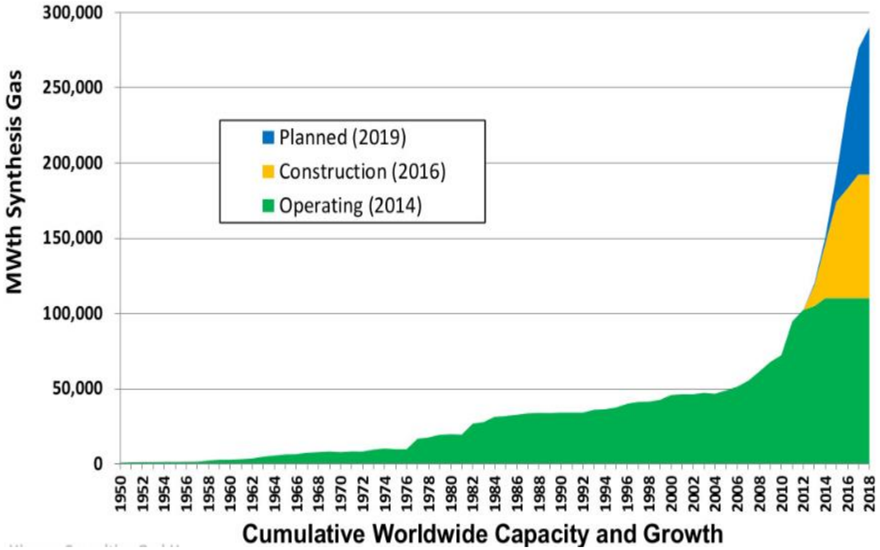


Report available from NETL website:

Link

Gasification Market Review

Gasification Market Review



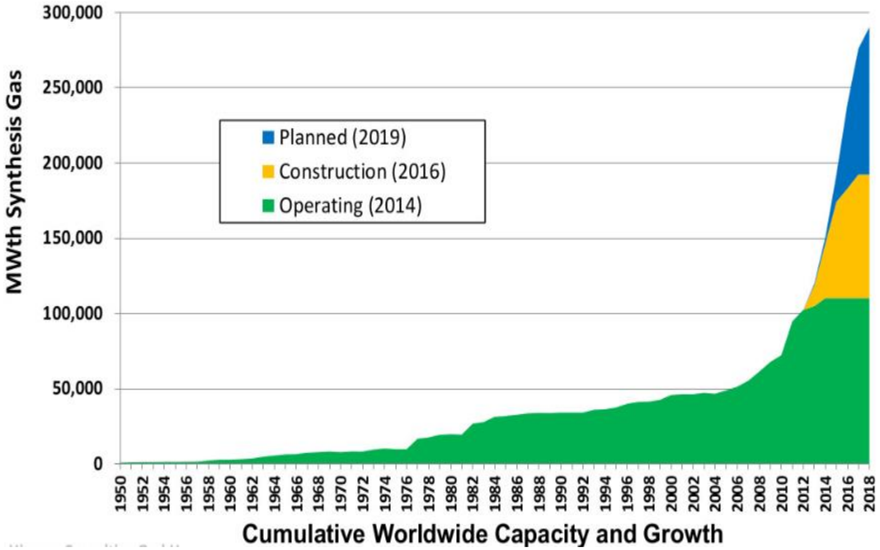
Key findings:

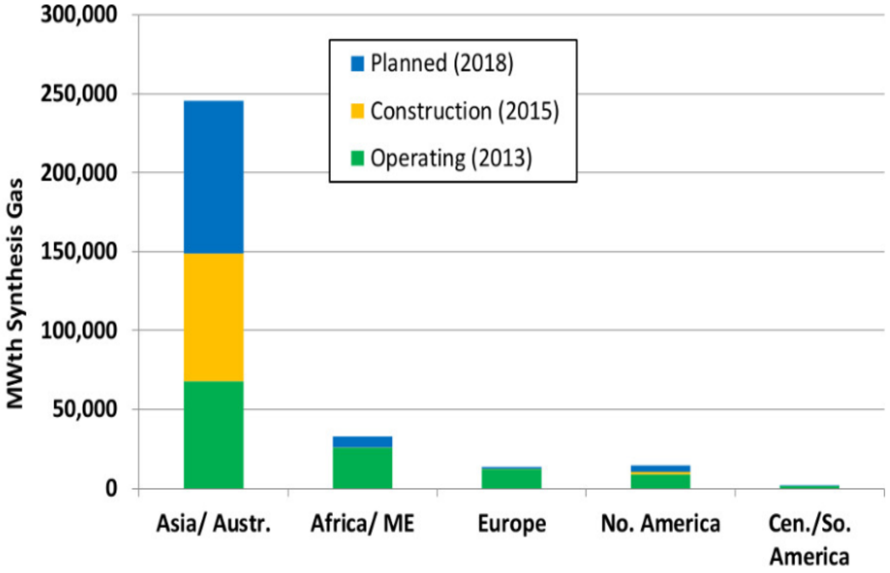
- Global syngas production is increasing

Figures from https://www.globalsyngas.org/resources/the-gasification-industry/

[1] Syngas & Derivatives Market by Production Technology, Gasifier Type, Feedstock, Application and Region - Global Forecast to 2025, Report ID: 5125724

Gasification Market Review





Key findings:

- Global syngas production is increasing
- Majority of syngas production growth is occurring in Asia (particularly China)

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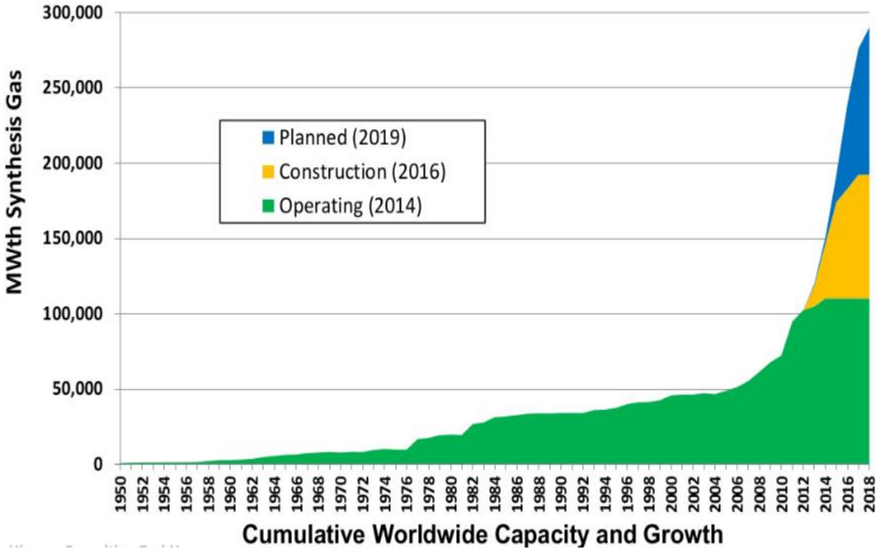

