World Scale Hydrogen Production

Presentation by

Dr Vince White

Senior Research Associate

Air Products

Hersham Place Technology Park

Molesey Road – Walton-on-Thames - UK

IMechE/IChemE Evening Seminar: 2019 Hydrogen event
Birdcage Walk, 7th March

Agenda

- Air Products
- Hydrogen production from Steam Methane Reformers (SMRs)
- CO_2 capture from SMRs
  - Options and Port Arthur Project
- Autothermal Reformers (ATRs) and Gas Heated Reformers (GHRs)
- Gasification
- Hydrogen Pipelines
- Vehicle Fuelling

Air Products Today

$8.9 billion in sales	~16,000 employees	50+ countries
~$35B market cap	7+ decades in business	170,000+ customers
1,800 miles of industrial gas pipeline	750+ production facilities	30+ industries served

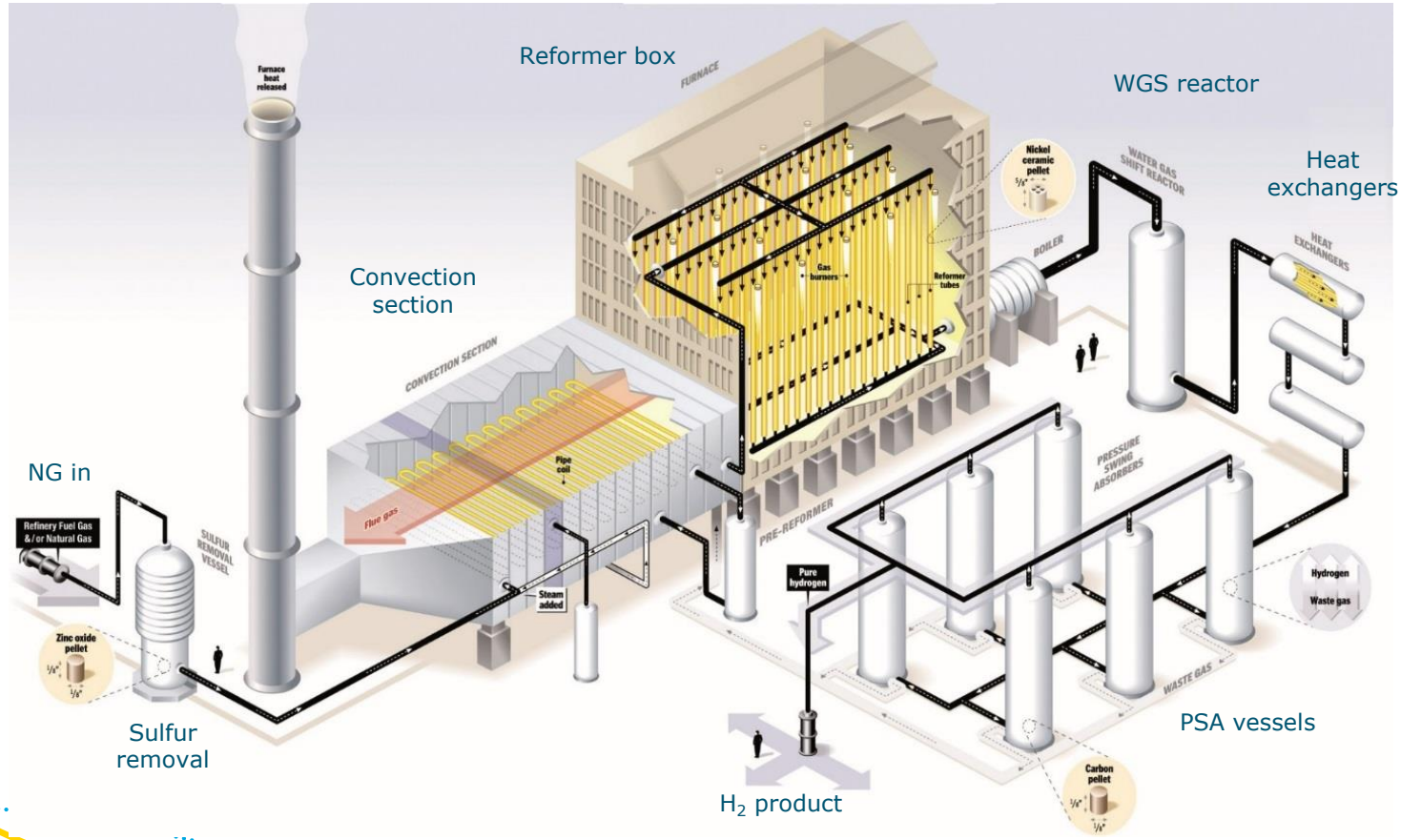
Production of Hydrogen 1 - SMR

Process Characteristics

- External heating of a catalytic reactor
- Combustion products vented to atmosphere
- 40% of CO_2 emissions from combustion
- 60% from "shifted" syngas
- CO_2 removal from syngas less expensive than from flue gas

