Technology status of hydrogen production from fossil fuels w/CCS
Agenda

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

- Approximately 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

2018 Figures
Different Syngas ($H_2 / CO / CO_2$) Generation Technologies

<table>
<thead>
<tr>
<th>Process</th>
<th>H$_2$/CO Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMR</td>
<td>5</td>
</tr>
<tr>
<td>ATR</td>
<td>2</td>
</tr>
<tr>
<td>POX</td>
<td>1</td>
</tr>
</tbody>
</table>

![Diagram of hydrogen production from fossil fuels with CCS](image)
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

Indirect
12.4 Mt

Direct GHG : Scope 1 from Assets owned or controlled

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

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

- 93% for the supply of air separation units

CO₂ emitted in total
27.8 Mt

Direct GHG emissions in 2018:
- 15.4 Mt Direct GHG (Scope 1)

Indirect GHG emissions in 2018:
- 12.4 Mt Indirect GHG (Scope 2)

Greenhouse gas emissions within Air Liquide:
- Direct: 15.4 Mt
- Indirect: 12.4 Mt

Total CO₂ emissions: 27.8 Mt
- 9.5 Mt from hydrogen production units
- 5.0 Mt from cogenerations
- 0.7 Mt from transportation activities
- 93% for the supply of air separation units
CLIMATE OBJECTIVES

A global approach

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

Technology status of hydrogen production from fossil fuels w/CCS
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
  - Long term purchase agreement for 50 MW renewable electricity in Texas
  - 20.5 M$ Strategic investment in electrolysis technology (Hydrogenics)
  - Investment in 20 MW water electrolysis plant in Canada
  - Steel industry - hydrogen injection to blast furnace with ThyssenKrupp
  - Steel industry - CCU on blast furnace with ArcelorMittal
  - 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™
  - POROGEN™
- ** ADSORPTION**

**CO₂ Content in Feed Gas**

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

**CO₂ Product Purity**

- 70% 90%
Overview of Capture Solutions for SMR Plants

- **Solution 1**: Absorption Amine Unit
  - Absorption Amine Unit
  - Or cold membranes (under development)

- **Solution 2**: Cryocap H₂™
  - PSA Tail Gas
  - ~60% of CO₂ emissions

- **Solution 3**: Absorption Amine Unit
  - Flue gas
  - ~100% of CO₂ emissions

- **SMR**
  - Natural Gas

- **SHIFT**
  - Syngas
  - ~60% of CO₂ emissions

- **PSA**
  - H₂
# 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>
</tbody>
</table>
| 2  | Cryocap™              | ~60% of total emissions | ● +13 to +20% H₂ production  
OR  
● -4% specific NG consumption  
● -5 to -8% capex, balance of plant | $20 - 40 / mton            |
| 3  | Amines (flue gas)     | ~90% of total emissions |                                                                              | $60 - 80 / mton           |

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
- CO₂ product can be directly pumped or produced liq
- High level of CO₂ recovery
- High level of modularization with membranes
- Possibility to integrate heat of compression

Air Liquide patented technology
3

CO$_2$ capture from ATR
ATR reactor

**Oxygen**

**Natural Gas Steam**

**Multilayer Refractory Lining**

**Catalyst**

**Support Material**

**Synthesis Gas**

\[ H_2, CO, CO_2 \]
Example of ATR Based Hydrogen Production + CCS

- Natural Gas
- Electricity
- Water

ASU → Oxygen

HDS + Sulphur Removal → ATR (w heat recovery)

ATR (w heat recovery) → MT Shift (w heat recovery)

MT Shift (w heat recovery) → Rectisol

Rectisol → CO₂ captured: 88.0% (inc. Product slip)

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

Some of the product H₂ is used as fuel to replace NG fuel.

Fire Heater

Offsites and Utilities

Oxygen

CO₂: > 95 % -vol
Rest: inerts

Carbon Dioxide

Natural Gas

Electricity

Water

Hydrogen

CO₂: > 95 % -vol
Rest: inerts

Carbon Dioxide

Some of the product H₂ is used as fuel to replace NG fuel.

Offsites and Utilities

Carbon Dioxide

CO₂: > 95 % -vol
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AIR LIQUIDE Lurgi’s Large ATR - World Map of References

AIR LIQUIDE, THE WORLD LEADER IN GASES, TECHNOLOGIES AND SERVICES FOR INDUSTRY AND HEALTH

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Chatou France
November 6th 2019
Fabrice Del Corso • R&D

P.T. Kaltim Methanol Industry Location: Indonesia Product: 2,000 mtpd Methanol Start-up: 1998

TITAN and ATLAS Methanol Location: Trinidad Product: 2,500 / 5,000 mtpd Methanol Start-up: 1999 / 2004

Methanex Chile IV Location: Chile Product: 2,400 mtpd Methanol Start-up: 2005

South Africa Product: 15.3 / 21 mil Nm³/d Syngas Start-up: 1979 / 1988

Freiberg Test Lab Location: Germany Product: Start-up: Natgasoline Location: Texas / USA Product: 4,950 mtpd Methanol Start-up: 2018

YCI-M1 Location: Louisiana / USA Product: 4,950 mtpd Methanol Start-up: 2018

ZAGROS 1 / ZAGROS 2 Location: Iran Product: 5,000 / 5,000 mtpd Methanol Start-up: 2006 / 2009
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