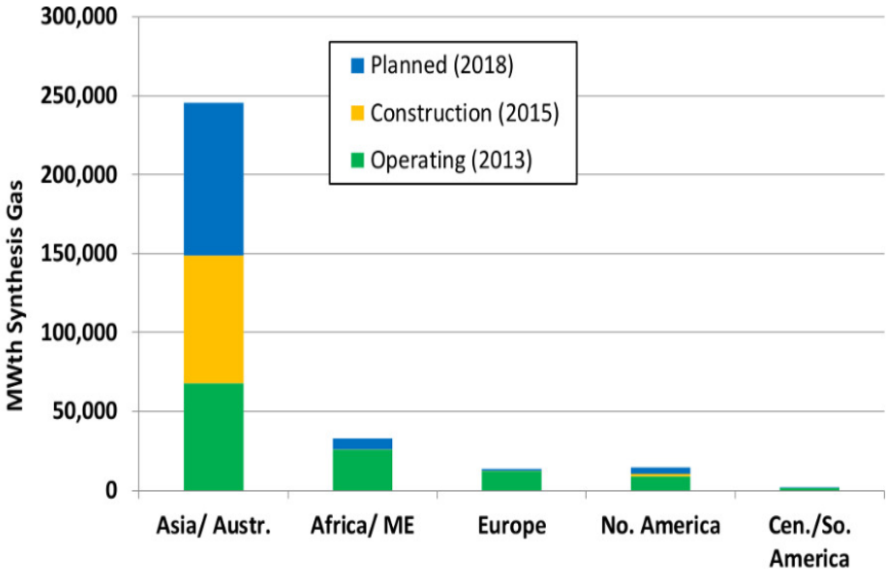

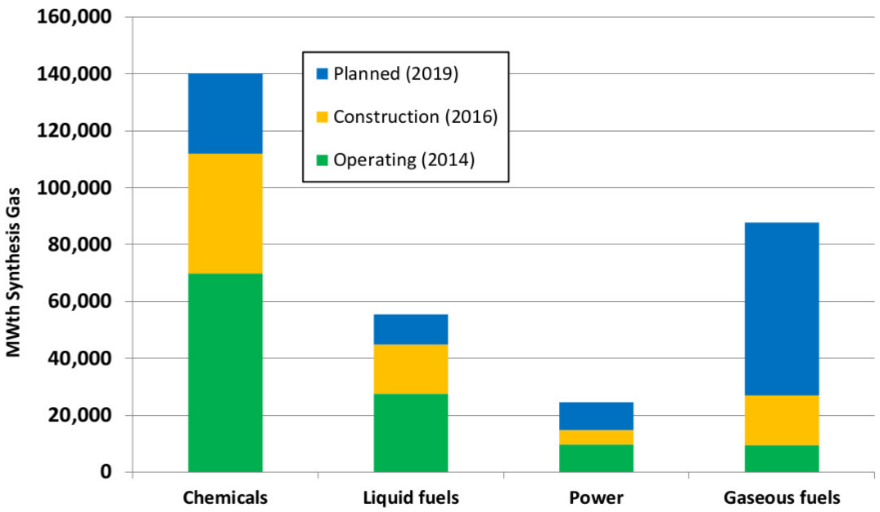

Key findings:

- Global syngas production is increasing
- Majority of syngas production growth is occurring in Asia (particularly China)
- Most syngas is being used for production of chemicals
- Potential for global growth in production of syngas for producing gaseous fuels (due to low access to natural gas in countries outside of U.S.)

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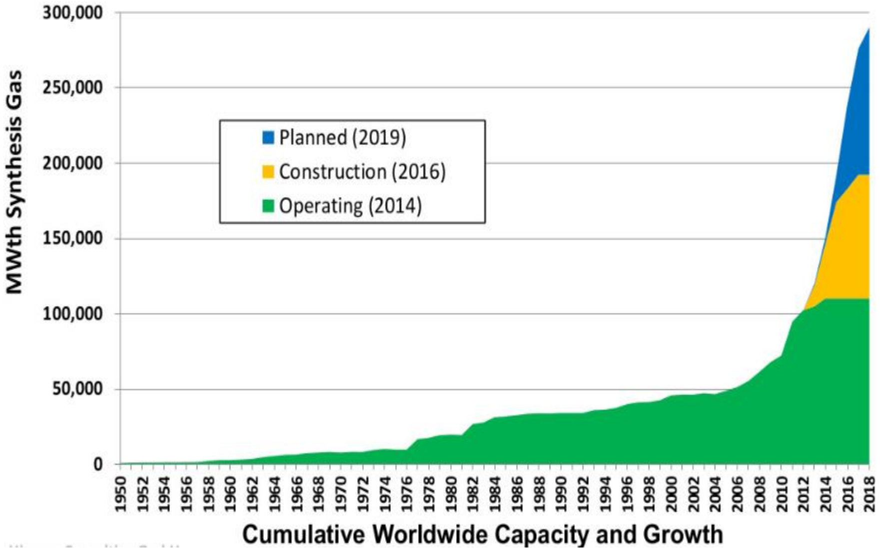

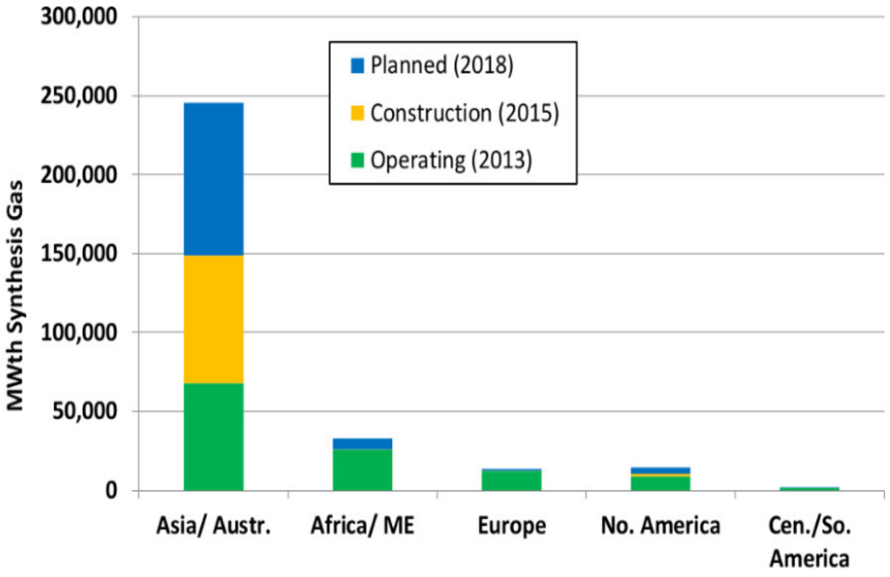

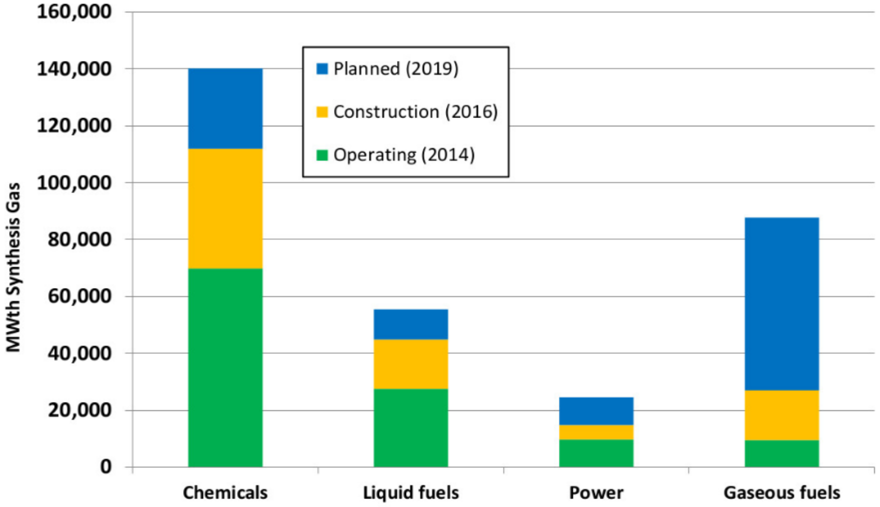

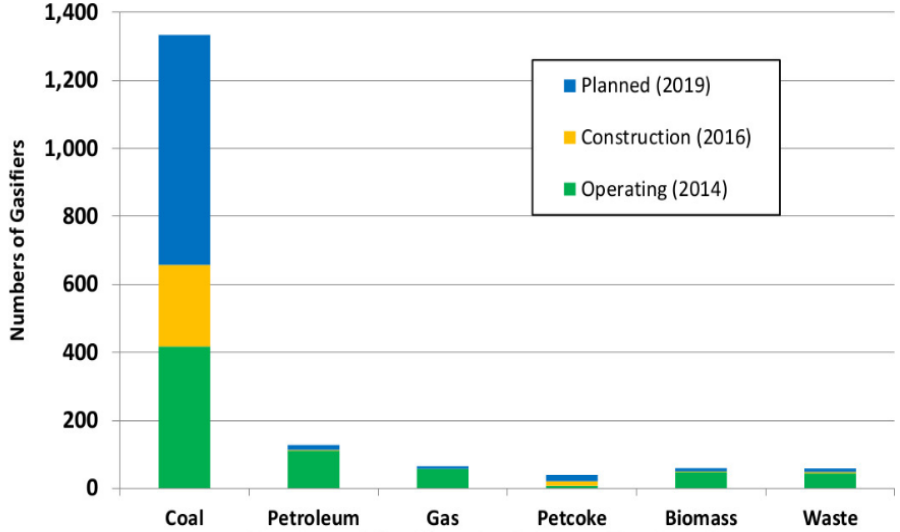

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- Most syngas is being used for production of chemicals
- Potential for global growth in production of syngas for producing gaseous fuels (due to low access to natural gas in countries outside of U.S.)
- Coal is still the dominant feedstock for gasification processes
- Biomass/waste is projected to be the fastest-growing feedstock in the syngas & derivatives market for 2020-2025[1]

