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Overview of Carbon Capture Technologies for Small Scale Biomass Combustion Facilities and a Canadian Case Study

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CanmetENERGY-Ottawa (CE-O) at Natural Resources Canada

- Over 100 years of advancing science and technology in the field of clean energy
- With over 200 scientists, engineers, technologists, managers, and support staff, developing and directing S&T programs and services aimed at a low-carbon future
- Mission is to lead the development of energy science and technology solutions for environmental and economic benefits of Canadians

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Why BECCS for decarbonisation?

When integrated with sustainable bioenergy, CCS becomes a pathway for negative emissions removing CO2 permanently from the carbon cycle. BECCS is used in 3 out of the 4 model pathways the IPPCC has set out to limit global warming to 1.5 deg. C.

This presentation …

- Provide high level technology overview of potential carbon capture technology types, suitable for small scale biomass heating and combined heat and power (CHP) plants
- Share the results of option analysis to evaluate CCU technologies for a potential demonstration at a 1.5 MW_{th} district heating plant in Ottawa, Ontario, Canada

Scope and Methodology

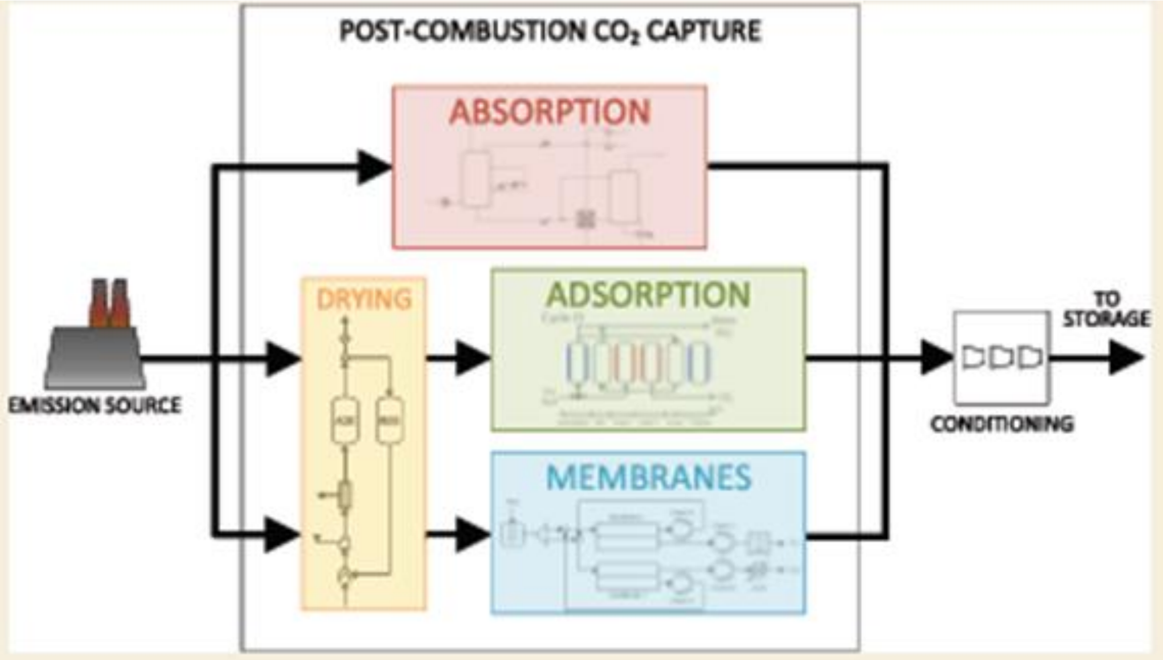
- Based on 2019 assessment of CCU technology options for a 1.5MW_{th} district heating facility in Ottawa, Ontario
- Focus on carbon capture technologies applicable for biomass heating or CHP plants up to 5 MW_{th}
- Technologies with TRL of 7 or higher in 2023 were included in this study
  - *TRL 7 means technology is prototype, near or at planned operational systems, examples: field testing or field trials*
- Characteristics of interest: Technology Specific; Operational Flexibility; Environmental; and Economic Related
- Relied on publicly available information

High Level Technology Overview Of Potential Carbon Capture Technology Types

Carbon Capture Technology Types Considered (TRL >7)

- **Post Combustion Capture Technologies**
  - Adsorption
    - Temperature Swing Adsorption (TSA)
  - Absorption
    - Amine Absorption
    - Enzyme-Enhanced Carbonate-Based Absorption
  - Membrane
  - Cryogenic Carbon Capture

- **Alternative Approaches**
  - Oxy-combustion



Taken from Zarco et.al. 2021 ..... [Postcombustion CO2 Capture: A Comparative Techno-Economic Assessment of Three Technologies Using a Solvent, an Adsorbent, and a Membrane | ACS Engineering Au]

