Outlook for CO$_2$ capture technologies

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Post-combustion

Low-medium CO$_2$ partial pressure

Medium-high CO$_2$ partial pressure

High CO$_2$ partial pressure

CO$_2$ partial pressure = molar fraction*gas pressure
Post-combustion: Dilution of CO₂

Pressure ≈ 1 atm
CO₂ partial pressure 0.03-0.15 atm
Absorption – process

Absorption process diagram showing:
- Feed gas entering a gas cooler
- C.W. (coolant water) flow
- Treated gas outlet
- Water wash
- Absorber
- Rich solvent
- Lean solvent
- C.W.
- CO₂
- Stripper/desorber
- Steam
- Reboiler

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Absorption

CO\textsubscript{2} partial pressure

Energy consumption

0.6 GJ/t CO\textsubscript{2}
1.5 GJ/t CO\textsubscript{2}
2.4 GJ/t CO\textsubscript{2}
3.3 GJ/t CO\textsubscript{2}
4.2 GJ/t CO\textsubscript{2}

Physical solvents
Selexol, Rectisol, Purisol,…

MDEA

Benfield/K\textsubscript{2}CO\textsubscript{3}

ECONAMINE FG+
KM CDR/KS-1

New?

MEA

State-of-the-art
Power plant flue gas

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Absorption – Outlook?

- **Phase-change solvents**
  - Amino acid salts
  - NH$_3$/ammonium carbonate/ammonium bicarbonate
  - NH$_3$/amine mixtures
  - Amines

- **Challenges – still**
  - Energy consumption (3.8 MJ/kg CO$_2$)
  - Corrosion
  - Amine degradation, oxidation (SO$_x$, COS, C$_2$S, NO$_2$, O$_2$, fly ash)
  - Amine/ammonia emission to air
Absorption – Exhaust gas recycle

Reduction volumetric flow rate
-> reduction absorber diameter
Higher CO₂ fraction, y_CO₂=6-8%
-> reduction absorber height
Pre-combustion

- **Current**
  - **IGCC** (Integrated Gasification Combined Cycle)
    - Commercial gas separation technology available
  - **IRCC** (Integrated Reforming Combined Cycle)
    - Commercial gas separation technology available

- **Next?**
  - $\text{H}_2/\text{O}_2/\text{CO}_2$ membranes
  - $\text{CO}_2$ sorbents
Pre-combustion: Dilution of CO₂

Pre-combustion natural gas, air-blown reforming

- CO: 0.5%
- N₂: 34.6%
- H₂: 46.8%
- H₂O: 0.1%
- CH₄: 0.2%
- SO₂: Ar: 0.4%

Pre-combustion - IGCC

- CO: 2.2%
- N₂: 2.5%
- CO₂: 38.3%
- H₂: 56.1%
- H₂O: 0.2%
- CH₄: 0.1%

Pressure ≈ 20-70 atm
CO₂ partial pressure 3.5-27 atm

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IGCC without CO₂ capture
Integrated Gasification Combined Cycle

Quench water
Recovered heat

Coal feed
O₂

Gasifier

Air Separation Unit

Compressed air

Quench/heat recovery
Particulate removal
Sulfur removal

H₂S

Gas turbine

HRSG

Recycled heat

H₂S

Hydrogen-rich gas

Air

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IGCC with CO$_2$ capture
Integrated Gasification Combined Cycle

- Quench water
  - Recovered heat
- Raw syngas
  - Quench
  - Heat recovery
- Gasifier
  - Recovery of heat
- Quench
  - Size big
  - Cooling
  - Shift reaction
  - Selexol
  - Rectisol
  - Fluor Solvent
  - Low Temp!
- Hydrogen-rich gas
- CO$_2$ capture
- H$_2$S
- CO$_2$
- CO$_2$ storage

- Coal feed
  - O$_2$
- Air
  - Separation Unit
  - N$_2$
- Compressed air
  - HRSG
  - ST
  - Gas turbine
  - Air
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IGCC with CO$_2$ capture
Integrated Gasification Combined Cycle

Quench/heat recovery

Particulate removal

Shift reaction

Sulfur removal

CO$_2$ capture

Quench water

Recovered heat

Raw syngas

Coal feed

O$_2$

Gasifier

Air Separation Unit

N$_2$

Compressed air

Air

Nitrogen

Gas turbine

HRSG

ST

Fuel dilution

TIT reduction

CO$_2$ storage

Hydrogen-rich gas

Steam

H$_2$S

ST
Pre-combustion – SEWGS
Sorption Enhanced Water Gas Shift

\[
\text{Fuel} \rightarrow \text{Gasifier} \rightarrow \text{Reformer} \rightarrow \text{WGS gas-shift (WGS)} \rightarrow \text{CO}_2 \text{ capture} \rightarrow \text{WGS + gas separation}
\]

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{CO}_2
\]

\[
\text{CO}_2 + \text{sorbent} \rightarrow \text{sorbent} \times \text{CO}_2
\]

\[
\dot{Q} \rightarrow \text{Regeneration of sorbent}
\]

Sorbent

\[
\dot{Q} \rightarrow \text{Regeneration of sorbent}
\]

\[
\text{Lithium orthosilicate (Li}_4\text{SiO}_4\text{)}
\]

\[
\text{Hydrotalcite (Mg}_6\text{Al}_2\text{(OH)}_{16}\text{[CO}_3\text{]} \times 4\text{H}_2\text{O/K}_2\text{CO}_3}
\]

\[
\text{Dolomite (CaCO}_3 \times \text{MgCO}_3\text{)}
\]

\[
\text{Calcium carbonate (CaCO}_3\text{)}
\]

\[
\text{CPO-27-Ni (MOF)}
\]
Hydrogen Membrane Reactor (HMR)