Figures from https://www.globalsyngas.org/resources/the-gasification-industry/

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Gasification Applications

- Coal gasification demand for non-power applications is increasing.
- Specifically, there is rising demand for syngas & derivatives such as methanol, ammonia, and FT synthesis products to produce chemical intermediates.
- Polygeneration gasification power plants, which produce multiple products including electricity from the same initial stream of syngas, have promising potential for future development as the chemical products often realize a higher added value in comparison to pure electricity generation

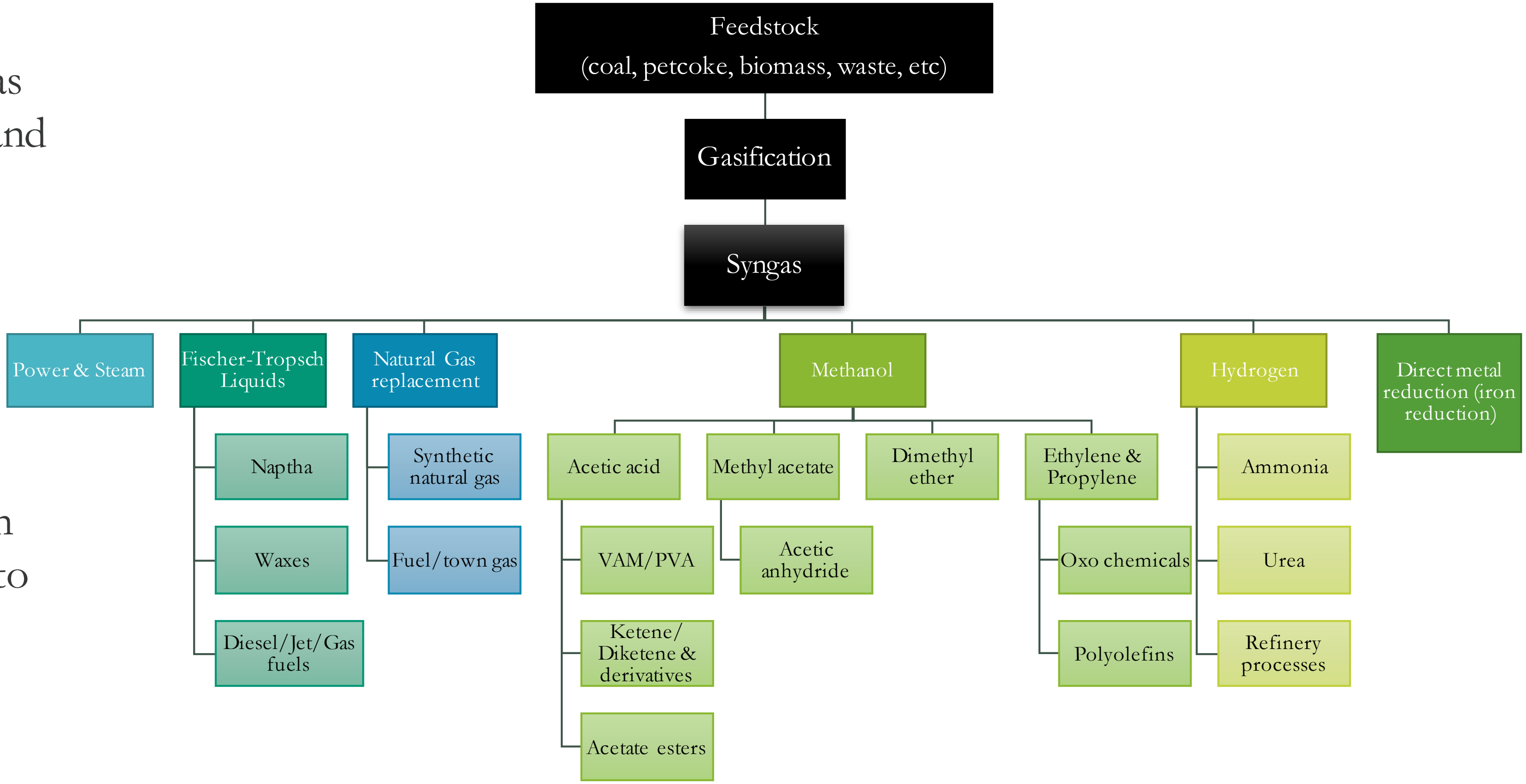

Figure adapted from: https://netl.doe.gov/research/Coal/energy-systems/gasification/gasifipedia/chemicals

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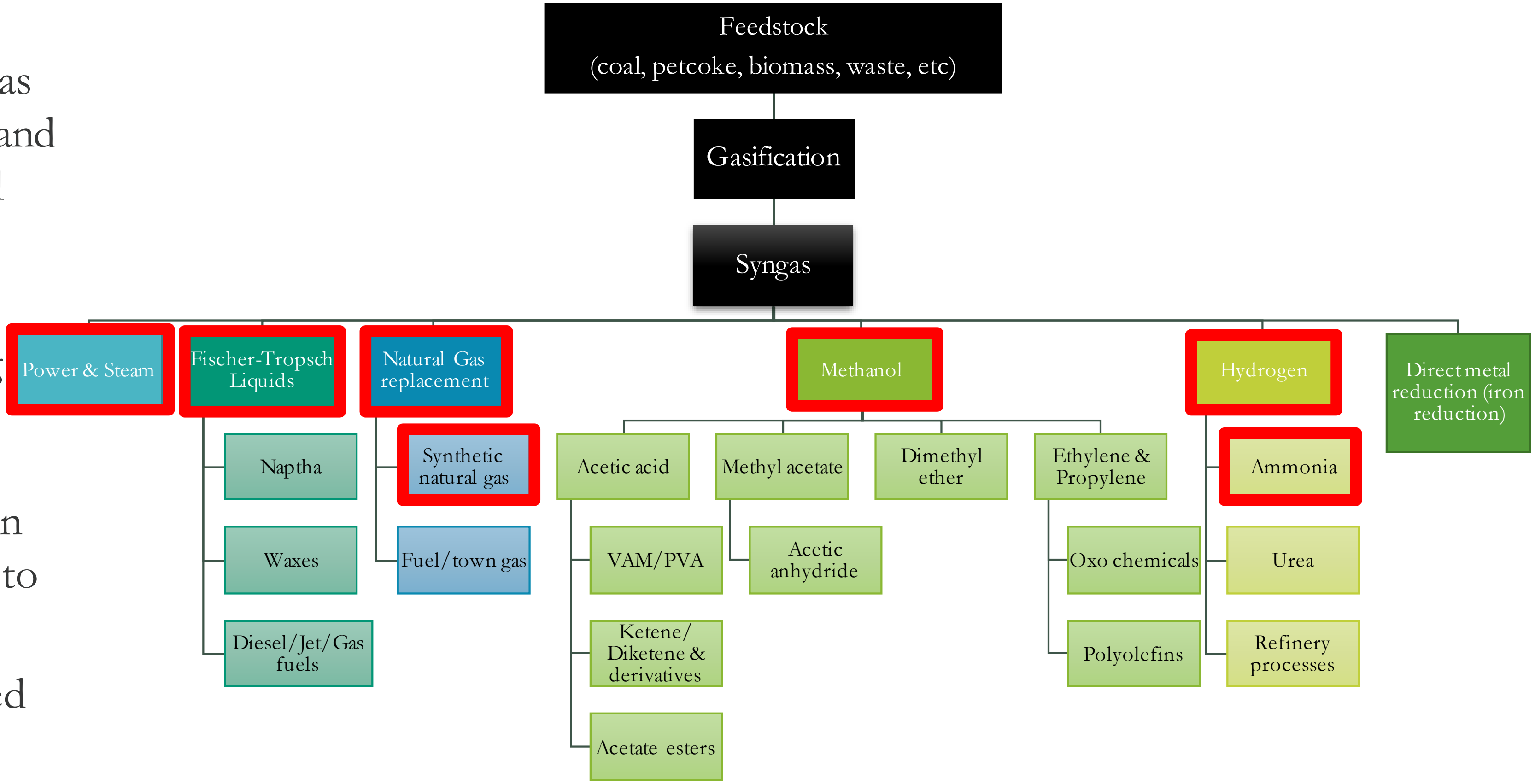
- Applications highlighted in red are discussed in the Gap Analysis Report.