Technology Characteristics Considered

- **Technology Specific**
  - TRL (as of 2023); CO_2 Recovery rate (%); Maximum achievable CO_2 purity (%); Process inputs and utilities needed; Electricity needed (kWh/tonne CO_2); Heating requirements; Water usage; Type of products/by-products; Technology suitability for small scale
- **Environmental Related**
  - Liquid and gas disposal (toxic/harmful materials)
- **Operational Flexibility**
  - Sensitivity to flue gas composition (PM, NOX, Water, trace metals, ash etc .)
- **Economic Related**
  - Total Annualized Cost (\$/tCO_2)

Overview of Carbon Capture Technologies - I

Key Metric/ Technology Type	Adsorption (TSA)	Absorption (Amine)	Absorption (Enzyme-Enhanced Carbonate-Based)	Membrane	Cryogenic Carbon Capture	Oxy-combustion
TRL (as of 2023)	8	7 -9	8	8	7	7
TECHNOLOGY SPECIFIC						
CO_2 Recovery rate (%)	90	80-95	83-90 (Fradette, 2017)	70-90	90-98	90
Maximum achievable CO_2 purity	95% CO_2(g)	99.9% CO_2(g)	99.95% CO_2(g) (Fradette, 2017)	95% CO_2(g) (Xu, 2019)	99.99% CO_2	98% CO_2
Process inputs and utilities needed	Air, natural gas (for steam), cooling water, power	Cooling water, steam, power, amine solvent, process water	Hot water, power, cooling water, solvent and enzyme	Cooling water, power	Power (electricity), cooling water	Power, cooling/chilled water
Electricity needed (kWh/tonne CO_2)	189 (White, 2016)	160 (Rodrigues, 2021)	169 (Fradette, 2017)	374 (Sato, 2022)	410 (Rodrigues, 2021)	341 (Symonds, 2020)
Heating requirements	Steam needed for regenerating adsorbent	Steam needed for regenerating amine solvent	Hot water needed for regenerating non-amine solvent	N/A	N/A	Fuel to operate oxygen removal
Water usage	• Direct contact cooling • Steam generation	• Direct contact cooling • Solvent dilution • Steam generation	• Direct contact cooling • Hot water for solvent regeneration • Stripper column	• Direct contact cooling	• Process cooling	• Direct contact cooling
Type of products / by-products	CO_2, flue gas condensate	CO_2, Flue gas condensate	CO_2, flue gas condensate	CO_2, Flue gas condensate	CO_2(l)	CO_2, water, wastewater
Technology suitability for small scale	Yes	Yes	Yes	Yes	Yes	Yes
Comments		Requires a lot of heat (in form of steam)		Requires multi-stage membrane to achieve high purity and capture	Secondary purification step	Retrofit may be required

Overview of Carbon Capture Technologies - II

Key Metric/Technology Type	Adsorption (TSA)	Absorption (Amine)	Absorption (Enzyme-Enhanced Carbonate-Based)	Membrane	Cryogenic Carbon Capture	Oxy-combustion
ENVIRONMENTAL RELATED						
Liquid and Gas Disposal (toxic materials)	No toxic materials	Yes Many solvents are toxic	Yes Less toxic than amine solvents	Yes pH too low to discharge to municipal water	No toxic materials	No toxic materials
OPERATIONAL FLEXIBILITY						
Sensitivity to Flue Gas Composition	Yes Ash deposition risk on sorbent	Yes Remove NO_x and SO_x before absorption column	Yes Remove NO_x and SO_x before absorption column	Yes Remove ash and NO_x and SO_x	No Can handle impurities from gas stream, including NO_x	No Can handle impurities from gas stream, including NO_x
ECONOMIC RELATED						
Total Annualized cost ($CAD/tonne CO2)*	146 (Zanco, 2021)	60 (Zanco, 2021)	39 (Fradette, 2017)	131 (Zanco, 2021)	46 (Rodrigues, 2021)	More expensive due to large cost from air separation unit

** Cost estimates are updated for 2023*

Highlights from a Case Study for 1.5 MW_{th} District Heating Plant in Ottawa, Ontario, Canada

Study Background and Design Basis

- Confederation Heights Central Heating Plant in Ottawa, ON, supplies hot water to a district heating network comprised of 8 buildings
- Public Services and Procurement Canada (PSPC) initiated a study for potential implementation of a carbon capture and utilization (CCU) technology to meet Greening Government Strategy target of min. of 50% net reductions in GHG emissions
- 1.5 MW_{th} wood chip-fired boiler with particulate removal via multi-cyclone and baghouse
- Biomass boiler emits ~16 tpd CO_2
- Design basis:
  - Capture rate of 10 tpd CO2 (~62%) to provide a buffer for indirect emissions
  - Desired on-stream factor is 220 days per year
  - All rotating equipment drivers shall be electric