Fuel → **Gasifier** → **Reformer** → Water gas-shift (WGS) → **CO2 capture** → H2

Fuel + H2O → **Membrane** → Sweep gas + H2

Sweep gas, e.g. H2O, N2, air

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Oxy-combustion - Dilution of CO₂

Pressure ≈ 1 atm
CO₂ partial pressure 0.6-0.8 atm

Oxy-combustion

natural gas

coal

H₂O; 14.3 %
N₂; 3.2 %
Ar; 4.8 %
O₂; 2.0 %
CO₂; 75.7 %

H₂O; 16.9 %
SO₂; 0.3 %
N₂; 13.5 %
Ar; 1.9 %
O₂; 4.9 %
CO₂; 62.5 %
Oxy-combustion principles
Recirculation of gaseous CO₂ – atmospheric cycle

Steam power cycle

Preheater

Combustion

CO₂(g) + H₂O(g)

CO₂(g) + H₂O(g)

Fan

Cooler

To CO₂ compression & conditioning

H₂O(l)

CO₂(g) + H₂O(g)

Fuel

Oxygen
Oxy-combustion coal 30 MW$_{\text{thermal}}$

Schwarze Pumpe

Commissioning Sept 9, 2008

Vattenfall
Germany

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Oxy-combustion – outlook

- Coal: plants are being built!
  - Purification of CO$_2$ before transport/storage
- Natural gas
  - oxy-combustion gas turbines less likely
  - though cost is rather low
- Air separation
  - **Cryogenic distillation** dominating for the foreseeable future
  - Ceramic mixed ion/electron conducting membranes – progress?
Oxy-combustion - air separation

- Air Separation Technologies
  - Membrane
    - Polymeric membrane
    - Ceramic membrane
      - Electrically driven membrane
      - Partial pressure driven membrane
  - Cryogenic distillation
  - Adsorption
    - Pressure Swing Adsorption (PSA)
    - Vacuum Swing Adsorption (VSA)
    - Vacuum Pressure Swing Adsorption (VPSA)
Oxygen ion transport membranes

ZrO$_2$-Y$_2$O$_3$, 
CeO$_2$, 
La$_{1-x}$Sr$_x$Co$_{1-y}$Fe$_y$O$_3$-d, 
Sr$_2$Fe$_2$O$_5$, 
LaGaO$_{3-d}$, 
(Bi$_2$O$_2$)(A$_{n-1}$B$_n$O$_x$), 
La$_2$NiO$_{4+d}$

Efficiency potential very good

Oxygen ion conducting membrane, e.g. SOFC

Mixed conducting membrane AZEP
Oxygen ion transport membranes

- When integrated in power cycles with CO2 capture
  - High efficiency potential (AZEP, SOFC)

- Challenges:
  - Carbonate formation
  - Oxidation
  - Runaways and hot spots
  - Limited pressure gradient across membrane
  - Sulfur tolerance
  - Transient limitations
  - Ceramic material evaporation
Chemical Looping Combustion (CLC)

\[
\text{Fuel Reactor: } \text{Me}(s) + \frac{1}{2}\text{O}_2(g) \xrightarrow{\text{Oxidation}} \text{MeO}(s) \\
\text{Air Reactor: } \text{O}_2/1\text{Me}(s) + \text{MeO}(s) \xrightarrow{\text{Oxidation}} 2\text{CO}(s) + 2\text{H}_2(s) \\
\text{Air: } \text{CH}_4(g) + 4\text{MeO}(s) \xrightarrow{\text{Reduction}} \text{CO}_2(g) + 2\text{H}_2\text{O}(g) + 4\text{Me}(s)
\]
Chemical Looping Combustion (CLC)

- **Natural gas**
  - In power plants; needs to be pressurised
    → Gas turbine Combined Cycle, high efficiency
    - Preferably high temperature >900 °C
    - Materials?
  - Process heaters, atmospheric, < 900 °C
  - Syngas production

- **Coal**
  - Ash and oxygen carrier separation
  - Carbon conversion
Conclusions

- No clear winner (still)
  - The will to build demo plants moves many towards post-combustion methods
  - IGCC more expensive than PC, in favour of post-combustion
- Coal: Pre-, post, oxy-combustion?
- Membranes
  - High-temperature ion/mixed conduction, high potential, long way to go
  - Low-temperature membrane, potential for high partial pressure applications, but not yet
- Environmental impact of emissions of chemicals to air needs proper attention
Thank you!

TCCS-5
5th Trondheim Conference on CCS
## Technology status

### CO₂ capture in power plants

<table>
<thead>
<tr>
<th>Natural gas</th>
<th>Post-combustion</th>
<th>Pre-combustion</th>
<th>Oxy-combustion</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Commercial readiness</td>
<td>Improvement potential</td>
<td>Commercial readiness</td>
</tr>
</tbody>
</table>

- **High**
- **Medium**
- **Low**

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### Technology status

#### CO₂ capture in power plants

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Post-combustion</th>
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<tbody>
<tr>
<td>Coal</td>
<td></td>
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<tr>
<td>Natural gas</td>
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</tbody>
</table>

**Coal**
- Commercial readiness: High
- Improvement potential: Medium-high

**Natural gas**
- Commercial readiness: Medium-low
- Improvement potential: Low

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- NTNU
- SINTEF

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