Power generation from coal gasification

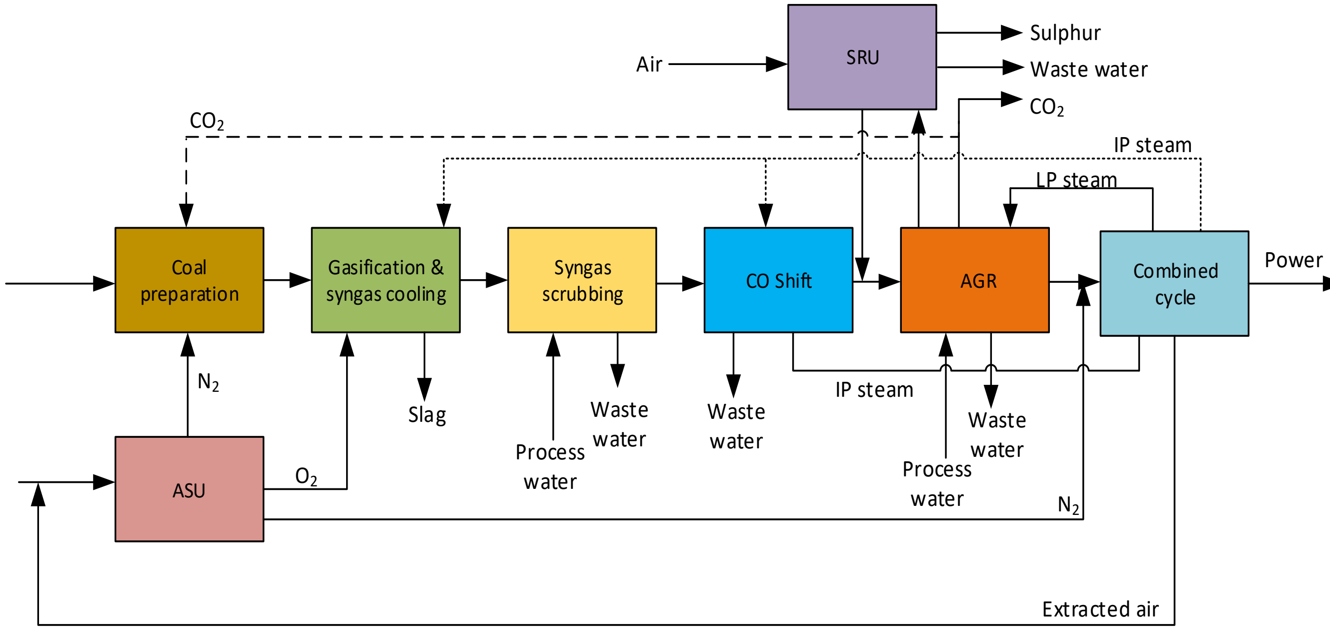
IGCC with pre-combustion CO_2 capture:

ADVANTAGES

+ Lower emissions & higher efficiency
+ Lower cost mercury removal and CO_2 removal
+ Lower water use
+ Product flexibility

CHALLENGES

- Costs (high capital costs, uncertainty in costs, need for equipment licences, financing issues…)
- Low availability (due to high complexity)
- Need for consistent feedstock (composition and rates)
- Long construction & commissioning time
- Low NG prices (in U.S.)



Integrated gasification combined cycle power plant with CO_2 capture

IGCC power plants of the future

IGCC power plants of the future

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Modular design

- Mass production of equipment
- Advanced manufacturing techniques
- Multiple parallel modular scale units will improve plant availability
- Standard equipment, rather than licensed commercial processes
- Pre-assembly and testing before shipment to site

IGCC power plants of the future

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Location

- Plant needs to be flexible to changing environmental regulations
- May be brown vs. green field
- Water may be scarce
- Need for multiple products (e.g. power and fertilizer)
- Make use of local feedstock (& limit fuel imports)

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Diverse feedstocks

- Coal (bituminous, lignite, etc)
- Petcoke
- Waste coal & coal fines
- Municipal Solid Waste (MSW)
- Biomass
- Petroleum
- Gas co-feed

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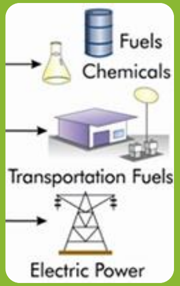
Polygeneration



- Provides multiple valuable products (e.g. production of fertilizer in rural areas)
- Reduces uncertainties (adds a new revenue stream)
- Potential to integrate with intermittent renewable power

Future R&D for Gasification & CO_2 Capture Processes

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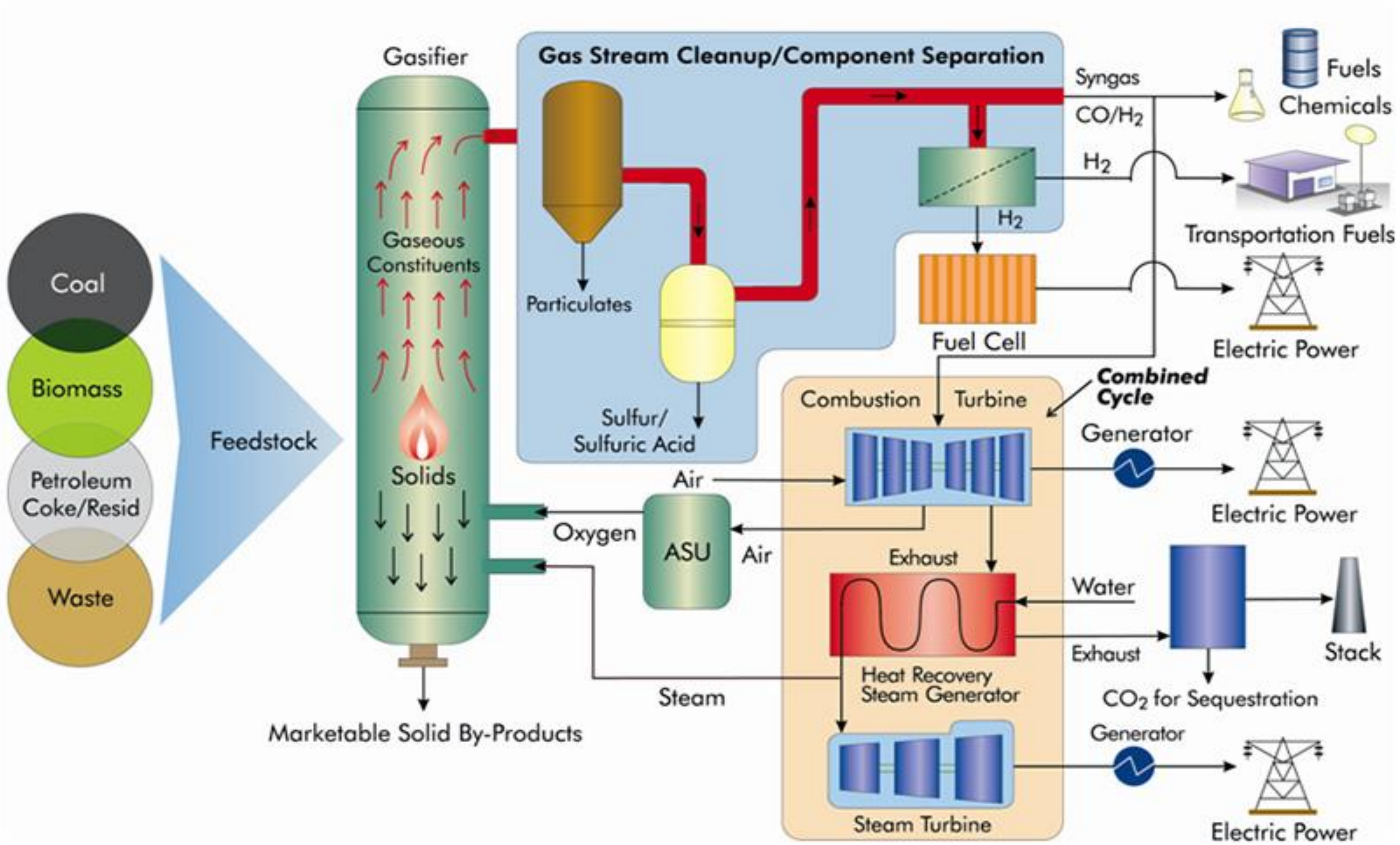
- DOE ***Gasification Systems Program*** is developing innovative modular designs for converting diverse types of coal into clean synthesis gas to enable the low-cost production of electricity, transportation fuels, chemicals, hydrogen, and other useful products to suit market needs.
- Syngas processing including **CO_2 capture will be required.**