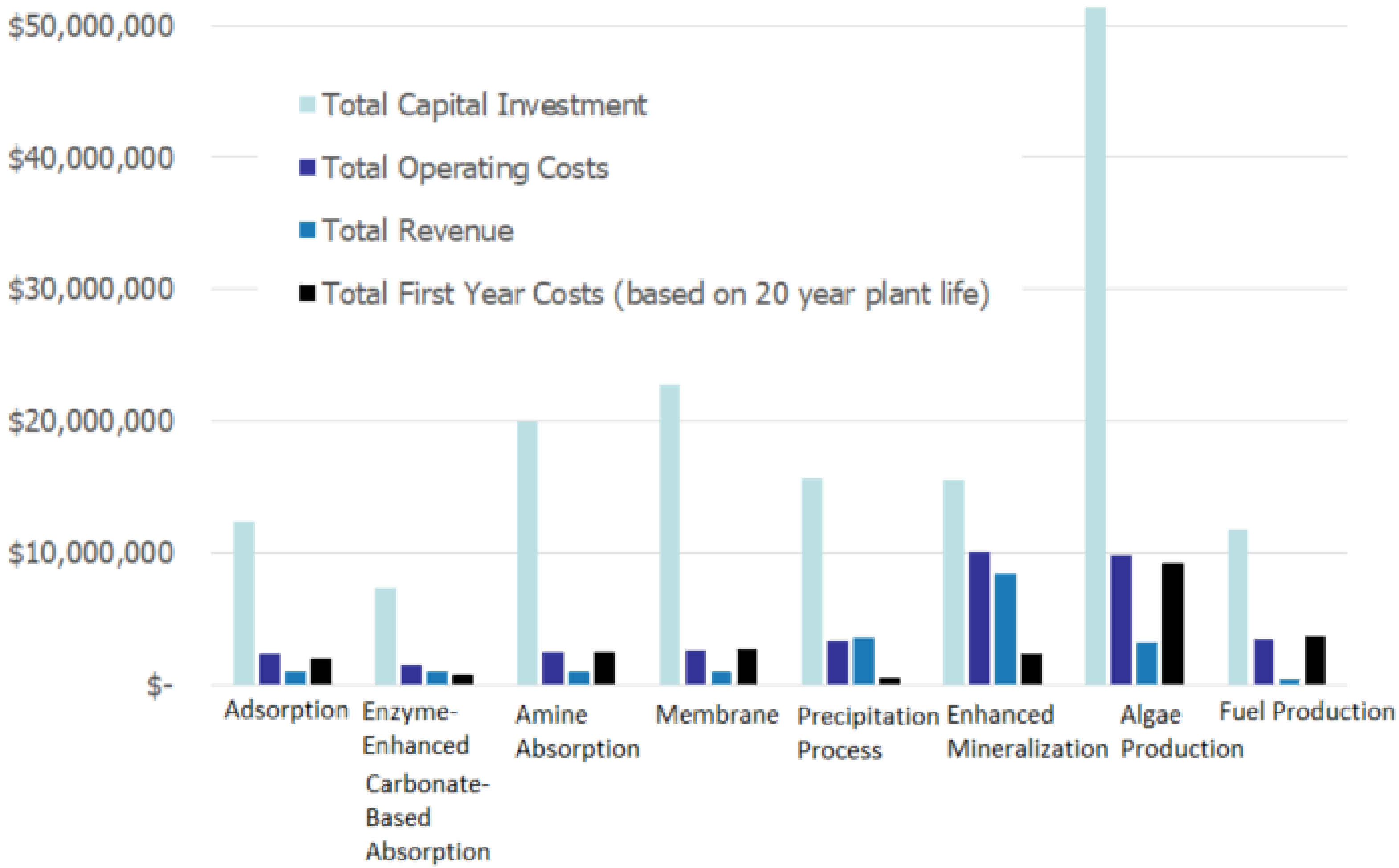
Selection of CCU Technology Options

- Level 1 Screening
  - Identified technologies sufficiently developed to meet the needs of the facility (TRL 7+ for capture, 6+ for utilization)
  - Close to 50 technologies passed Level 1 Screening (20 capture, 21 utilization, 7 combined)
- Level 2 Screening
  - Technology has been demonstrated at the scale required at the facility
  - Technology provider has a commercial presence in North America
  - Application is logistically feasible at the heating plant
  - Sufficient information available to complete the next stage of analysis

