World Scale Hydrogen Production – Opportunities for large-scale CO₂ capture

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Global Hydrogen Capabilities and Experience

- Worldwide leadership position in outsourced Hydrogen production and recovery
  - Hydrogen supplier since 1975
  - Supply >3.7 million Nm$^3$/h of hydrogen
- Strong focus on the refining and chemical industries
- Own and operate over 80 hydrogen plants around the world
- Established reputation for high reliability operation
  - Over 1400 operating years for Hydrogen plants
- Complete technology portfolio in Hydrogen, CO, Syngas equipment
  - Proprietary Separation Systems (membrane, PSA, cold boxes)
  - Global Alliance with TechnipFMC for reforming technology
Air Products builds and operates hydrogen plants of all sizes, from <1 kNm³/h to >170 kNm³/h, tied to pipelines or as standalone “on-site” facilities.

- **Catlettsburg, Kentucky**
  - >35 kNm³/h

- **Norco, Louisiana**
  - >170 kNm³/h

- **Tarragona, Spain**
  - 66 kNm³/h

- **Mantova, Italy**
  - 17 kNm³/h

- **Rotterdam, Netherlands**
  - > 130 kNm³/h H₂

- **Chengdu, China**
  - 100 kNm³/h H₂

- **Cressier, Switzerland**
  - 8 kNm³/h

**PHG Range**
- 100 – 830 Nm³
Leading Global Hydrogen Pipeline Positions
“Colours” of hydrogen in the energy transition

- Most hydrogen is from fossil fuels
  - if all the associated CO₂ is emitted to atmosphere, that hydrogen is “grey”
- Fully renewable “green” hydrogen can be produced by (a) electrolysis from renewable electricity or (b) reforming of biogas
  - “green” cannot yet replace “grey” hydrogen
- “Blue” hydrogen – is hydrogen from fossil fuels but with CO₂ capture – this is widely seen as essential step in the energy transition
  - “Blue” hydrogen creates the infrastructure to enable the expansion of “green” hydrogen
  - “Blue” hydrogen can achieve negative emissions when fed with biogas
Decarbonised Hydrogen

$CO_2$ removal from SMR – 3 options

**Table 1**: Levelised Cost of H₂ (LCOH), $CO_2$ Avoidance Cost and Overall $CO_2$ Capture Rate

<table>
<thead>
<tr>
<th>Capture Case</th>
<th>LCOH Euro Cent/Nm³</th>
<th>$CO_2$ Avoidance Cost Euro/t</th>
<th>Overall $CO_2$ Capture Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>No capture</td>
<td>11.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Option 1</td>
<td>13.5</td>
<td>47.1</td>
<td>56%</td>
</tr>
<tr>
<td>Option 2</td>
<td>14.2</td>
<td>66.3</td>
<td>54%</td>
</tr>
<tr>
<td>Option 3</td>
<td>16.5</td>
<td>69.8</td>
<td>90%</td>
</tr>
</tbody>
</table>

**Port Arthur $CO_2$ Project**

$CO_2$ capture from syngas by $CO_2$ VSA Option 1

*Figure 1: Steam methane reforming - $CO_2$ capture options*
Air Products’ Port Arthur CO2 Project

New technology to recover anthropogenic CO2 for EOR

- Retrofit of two Steam-Methane Reformers (SMR) located in the middle of a refinery
- Capture and purification of CO2 from hydrogen plants (see previous slide “Option 1”) for EOR
- Technology developed by Air Products
- 90%+ capture of CO2 from syngas
- ~2600 t/d (50 MMSCFD) of CO2 to Denbury’s Green Pipeline for West Hastings oilfield
- 30 MWe cogeneration unit to generate power and make-up steam
- Full capacity achieved April 2013

Capturing 1 million tonnes/year of CO2 since 2013
CO$_2$ Capture – Port Arthur Project Answers

- **Where will the CO$_2$ go?**
  - Port Arthur is 13 miles (21 km) from Denbury’s existing “Green” 300+ Mile (~500 km) CO$_2$ Pipeline used for CO$_2$ EOR

- **Who will pay for the CO$_2$ capital and operating costs?**
  - US Government grant from the recovery act
  - Tax credits 45Q for CO$_2$ stored by EOR
  - Denbury pays for CO$_2$ to use in EOR applications

Scale is important: **1 million tonnes/year of CO$_2$**
Air Products has the Core Competencies required to be a supplier of Syngas

Acquired Shell and GE gasification technologies to enhance our core competency in gasification
Benefits of Gasification

A versatile and mature technology

- Gasification technology has been in use since the 1800s
  - Widely used to produce transportation fuel due to petroleum shortage in WWII

- Adaptable to various hydrocarbon feedstocks
  - Coal, pet coke, oil residue, natural gas, and others
  - Utilizes natural resources available

- Diverse applications / end products
  - Syngas for power generation and chemicals
  - H₂ for refineries
  - CO for chemicals

- Sustainability
  - No smog-causing particulates
  - Concentrated, capture-ready CO₂ stream
  - Sulfur removal allows the use of high sulfur coal

- Low incremental operating cost
  - Economical in low oil price environment
Executing our gasification strategy

Energy, environmental, emerging markets

GE Gasification Technology Announcement (November 2018)

Shell Gasification Technology acquisition (May 2018)

Large ASUs for China coal gasification

Lu’An JV $1.5B 2019

Jazan ASUs JV $8B 2019

Jazan Gasifier/Power JV $3.5B 2022

Yankuang JV 100% APD $0.65B 2022

Juitai 100% APD 2022

Project capital represents 100%, not APD share
Project dates represent expected onstream
CO\textsubscript{2} Capture from Gasification

- Gasification for syngas typically has a CO\textsubscript{2} removal step
  - Minimising additional capital for capture costs
  - Still requires dehydration, CO\textsubscript{2} compression, pipelines
- Gasification with CO\textsubscript{2} capture allows you to use high carbon content feed stocks to produce high value products with zero carbon emissions
- Air Products has developed a Road Map of technology applications for CO\textsubscript{2} capture on coal and heavy resid feedstocks
Summary

● Large scale hydrogen production from steam methane reforming is widely practised

● Piping hydrogen is well understood: 100’s miles of hydrogen pipelines around the world, connecting dozens of hydrogen plants with many customers

● Syngas production by gasification or reforming produces CO\(_2\) in quantities amenable for use in enhanced oil recovery (EOR)

● Air Products has demonstrated CO\(_2\) capture from SMRs
  - However, ATRs may be better suited to high levels of CO\(_2\) capture from natural gas

● Gasification (of bottom of the barrel, petcoke, coal) could play a part in Blue hydrogen

● There are many demonstrated technology options for CCS but the problem remains:

Where will the CO\(_2\) go?
Who will pay?
And pay attention to scale!
Thank You

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