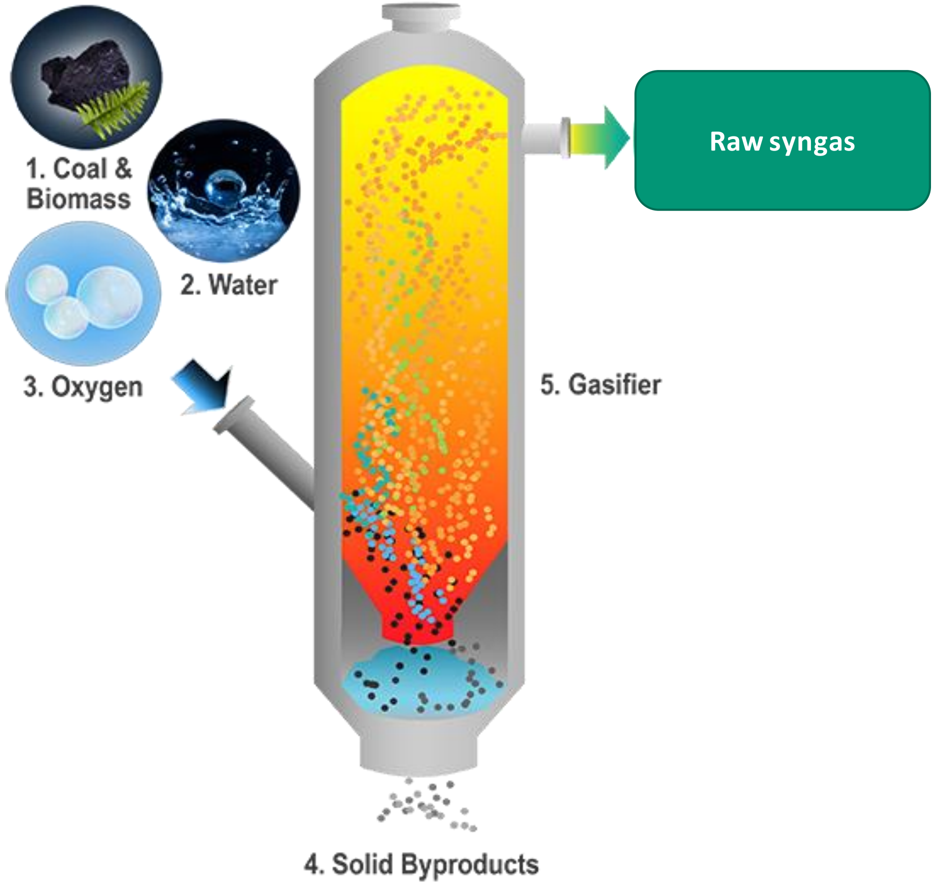


<u>Goal of Gap Analysis Report</u> is to help answer:

1. What are the properties of the raw syngas from different gasification systems?
2. What are the syngas requirements for different end products?
3. Considering the different syngas properties and requirements for end products, what pre-combustion carbon capture technologies are best suited at modular scale?

1. What are the properties of the raw syngas from different gasification systems?

- Feedstock
- Gasifier type
- Oxidation conditions
- Operating conditions
- etc…



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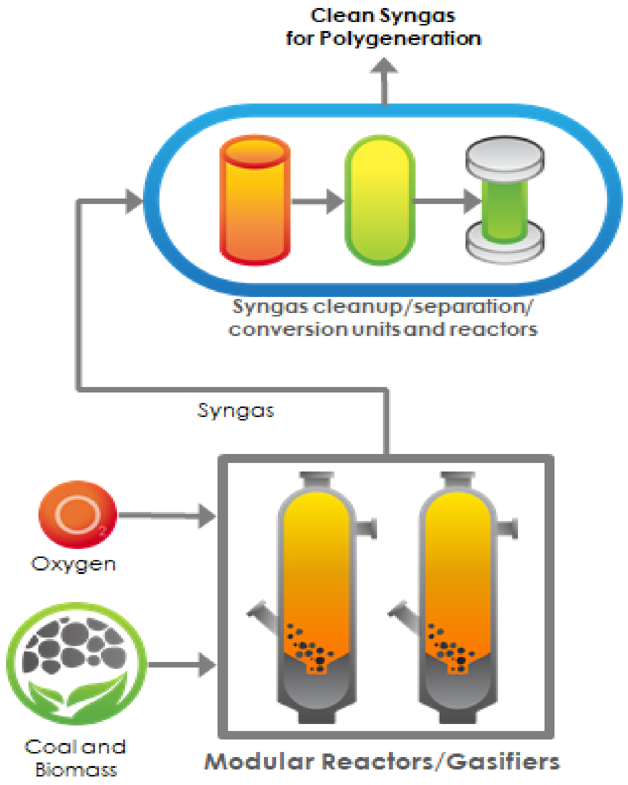
Gasifier characteristics and typical raw syngas composition

Gasifier technology	Shell Coal Gasification Process		Siemens Fuel Gasification Technology (SFG)		E-Gas		GE	HTW (High Temperature Winkler)		KBR transport gasifier (TRIGTM)	Transport gasifier (TRIGTM) – Kemper project	BGL (British Gas Lurgi)		Sasol-Lurgi
Gasifier type	Entrained flow		Entrained flow		Entrained flow		Entrained flow	Fluidized bed		Fluidized bed	Fluidized bed	Moving bed		Moving bed
Feedstock	Bituminous coal	Lignite	Bituminous coal	Lignite	Bituminous coal	Lignite	Bituminous coal	Lignite	Lignite	Sub-bituminous coal	Lignite	Bituminous coal	Lignite	Bituminous coal
Coal size, mm	<0.1		<0.1		<0.1		<0.1	0.5-5	0.5-5	<2.5-6	0.3-0.5	Lump (5-50 mm)		Lump (5-50 mm)
Oxidant	oxygen		oxygen		oxygen		oxygen	oxygen + steam	air	oxygen	air	oxygen		oxygen
Pressure, MPa	2-4.5		2.5-4		2-4.1		3-8	2.5-3	2.5-3	1.5	<3.6	2.5-7		3.1
Exit gas temperature, °C	900 (after internal gas quench)		170-230 (after internal quench)		1040		760 (after syngas cooler) 200-300 (after quenching)	800-900	800-900	930	950	260-700 (typically <540)		200-650
Proven products / Applications	Power, chemicals		Power, chemicals		power		Power, chemicals	Chemicals	Chemicals	Power	Power, CO_2 for EOR, chemicals (H_2SO_4, NH_3)	Power (small scale), chemicals		Power, chemicals & liquid fuels
Feedstock→ Syngas composition (dry basis) vol% ↓	Bituminous coal	Lignite	Bituminous coal	Lignite	Bituminous coal	Lignite	Bituminous coal	Low ash lignite (Oxygen + steam blown)	High ash lignite (Air blown)	Sub-bituminous coal	Lignite	Bituminous coal	Lignite	Bituminous coal
H_2	27.2	28.4	26.6	31.0	37.5	37.4	36.3	35.8	16.3	36.2	12.2	31.6	28.3	55.2
CO	64.4	62.4	63.1	55.1	50.0	33.2	47.4	35.7	21.7	41.3	19.4	54.8	56.5	31.2
CO_2	1.5	2.9	2.9	8.01	8.9	26.2	12.9	22.8	8.8	17.7	9.37	3.47	2.83	5.9
CH_4	0.03	<0.1	<0.1	<0.1	0.6	0.15	0.12	4.9	1.8	3.1	2.95	4.55	6.05	4.7
N_2 + Ar	5.3	5.4	5.4	4.31	1.5	1.9	1.92	0.61	50.5	1.3	55.4	3.95	6.05	1.5
H_2S	1.3	0.3	0.45	0.2	1.0	0.46	1.20	0.12	0.11	0.11	0.36	1.20	0.30	0.95
COS	0.1	<0.1	0.04	0.02	0.11	0.15	0.02	0.00	0.00	0.00	0.02	0.12	0.00	0.04
NH_3 + HCN	0.02	<0.1	1.4	1.2	0.22	0.30	0.12	0.18	0.81	0.32	0.36	0.24	0.00	0.53
HCl	0.03	<0.10	-	-	0.11	0.15	0.02	-	-	-	-	0.04	0.00	0.00
C_nH_m	-	-	-	-	-	-	-	-	-	-	-	0.24	0.61	0.32

Adapted from: Wang, T. & Stiegel, G. 2017, *Integrated Gasification Combined Cycle (IGCC) Technologies*, Woodhead Publishing.
Carpenter, A.M. 2008, Polygeneration from coal, CCC/139, I.C.C. Centre.