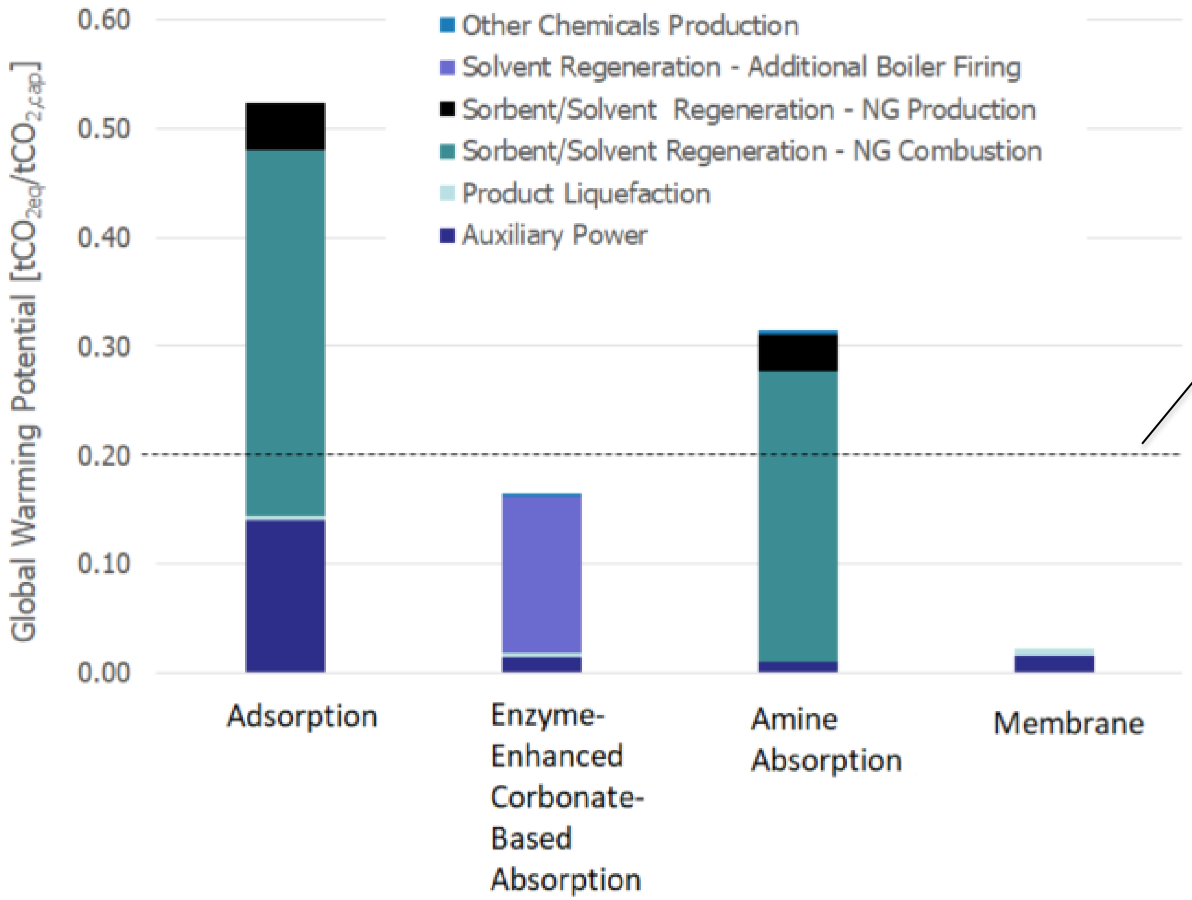
Further detailed analysis were performed on a narrowed list of options: 4 capture technologies, 4 utilization technologies, and 3 combined capture/utilization technologies

Key Metric	Adsorption	Enzyme-Enhanced Carbonate-Based Absorption	Amine Absorption	Membrane	Precipitation Process	Enhanced Mineralization	Algae Production	Fuel Production	Greenhouse	Gas Distributor	Animal Feed Production
Technology type	Capture	Capture	Capture	Capture	Capture & utilization	Capture & utilization	Capture & utilization	Utilization	Utilization	Utilization	Utilization
TRL	7	7	7	7	5; expected to be 7 by end of 2019	7	7	5; expected to be 7 by end of 2019	9	9	4; 7 by end of 2019
Resulting CO_2 product	95% $CO_2(g)$	99.95 % $CO_2(g)$	$CO_2(l)$	$CO_2(g)/N_2(g)$ mixture	PCC and PCM	Fertilizer	Algae for use as animal feed	Methanol and/or DME	Food	N/A	Biomass for use as animal feed
CO_2 emission reduction [%]	29.8	52.2	42.6	61.1	58.3	-902.6	48.7	-2.8 (SMR), 40.0 (electrolysis, ON)	Unknown	N/A	Unknown
CO_2 retention time	N/A	N/A	N/A	N/A	Long	Long	Short	Short	Short	Short (most applications)	Short
Energy req. [kWh/tCO_2]	350	351	244	382	70	55-210	3000-5500	Unknown	N/A	N/A	Unknown
Trucks/month, inputs	0	1	1	0	4	48	1	8	N/A	N/A	Unknown
Trucks/month, outputs	15	15	15	15	15	30	4	2	N/A	N/A	Unknown
Space req.	80-100 m^2	400 m^2	260 m^2	60 m^2	100 m^2	450 m^2	1250 m^2	120 m^2	20-40 ha	N/A	Unknown
Building/tower/stack height	No higher than existing buildings	Tower: 20-30 m; RPB: fits within existing building	15 m	3 m	8 m	7.7 m	Unknown	No higher than existing buildings	N/A	N/A	No higher than existing buildings