Air Products builds and operates hydrogen plants of all sizes, from <1 kNm^3/h to >170 kNm^3/h, tied to pipelines or as standalone "on-site" facilities

SMR schematic



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Decarbonised Hydrogen: CO_2 removal from SMR – 3 options

Table 1: Levelised Cost of H_2 (LCOH), CO_2 Avoidance Cost and Overall CO_2 Capture Rate (IEAGHG, Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS. Technical Report 2017-02, 2017)

Capture Case	LCOH Euro Cent/Nm^3	CO_2 Avoidance Cost Euro/t	Overall CO_2 Capture Rate
No capture	11.4	-	-
Option 1	13.5	47.1	56%
Option 2	14.2	66.3	54%
Option 3	16.5	69.8	90%

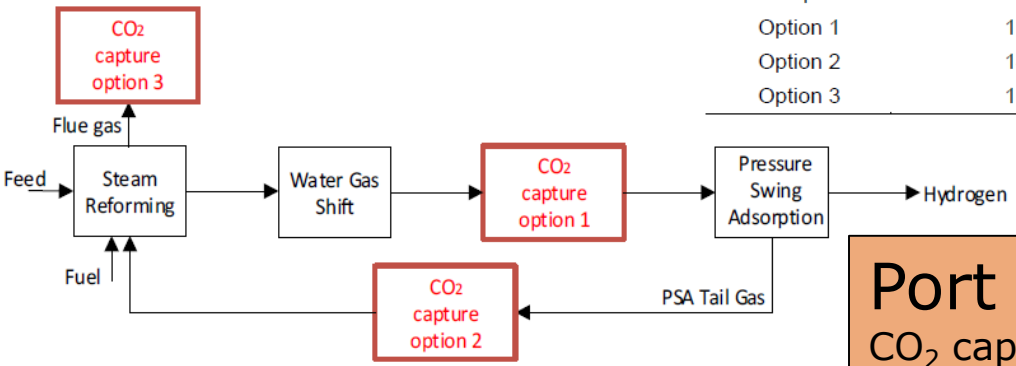


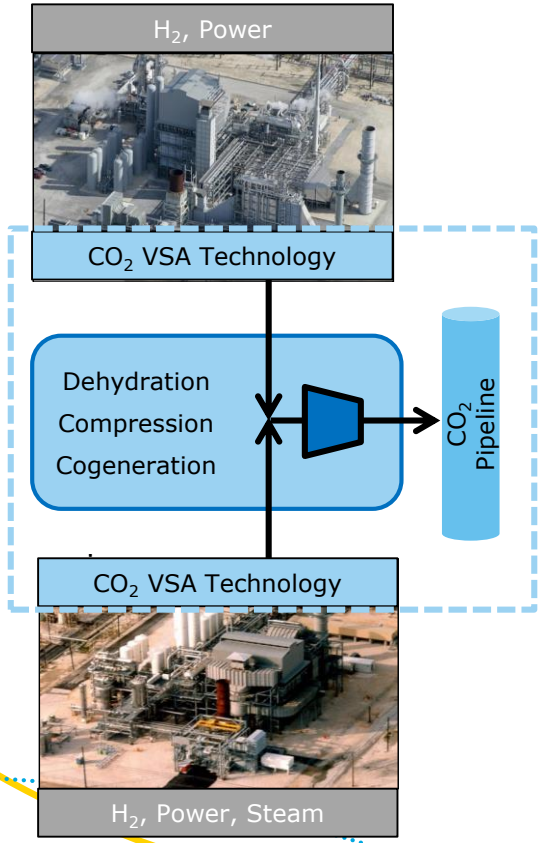
Figure 1: Steam methane reforming - CO_2 capture options

Port Arthur CO_2 Project

CO_2 capture from syngas by CO_2 VSA – Option 1

Air Products' Port Arthur CO_2 Project

New technology to recover anthropogenic CO_2 for EOR



- Retrofit of 2 Steam-Methane Reformers (SMR) located in the middle of a refinery
- Capture and purification of CO_2 from hydrogen plants (see previous slide "Option 1") for EOR
- Technology developed by Air Products
- 90%+ capture of CO_2 from syngas
- ~2600 t/d (50 MMSCFD) of CO_2 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
  - $1x10^6$ tonnes of CO_2 captured by April 2014
  - $4x10^6$ tonnes of CO_2 captured by Oct 2017