2. What are the syngas requirements for different end products?

- Contaminant limitations (particulates, NH_3, HCN, sulfur, etc)
- H_2:CO ratio
- Temperature
- Pressure
- Heating value
- etc



Desirable syngas properties for different applications

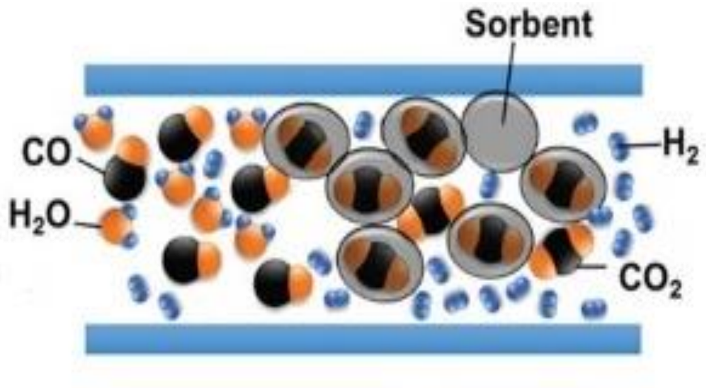
Product/Application	Variable	Optimum value
Electricity/IGCC (gas turbine)	H_2/CO	n/a (unless CO_2 capture required)
	$H_2S + COS + CS_2$	< 20 ppmv
	Particulates	< 2 ppmw
	Hydrogen Halides (HCl + HF)	< 1 – 2 ppmv
	Alkalis (Na + K)	0.03-0.2 ppmv
	CO_2	Not Critical
	Hydrocarbons	High
	N_2	Lowers heating value
	H_2O	Can be used in WGS & to control NOx
	Heating Value	High (improves efficiency)
	Pressure	~40 bar
	Temperature	500-600 °C
Fischer-Tropsch (F-T) Synthesis of Chemicals/fuels	H_2/CO	0.6 - 2 (depends on catalyst)
	CO_2	Low (1-2%)
	Hydrocarbons	Low
	NH_3 + HCN	<1 ppm
	H_2O	High (required fro WGS)
	Sulfur ($H_2S + COS + CS_2$)	<1 ppm
	Particulates	Low
	Heating value	Unimportant
	Pressure	~20 - 30 bar
	Temperature	200–300 °C (Co catalyst) or 300-400 °C (Fe catalyst)
Synthetic Natural Gas (SNG)	H_2/CO	3:1
	H_2	10% max
	CO_2	Low
	$(H_2/(3CO+4CO_2)$	0.98-1.03

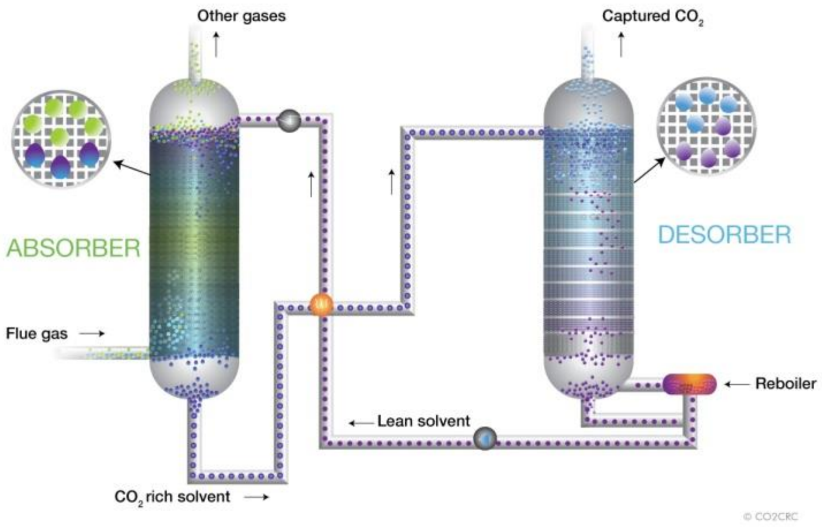
Product/Application	Variable	Optimum value
Hydrogen	H_2/CO	High (∞)
	CO_2	Not important (WGS will be required)
	Hydrocarbons	Low
	N_2	Low
	H_2O	High (required for WGS)
	Sulfur	< 1ppm
	Particulates	Low
	Heating value	Unimportant
	Pressure	~28 bar
	Temperature	100 – 200 °C
Methanol	H_2/CO	~2.0
	CO_2	Low
	Hydrocarbons	Low
	N_2	Low
	H_2O	Low
	Sulfur	<1 ppm
	Particulates	Low
	Heating value	Unimportant
	Pressure	~50 bar (liquid) ~140 bar (gas phase)
	Temperature	100 – 200 °C
Ammonia	H_2/N_2	3
	$CO + CO_2 + H_2O$	<30 ppm
	Sulfur	<1 ppm
	Inerts (including methane)	<2 % minimum
Urea	NH_3/CO_2	2.95
	CO_2 stream	>98.5 mol% CO_2 <0.15 mol% H_2 <10 ppmv methanol

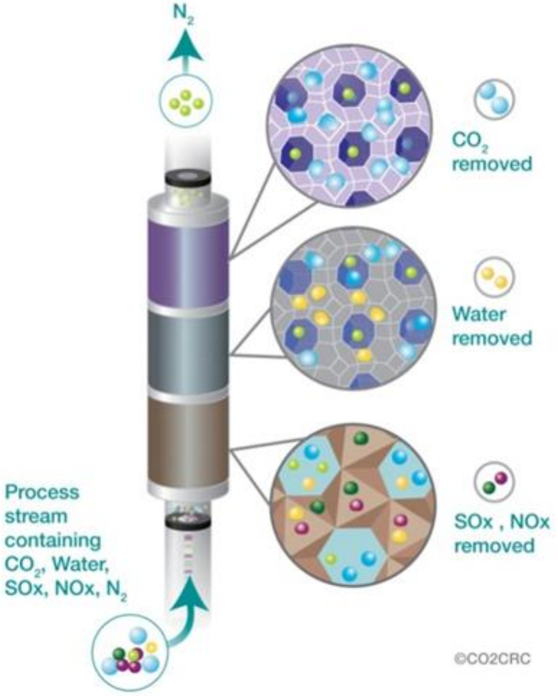
Adapted from:
Ciferno, J.P. and J.J. Marano, Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production. 2002, U.S. Department of Energy, National Energy Technology Laboratory
Carpenter, A. M. Polygeneration from coal; London, UK, 2008, IEA Clean Coal Centre.

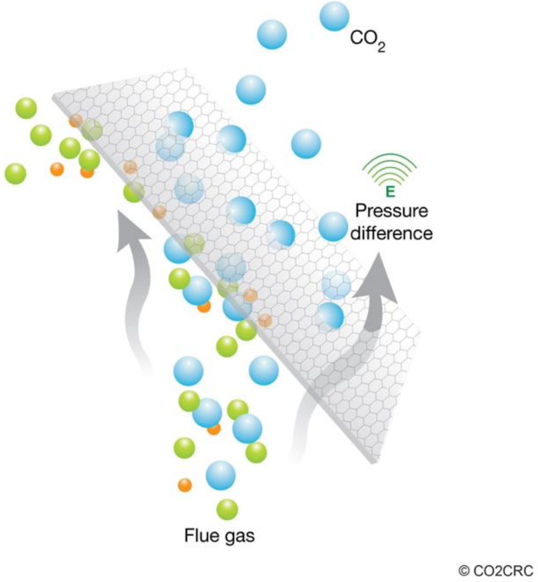
3. Considering the different syngas properties and requirements for end products, what pre-combustion carbon capture technologies are best suited at modular scale?