Cost Assessment



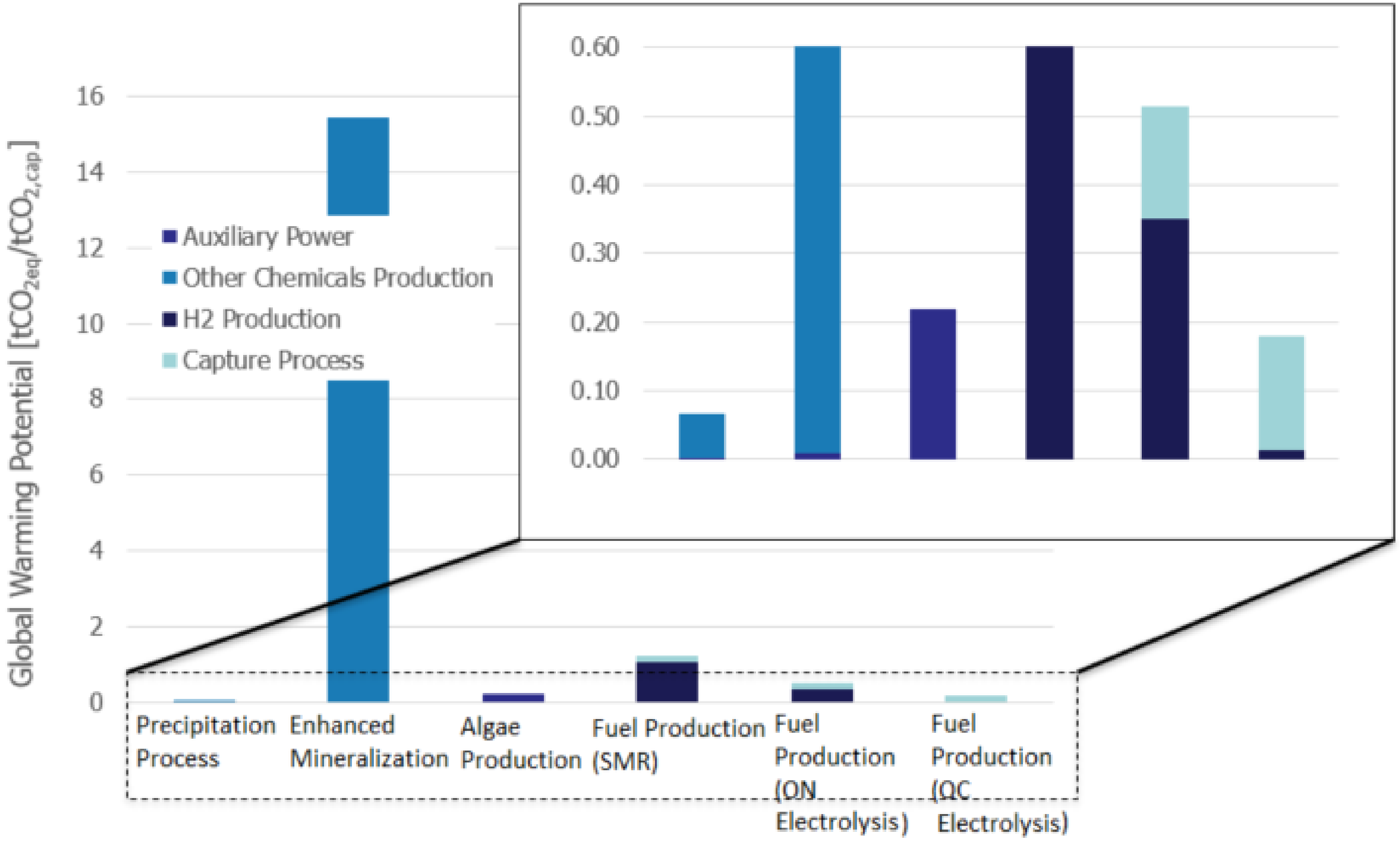
LCA Results: Capture Technologies



Threshold to meet 50% net reduction target

Design basis: 62% capture from flue gas

LCA Results: Utilization & Combined Technologies



Summary for Capture Technologies Overview

- Capture technology types included in the overview are adsorption (temperature swing), absorption (amine and enzyme-enhanced carbonate-based), membrane, cryogenic and oxy-combustion,
- The overview indicated that all the considered technology types show promise to be suitable for small scale biomass heating /CHP plants:
    - CO_2 capture in the range of 80 – 90 % with resulting CO_2 > 95%
    - Energy (electricity and heating/cooling) requirements vary widely depending on technology type
    - Adsorption (TSA), absorption and membrane technologies are sensitive to PM and NO_x, SO_x in the flue gas
    - Solvent can be toxic, and liquid effluents may need to be processed before discharging (pH too low)
    - Total annualized cost to capture one tonne of CO_2 varies widely.