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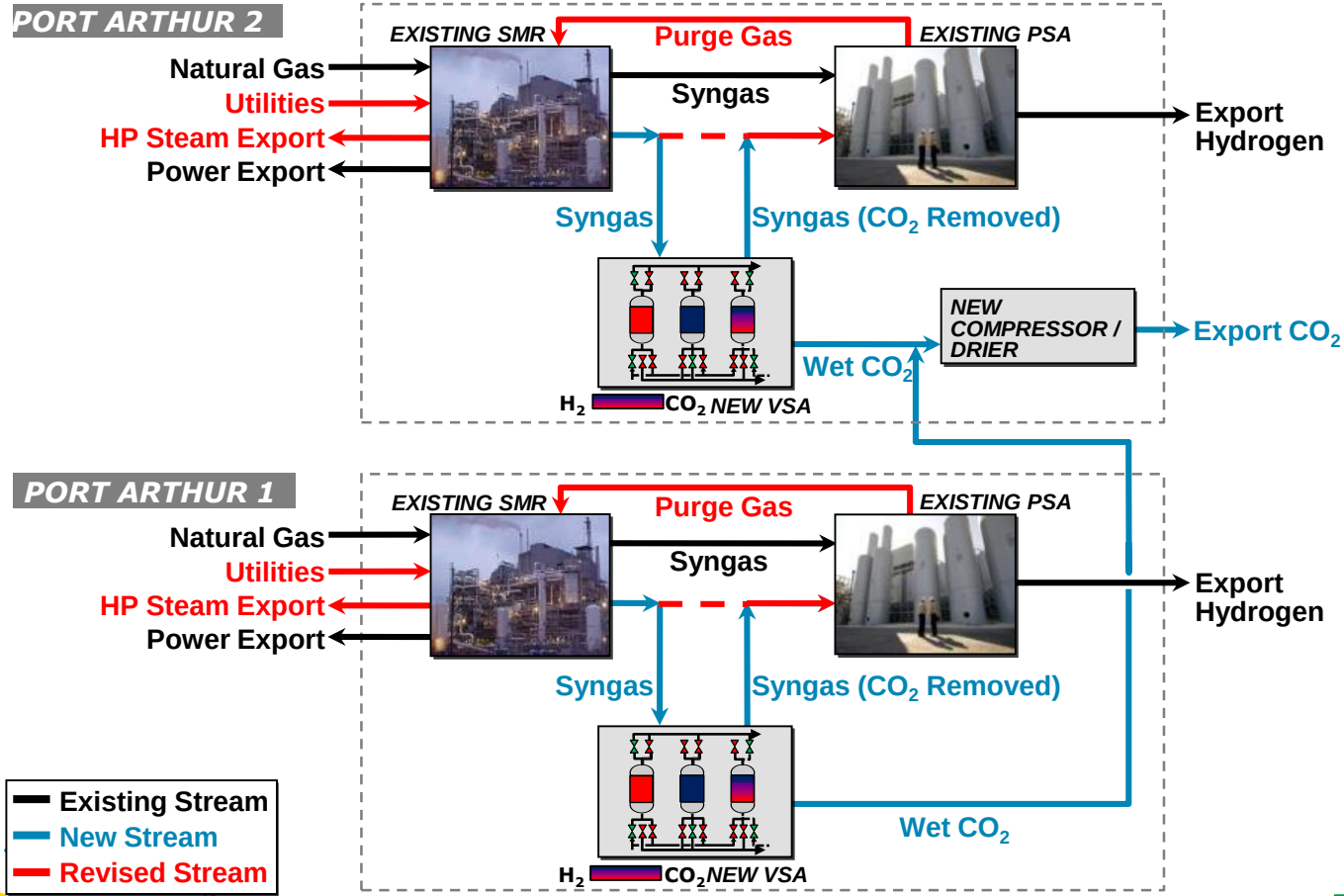
Simplified CO_2 Capture Block Flow Diagram