- Literature review of CO_2 capture processes
- Thermodynamic (energy) analysis of promising CO_2 capture processes
- Economic screening of promising CO_2 capture processes
- Ideal **modular** pre-combustion carbon capture processes:
  - ✓ Minimal heating/cooling of syngas
  - ✓ Integration of processes
  - ✓ Low capital cost & modular design

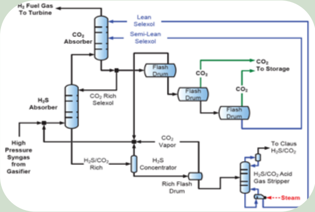
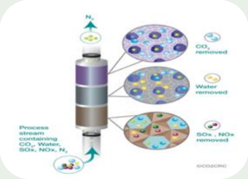
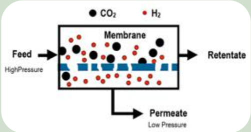
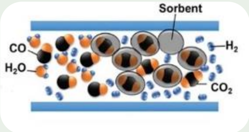
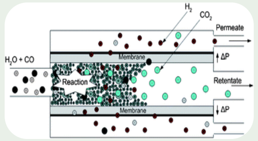








Modular Scale CO_2 Capture R&D

Capture Technology		R&D focus for modular scale
Solvent absorption		• Increase working capacity of solvent • Process intensification (eg. membrane contactor, novel packing) • Improve CO_2/H_2 selectivity • Reduce corrosivity & volatility
Sorbents		• Process design or sorbents that avoid cyclic operation • Sorbents with higher capacity and better selectivity for CO_2 (over H_2, N_2, CO…) • Better sorbent stability and water resistance
Membranes • H_2-selective • CO_2-selective		• Improve permeability & selectivity • Improve resistance to contaminants (eg. Sulfur) • Improve membrane stability (thermal, chemical & mechanical)
Integrated and hybrid processes	 	• Sorption Enhanced Water Gas Shift (SEWGS) • Water Gas Shift Membrane Reactor (WGSMR) • Membranes combined with solvents • Hybrid solvents (physical/chemical solvent process eg. Sulfinol) • Pressure Temperature Swing Adsorption (PTSA) process

Thermodynamic Analysis / Efficiency Screening

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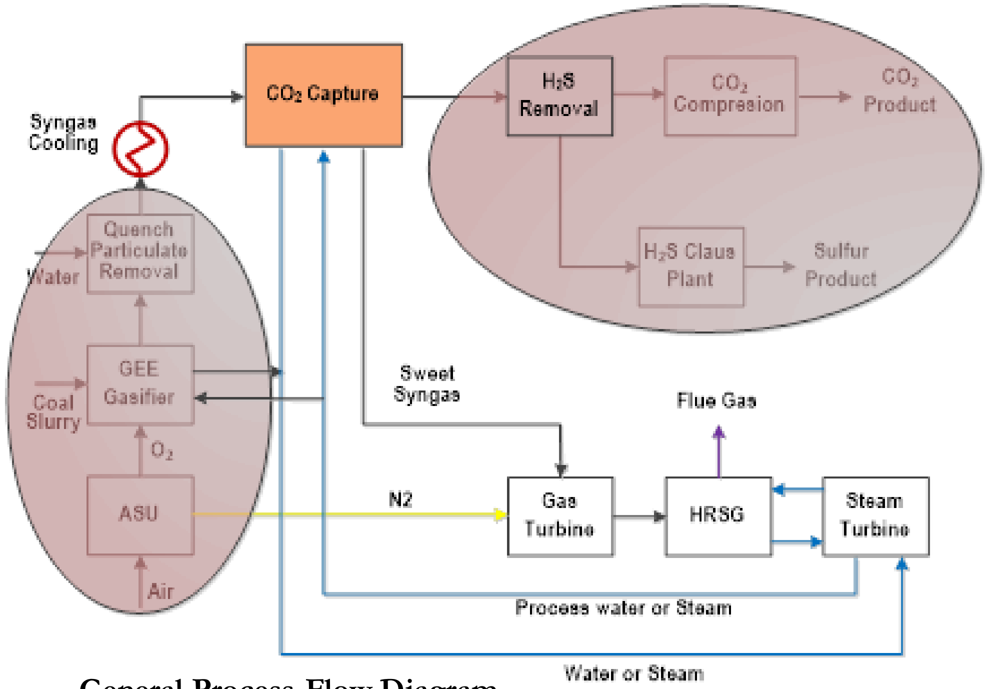
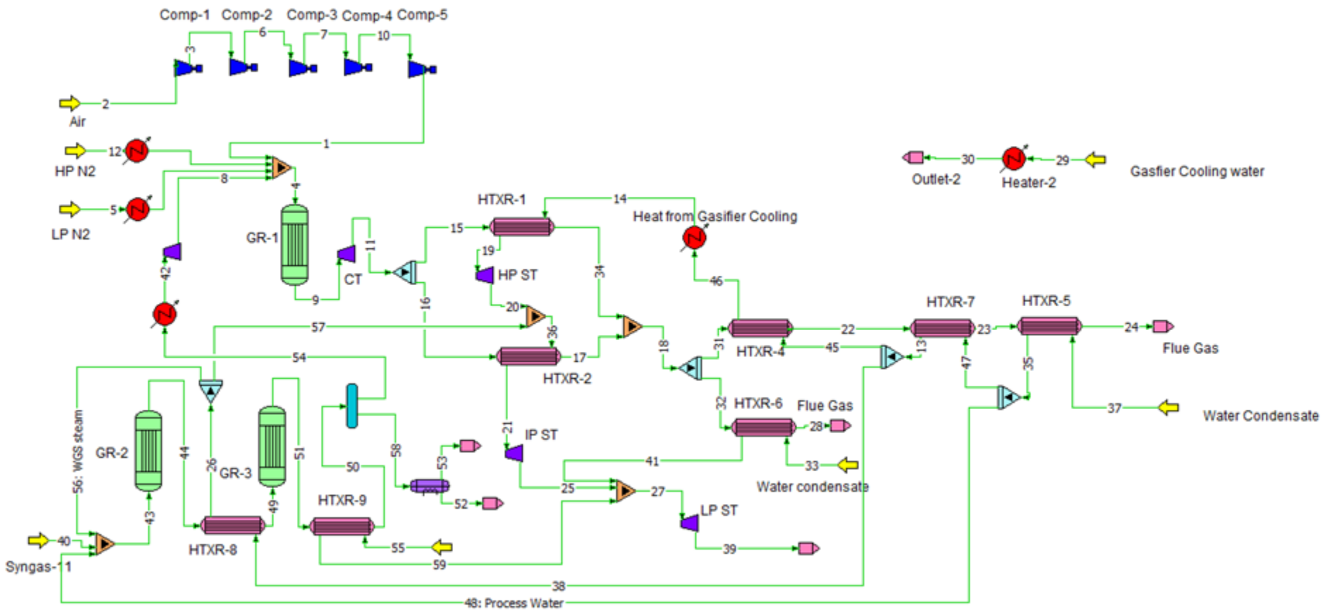
- Thermodynamic analysis of promising carbon capture technologies was completed to compare energy performance (using ProTreat Software)

Selected Technologies					
Baseline case – Selexol solvent	SEWGS PSA	H_2 Selective Membrane	CO_2 Selective Membrane	H_2 Selective Membrane Reactor	CO_2 Selective Membrane Reactor