Summary of 1.5 MW_{th} District Heating CCU Case Study Results

- Detailed technology option evaluation of CCU for a 1.5 MW_{th} wood chip district heating plant, located in Ottawa, ON, included 4 capture technologies, 4 utilization technologies, and 3 combined capture/utilization technologies:
  - Capture-only technologies generally at higher TRL than utilization and combined capture/utilization
  - Wide range in capital investment costs among the capture, combined capture & utilization technologies
- CO_2 capture facilities not expected to add considerable complexities to operation of current heating plant; however CO_2 utilization facilities expected to bring complexities to operation of current heating plant
- Significant capital costs and additional O&M costs for CO_2 capture and utilization facility
  - CO_2 capture and utilization facilities will entail additional power consumption
  - Heat integration of new facilities with current plant is important to reduce additional power and natural gas consumption
  - Some additional costs could be offset through the sale of CO_2-derived products
- Wide variability in net emissions reduction attainable from a life cycle perspective

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Supplementary Material

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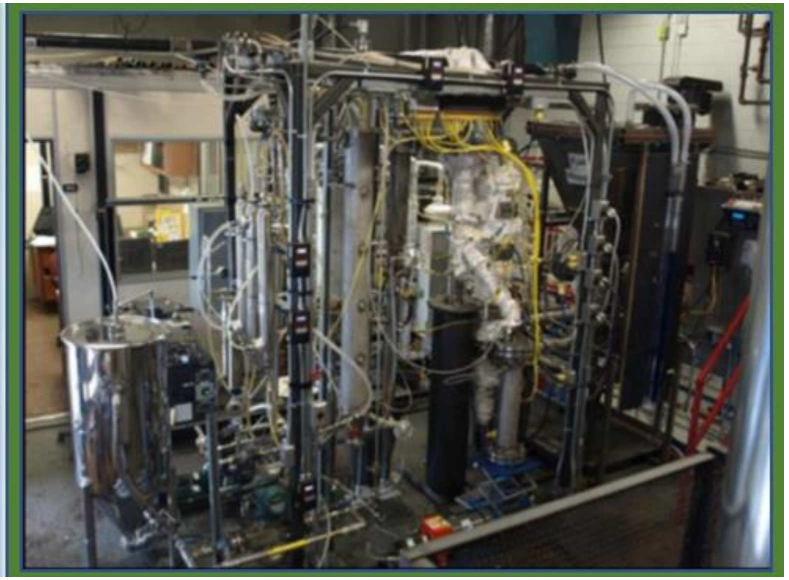
Bioenergy Program at CanmetENERGY-Ottawa

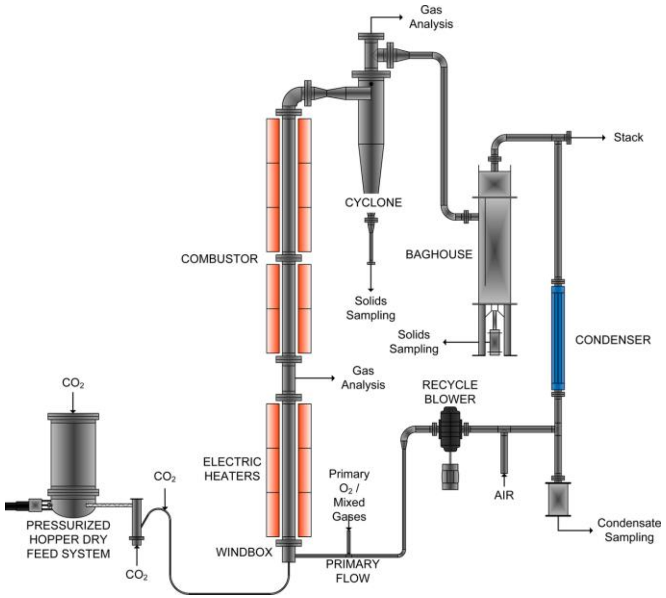
- Advancing increased utilization of biomass to lower carbon footprint of Canadian industries and communities and derive economic and employment benefits from the use of local, sustainable resources.
- Expertise: Bench and pilot scale experimental facilities, thermochemical conversion, catalytic and non-catalytic upgrading, TEA



