Technology status of hydrogen production from fossil fuels w/CCS

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Agenda

- Air Liquide Climate Objectives & Hydrogen production
- CO₂ Capture from SMR : Technologies Portfolio
- CO₂ Capture from ATR : Technologies Portfolio
2018 Key Figures

- **~66,000 Employees**
- **Present in 80 Countries**
- **More than 3.6 Million Customers & Patients**
- **Revenue**: €21bn
- **Net Profit (Group Share)**: €2.1bn
- **Investment Decisions**: >€3.1bn
Different Syngas (H\textsubscript{2} / CO / CO\textsubscript{2}) Generation Technologies

![Diagram showing different syngas generation technologies]

SMR

ATR

POX

H\textsubscript{2}/CO ratio
Syngas (H₂ / CO / CO₂) Generation Technologies

ATR is not limited by capacity, and can have an advantage with operation at higher pressure.
Greenhouse gas emissions within Air Liquide

Air Liquide GHG emissions in 2018

Direct
15.4 Mt

- 9.5 Mt from hydrogen production units
- 5.0 Mt from cogenerations
- 0.7 Mt from transportation activities

Indirect
12.4 Mt

- 93% for the supply of air separation units

CO₂
27.8 Mt
emitted in total

Direct GHG : Scope 1
from Assets owned or controlled

Indirect GHG : Scope 2
from Energy generated upstream (purchased electricity, steam...)

0.7 Mt
93%
5.0 Mt
from transportation activities
from cogenerations
from hydrogen production units
for the supply of air separation units
9.5 Mt
15.4 Mt
emissions in 2018

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CLIMATE OBJECTIVES

ASSETS
Reduce our carbon intensity in 2025 vs. 2015 by 30%

CUSTOMERS
Act for clean industry by developing low-carbon solutions

ECOSYSTEMS
Contribute to a new low-carbon society
Air Liquide Group CO₂ & Climate Objectives

- **Active projects** underlining Air Liquide’s ambition in the Energy Transition:
  - Liquid hydrogen production from biomethane SMR, US West Coast [Press release November 28, 2018]
  - Long term purchase agreement for 50 MW renewable electricity in Texas [Press release November 30, 2018]
  - 20.5 M$ Strategic investment in electrolysis technology (Hydrogenics) [Press release January 28, 2019]
  - Investment in 20 MW water electrolysis plant in Canada [Press release February 25, 2019]
  - Steel industry - hydrogen injection to blast furnace with ThyssenKrupp [Press release July 19, 2019]
  - Steel industry - CCU on blast furnace with ArcelorMittal [Press release October 17, 2019]
  - Hydrogen mobility - more than 120 Hydrogen refueling stations (HRS) installed by Air Liquide in the world
Air Liquide is actively engaged in development of CCS in the North Sea region

- Porthos CCS project, Port of Rotterdam (PoR), Netherlands
  - Investigation on capture of CO₂ from Air Liquide hydrogen plants

- H-vision study, PoR
  - Technical solution (ATR and Rectisol technologies)
  - Economics of blue hydrogen as means to cut emissions of a large industrial basin

- Northern Lights
  - Exploring cooperation on CO₂ capture, liquefaction, and transportation to Norway
CO₂ Capture from SMR
Air Liquide Carbon Capture Processes Portfolio

- **ABSORPTION**
  - RECTISOL™, aMDEA®

- **CRYOGENIC CAPTURE**
  - CRYOCAP™

- **MEMBRANES**
  - MEDAL™
  - PORÖGEN™

- **ADSORPTION**

**CO₂ Content in Feed Gas**

- 1%
- 20%
- 40%
- 60%
- 80%
- 100%

**CO₂ Product Purity**

- 70%
- 90%

**Product Purity**

- 100%
- 90%
- 70%
- 50%
- 30%

**CO₂ Content in Feed Gas**

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Overview of Capture Solutions for SMR Plants

Solution 3
Absorption Amine Unit
Or cold membranes (under development)