General Process Flow Diagram



Baseline process – ProTreat simulation

Thermodynamic Analysis Results

Performance Summary	Reference – Selexol solvent	SEWGS PSA	Membrane - H_2 selective	Membrane - CO_2 selective	WGSMR - H_2 selective	WGSMR - CO_2 selective
Combustion turbine power, MWe	464	485	455	477	462	496
Sweet gas expander power, MWe	3	12	0	11	0	15
HP	54	47	52	58	54	56
IP	86	115	101	93	109	104
LP	133	106	134	117	132	113
Total steam turbine power, MWe	274	268	287	267	295	274
Total Gross Power, MWe	741	765	742	755	756	785
CO_2 compression, MWe	31.7	43.1	8.0	19.7	8.0	27.5
Air separation unit main air compressor, MWe	71.3	71.3	71.3	71.3	71.3	71.3
Air separation unit booster compressor, MWe	5.6	5.6	5.6	5.6	5.6	5.6
N_2 compressors, MWe	36.6	36.6	36.6	36.6	36.6	36.6
Acid gas removal, MWe	11.6	11.6	11.6	11.6	11.6	11.6
Balance of plant, MWe	28.1	28.1	28.1	28.1	28.1	28.1
Total auxiliaries, MWe	185	196	161	173	161	181
Net power, MWe	556	569	581	582	595	604
HHV net plant efficiency	**34%**	**35%**	**35%**	**35%**	**36%**	**37%**
HHV Net Plant Heat Rate, kJ/kWh	10675	10446	10229	10201	9976	9832

Economic Screening – Physical solvent CO_2 capture

- Main disadvantage of modular approach is the loss of economy of scale
- Economic screening was completed for a CO_2 capture plant using a physical solvent absorption process at different power plant scales
- Analysis was completed by Husain Ashkanani & Dr Badie Morsi from University of Pittsburgh

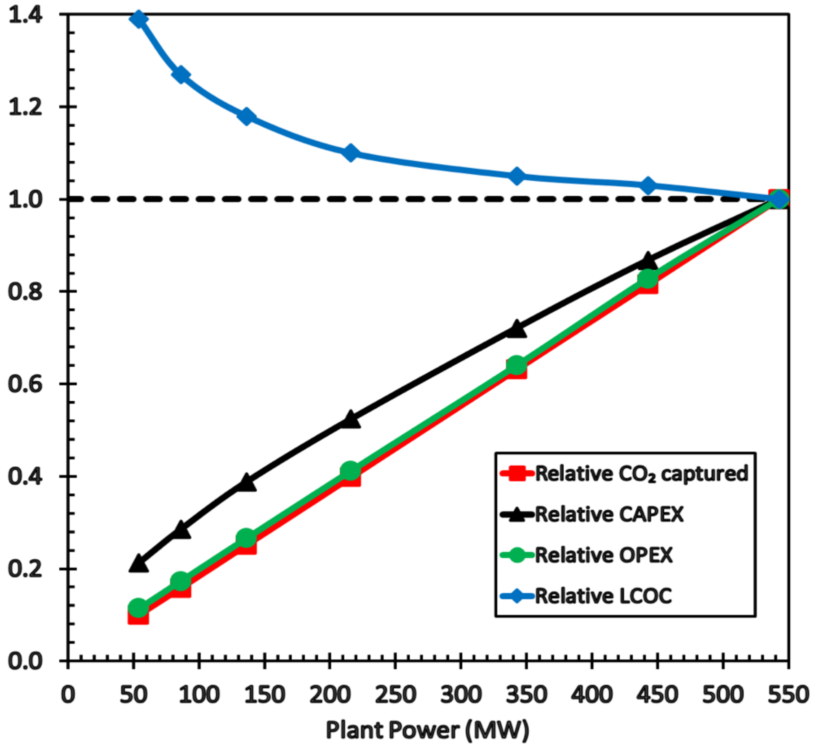


Figure: Relative change in CO_2 captured, CAPEX, OPEX & LCOC as power plant scale is reduced from 500 to 50 MW

- Levelized cost of capture (LCOC) was calculated at different power plant scales
  (Note: LCOC is for capture plant only and does not include WGS or changes to power cycle output)
- LCOC increased by ~ 40 % as power plant scale was reduced from 550 to 50 MW
- CAPEX per MW at modular scale was higher than the full-scale plant
- Highlights the importance of reducing CAPEX of modular scale capture processes

Ashkanani, H., et al. (2020). "Levelized Cost of CO_2 Captured Using Five Physical Solvents in Pre-combustion Applications". International Journal of Greenhouse Gas Control 101: 103135
Ashkanani, H., et al. (2020). "Effect of Power Plant Capacity on the CAPEX, OPEX, and LCOC of the CO2 Capture Process in Pre-Combustion Applications". 37th Annual International Pittsburgh Coal Conference, Virtual.

Applicable CO_2 capture processes for different gasification processes and end-use applications at modular scale

Syngas application→ Gasifier type & feedstock↓	Electricity generation only (IGCC with CO_2 capture)	H_2-Refinery / Ammonia	F-T Chemicals / Methanol / SNG
Oxygen-Blown Entrained Flow Gasifier (Coal/Pet Coke)	•Membrane/MR (H$_2$-selective & CO$_2$-selective) •SEWGS (PSA and high temp TSA) •Sorbent •Solvent •Hybrid options eg. H$_2$-selective membrane / solvent	•Membrane/MR (H$_2$-Selective) •Hybrid options with H$_2$-selective membrane •Solvent •Sorbent (PSA) •SEWGS (PSA, relatively low recovery)	•Membrane/MR (CO$_2$ selective) •Solvent (H$_2$S/CO$_2$/NH$_3$/ HCN) •SEWGS •Sorbent (PSA) (CO$_2$/H$_2$S selective)
Air-blown Transport Gasifier (Lignite)	•SEWGS (PSA) •Solvent (CO$_2$ & H$_2$S selective) •Membrane (high CO$_2$ selectivity)	•Large amounts of N$_2$ will complicate the process and increase the equipment size and hence capital cost of all steps (gasification, WGS reaction, gas cleanup, CO$_2$ removal). •For some chemical processes like F-T and methanol, N$_2$ may adversely impact conversion if not removed before synthesis.	
Oxygen-Blown Moving Bed Gasifier (Mixed Feedstock) High C1, C2, C3 Case	•Solvent (eg. MDEA) •SEWGS (90% CO$_2$ capture is difficult with approx. >10% C1 +) •Membrane (CO$_2$ selective facilitated transport membrane)	•Hybrid process with H$_2$-selective membrane and: •Solvent (eg. MDEA) •SEWGS	•SEWGS with upstream H$_2$S/NH$_3$/HCN removal and tar cracking •Solvent (eg. MDEA)

Conclusions

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GASIFICATION MARKET & TECHNOLOGY

- Global demand for coal gasification processes is increasing.
- Modular scale gasification will enable the use of mass manufacturing techniques, standard equipment, improved quality, quick assembly, and lower costs.
- A flexible and diverse path for further growth of coal gasification technology is through polygeneration ie. applications for power generation & production of other products like chemicals.
- Deployment of multiple small-scale gasifiers, rather than a few centralized large gasifiers, can increase the types of gasifier feedstock and potentially allow co-feeding of low cost or no cost feedstocks.
- IGCC power generation can provide low-cost, low-emission energy from locally sourced coal with superior carbon capture capabilities.
- Air blown gasification processes are unlikely to be suitable at modular scale for non-power applications due to the large amount of N_2 in the syngas which will increase the required equipment sizes and hence capital costs of all steps (gasification, gas cleanup, WGS reactor, CO_2 removal).
- All gasification applications will require syngas processing including CO_2 capture.

Conclusions

MODULAR PRE-COMBUSTION CO_2 CAPTURE

- R&D of modular scale CO_2 capture technologies is required, particularly to reduce CAPEX.
- Capture technologies that operate near the WGS syngas temperature and have low capital costs show most promise for pre-combustion CO_2 capture at modular scale.
  - Solvents: waste heat driven physical solvents & use of novel equipment (e.g. membrane contactors).
  - Membranes: H_2-selective membranes coupled with N_2 sweep; H_2-selective membrane coupled with a downstream waste heat driven solvent process for H_2S & CO_2 separation.
  - Sorbents: High temperature sorbents, particularly integrated with WGS.

EFFICIENCY SCREENING

- H_2-selective and CO_2-selective membrane reactors showed the best energy performance with net plant efficiencies of 36 % and 37 % respectively (compared to 33.7% for the baseline Selexol process).

ECONOMIC SCREENING

- For physical solvent absorption, as power plant size was reduced from full scale (500MW) to modular scale (50MW):
  - LCOC increased by ~ 40%.
  - Capital costs represented a larger portion of the LCOC at modular scale.

Future Work

- Work with NETL SEA on economic screening of modular capture processes (membrane, sorbent, etc…)
- Consider and develop modular scale polygeneration cases
- Assess performance of compact hybrid solvent-membrane system developed by NETL/RIC – novel and traditional physical solvent downstream of H_2-separation membrane

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