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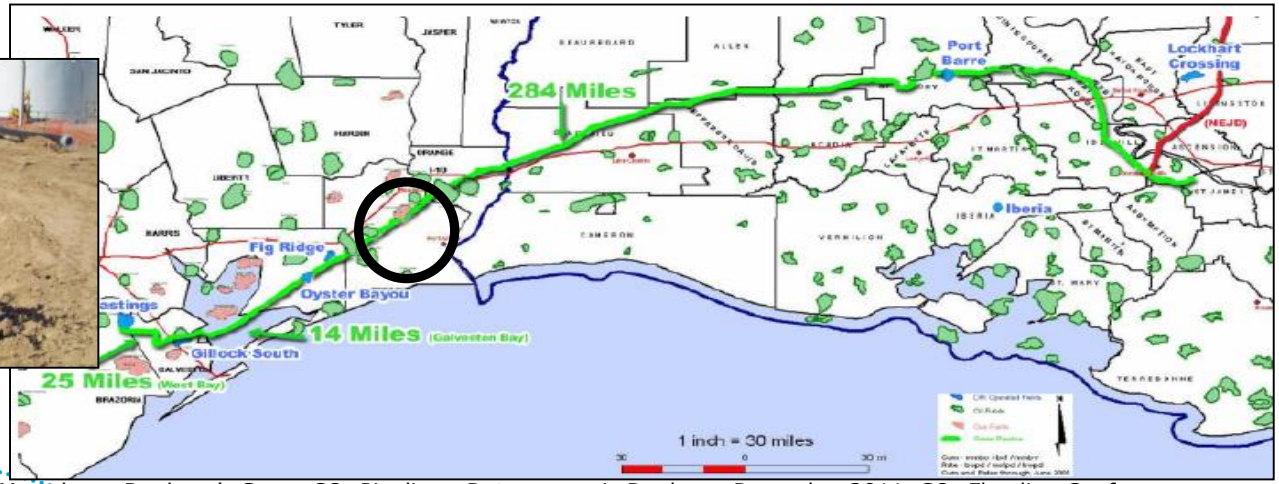
Key Project Components

Capturing CO_2 for Denbury's "Green Pipeline"

- Vacuum swing adsorption (VSA) vessels
- Tri-ethylene glycol (TEG) drier system
- CO_2 export compressor
  - 8 stages
  - Export pressure over 2000 psig (~140 bar)
- 13 mile (21 km) CO_2 Pipeline connecting to Denbury's "Green" 300+ Mile (~500 km) CO_2 Pipeline

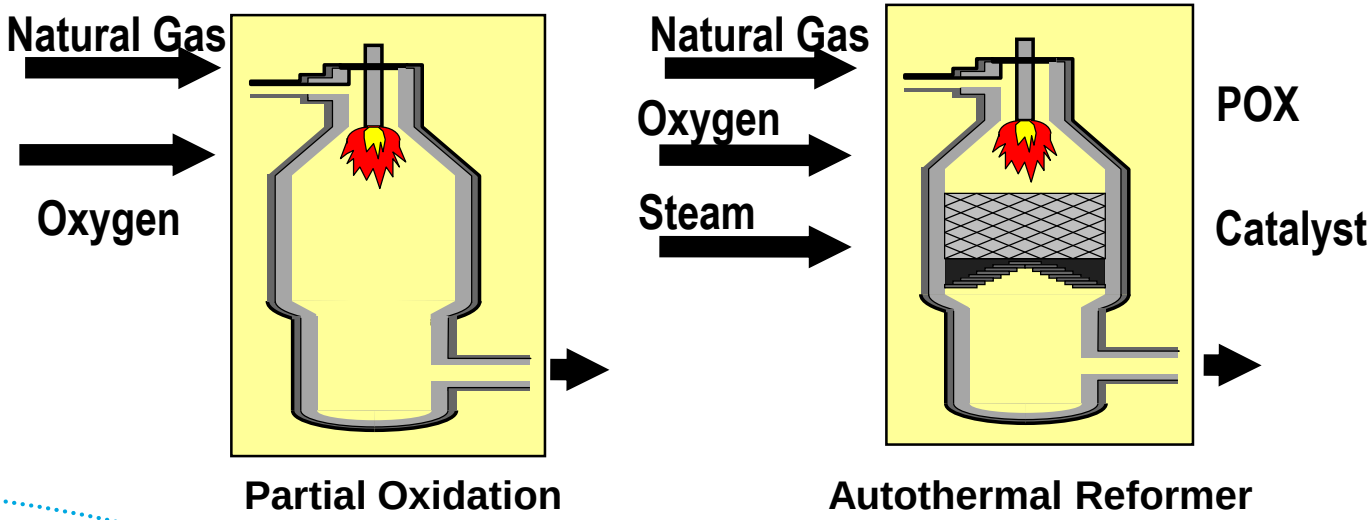


Map shows Denbury's Green CO_2 Pipeline. Data source is Denbury, December 2011, CO_2 Flooding Conference