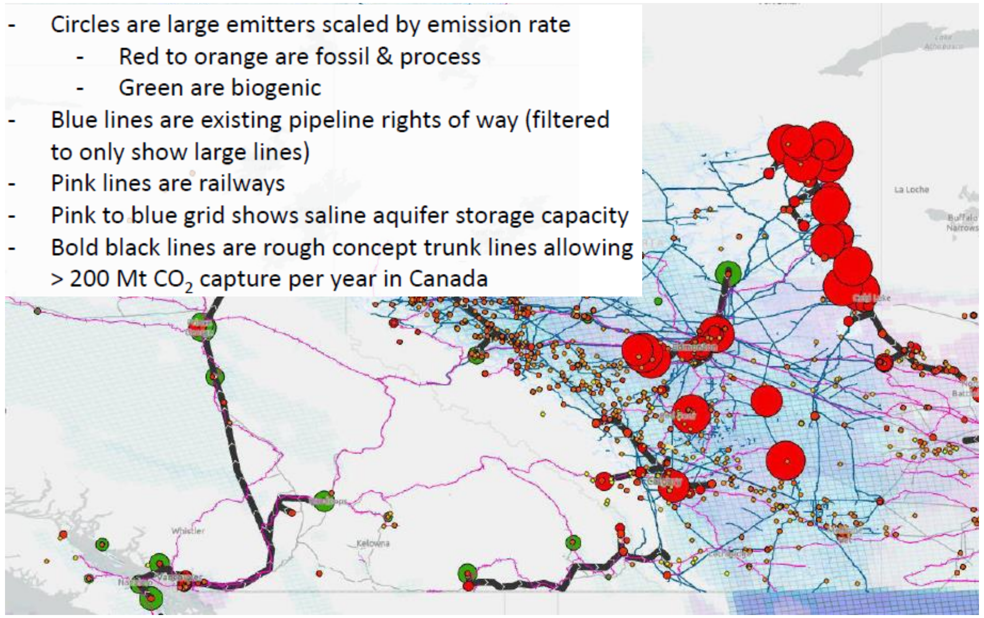
Link to Bioenergy webpage: Bioenergy (canada.ca)

Industrial Decarbonization Program at CanmetENERGY-Ottawa

- Supporting Canada’s industry in decarbonizing to meet net-zero ambitions
- Expertise: Bench- & pilot-scale experiments, Modeling, TEA-LCA, Python programming, Fluidization, Carbon capture



Experimental combustion and gasification of biomass for carbon capture



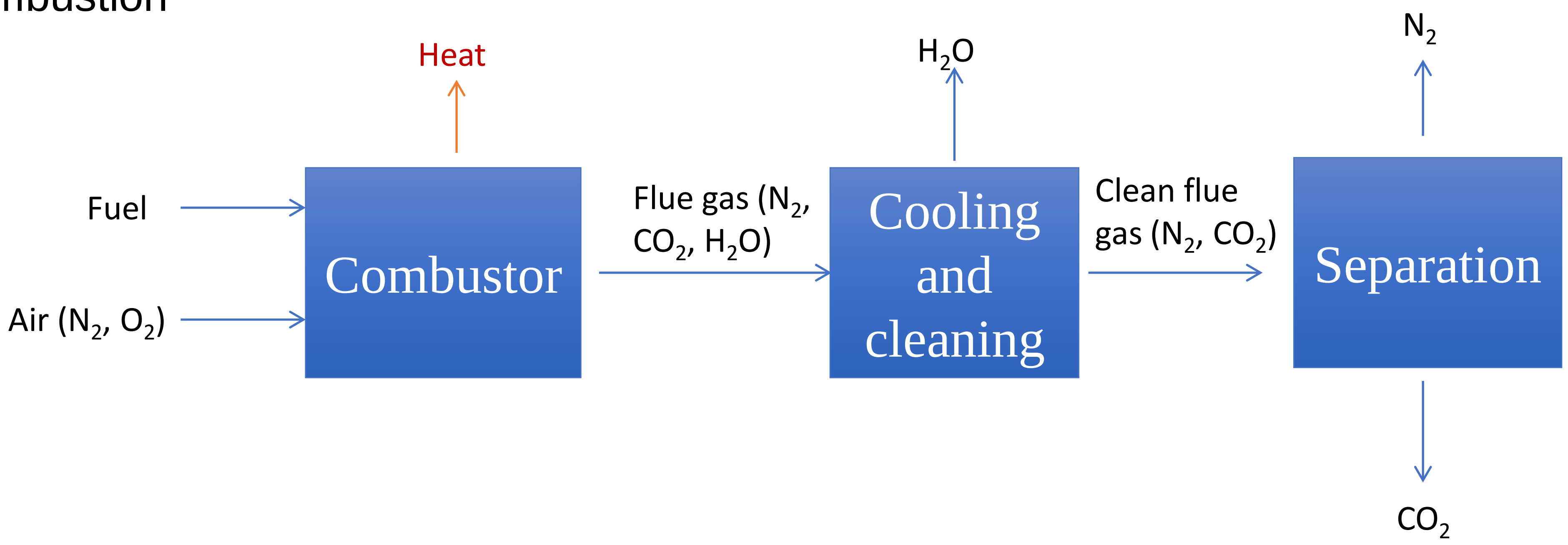
National CCUS Assessment Framework including biogenic CO_2