Flue gas
~100% of CO₂ emissions

Solution 1
Absorption Amine Unit

Syngas
~60% of CO₂ emissions

PSA Tail Gas
~60% of CO₂ emissions

Solution 2
Cryocap H₂™

Natural Gas

SMR

SHIFT

PSA

H₂

Flue gas

Absorption Amine Unit
### Overview of Capture Solutions for SMR Plants

<table>
<thead>
<tr>
<th>#</th>
<th>Technology</th>
<th>% CO₂ capture</th>
<th>Other Benefits</th>
<th>Capture Cost (USD / mton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Amines (syngas)</td>
<td>~60% of total emissions</td>
<td></td>
<td>$30 - 40 / mton</td>
</tr>
<tr>
<td>2</td>
<td>Cryocap™</td>
<td>~60% of total emissions</td>
<td>● +13 to +20% H₂ production OR ● -4% specific NG consumption ● -5 to -8% capex, balance of plant</td>
<td>$20 - 40 / mton</td>
</tr>
<tr>
<td>3</td>
<td>Amines (flue gas)</td>
<td>~90% of total emissions</td>
<td></td>
<td>$60 - 80 / mton</td>
</tr>
</tbody>
</table>

1) Capture cost defined as TCO delta divided by captured CO₂
2) Range in capture cost is dependant on Opex drivers (power, steam pricing) and CO₂ utilization (quality, pressure)
Selected References
Amine (Syngas) - Northern Alberta, Canada

- **Syngas Treatment with BASF OASE White**
  - Designed and constructed by Air Liquide
  - Start-up in 2016 - 161,000 Nm³/h H₂ SMR Train
  - Entire plant including Amine is modularized
  - Over 1,200 mtpd CO₂ captured from syngas
  - CO₂ intended for alkaline wastewater treatment

- **Flexible operation with or without CO₂ capture**

- **Air Liquide references include:**
  - Design or construction of over 80 units
  - Own and operating over 20 units
Selected References
Cryocap™ - Port Jerome, France

- Retrofit of an AL SMR
  - SMR supplying 50,000 Nm³/h H₂ to Exxon refinery
  - PSA off gas treated: 17,000 m³/h
  - 300 tons/day food-grade liquid CO₂ (99.9% purity)

- Start up in H₁ 2015
  - Integration to an existing SMR without impact on SMR operations
  - Reliable operation of the compressor, cold box and membranes
  - Increase of H₂ production flow
  - Centrifugal compression scalable for large plants
  - Additional module for food grade liquid CO₂

World’s only referenced cryogenic solution at industrial scale on syngas capture
New Technologies Development

Cold membrane development

Hybrid Membrane and Cryogenic Technology

Joint development with the DOE
Cold membrane tested at 10tpd scale

Key features

- Integration between flue gas compression and membrane residue expansion
- Membrane operated at mild cryogenic conditions
- CO\textsubscript{2} product can be directly pumped or produced liq
- High level of CO\textsubscript{2} recovery
- High level of modularization with membranes
- Possibility to integrate heat of compression

Air Liquide patented technology
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CO$_2$ capture from ATR
ATR reactor

\[ \text{H}_2, \text{CO}, \text{CO}_2 \]
Example of ATR Based Hydrogen Production + CCS

- Natural Gas
  - ASU
  - Oxygen

- HDS + Sulphur Removal

- ATR (w heat recovery) → MT Shift (w heat recovery) → Rectisol
  - Some of the product H₂ is used as fuel to replace NG fuel.

- Fire Heater

- Offsites and Utilities

- Carbon Dioxide
  - CO₂: > 95 %-vol
  - Rest: inerts

- Hydrogen
  - H₂: > 95.5 %-vol
  - Up to 60 bar (100 bar at demo level)
  - Rest: CH₄, CO + inerts

- Offsites and Utilities

- Water

- Electricity

Hydrogen

- ASU
- HDS + Sulphur Removal
- ATR (w heat recovery)
- MT Shift (w heat recovery)
- Rectisol
- Fire Heater
- Offsites and Utilities
- Natural Gas
- Electricity
- Water

- CO₂ captured: 88.0% (inc. Product slip)

- Natural Gas
  - NG fuel

- Some of the product H₂ is used as fuel to replace NG fuel.
AIR LIQUIDE Lurgi’s Large ATR - World Map of References
AL CO₂ Capture Technologies
Air Liquide Lurgi Rectisol™

- Applicable for very large scale, high pressure H₂ production from Autothermal Reforming (ATR) or gasification
- Patented Air Liquide technology
- 85 units in operation worldwide
- Achieves five steps in one unit
  - Bulk CO₂ removal
  - CO₂ purification
  - and in gasification application:
    - Trace contaminant removal
    - Desulfurization
    - Acid Gas Enrichment

Shenhua Rectisol Plant in Ningxia, China
**Four Trains:** 1.12MM Nm³/h each
**Startup:** June 2016
Thank you for your attention