Carbon Capture Technologies

- For storage, CO_2 stream must have high purity and pressure
- Capture technology categories:
  - Post-combustion
  - Pre-combustion
  - Oxy-fuel combustion

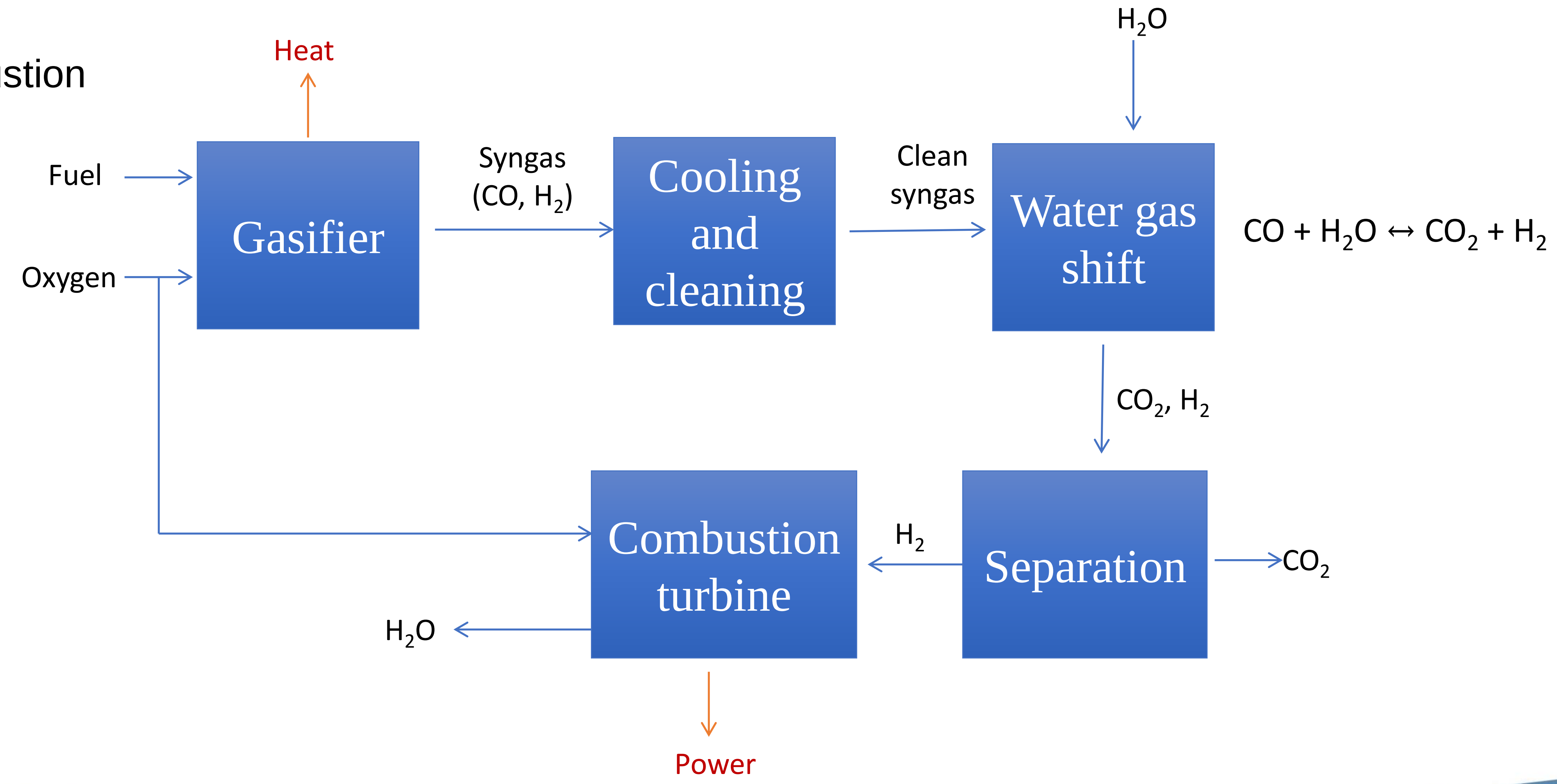
Carbon Capture Technologies

Post-combustion



Carbon Capture Technologies

Pre-combustion



Carbon Capture Technologies

Oxy-fuel combustion