Production of Hydrogen 2 – POX & ATR

Process Characteristics

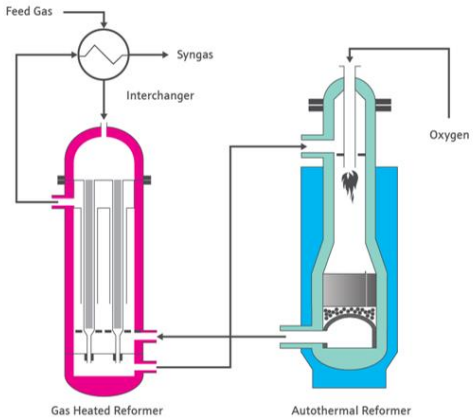
- Pressurised reactors with heat supplied by direct reaction with oxygen
- No venting of combustion products
- All CO_2 available for capture at pressure



Johnson Matthey's ATR/GHR improves on ATR by using high temperature $H_2/CO/CO_2$ syngas to heat a convective reformer

Advanced Steam Reforming – Leading Concept Hydrogen

- Low methane in product gas which lowers CO_2 emissions
- Low CO slip exit shift which lowers CO_2 emissions
- CO_2 captured from process at pressure so CO_2 removal system is well proven and cheap



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- Highest Efficiency - Lowest Cap Ex
- Lowest Levelised Cost of H_2
- Lowest Nat Gas usage per unit H_2
- Lowest amount of CO_2 produced per unit H_2
- Proven at scale in Methanol
- Advantageous to couple with Renewable Electricity generation as no steam is generated

source: Johnson Matthey

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Johnson Matthey's comparison of levelized cost of hydrogen, with 95% CO_2 capture

Cost of H_2 at 95% capture equivalent to just capturing process CO_2 from SMR, 56% capture

Parameter	Units	SMR Flowsheet	ATR Flowsheet	LCH Flowsheet
Natural Gas as Feed	kNm³/hr	39.74	41.22	38.31
Natural Gas as Fuel	kNm³/hr	5.36	0.19	0
Total Natural Gas	kNm³/hr	45.10	41.41	38.31
Natural Gas Energy	MW	439	432	400
Hydrogen Production	kNm³/hr	107.4	107.4	107.4
Hydrogen Energy	MW	322	322	322
Natural Gas Efficiency	%	73.3	74.5	80.6
CO2 Captured	mt/hr	83.7	83.6	76.3
CO2 Emitted	mt/hr	4.4	3.1	3.7
CO2 Captured	%	95	96.4	95.4
CAPEX	£M	260	195	160
LCOH	£/kNm³	165.8	137.6	128.3
Euro Cent/Nm³		18.9	15.7	14.5

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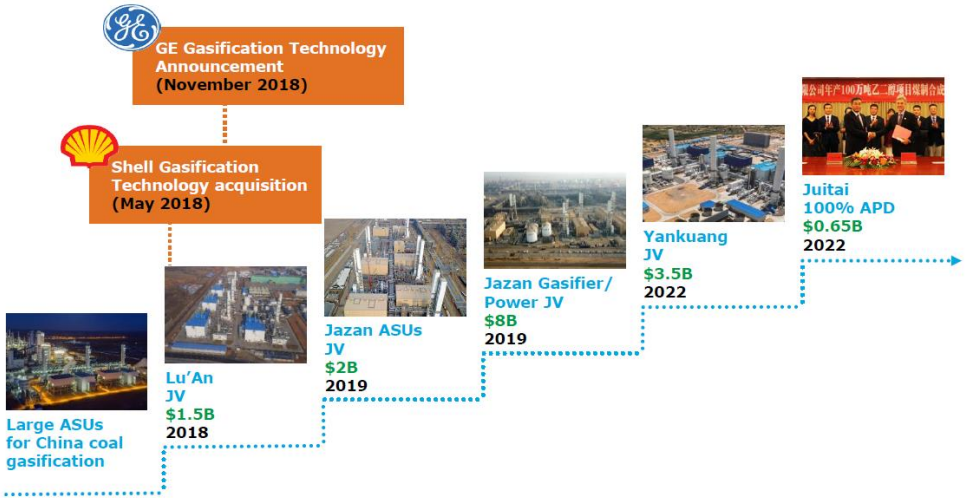
source: Johnson Matthey

Gasification

Executing our gasification strategy
Energy, environmental, emerging markets

Moving forward



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, petcoke, oil residue, natural gas, and others
  - Utilizes natural resources available
- Diverse applications / end products
  - Syngas for power generation and chemicals
  - H_2 for refineries
  - CO for chemicals
- Sustainability
  - No smog-causing particulates
  - Concentrated, capture-ready CO_2 stream
  - Sulfur removal allows the use of high sulfur coal
- Low incremental operating cost
  - Economical in low oil price environment

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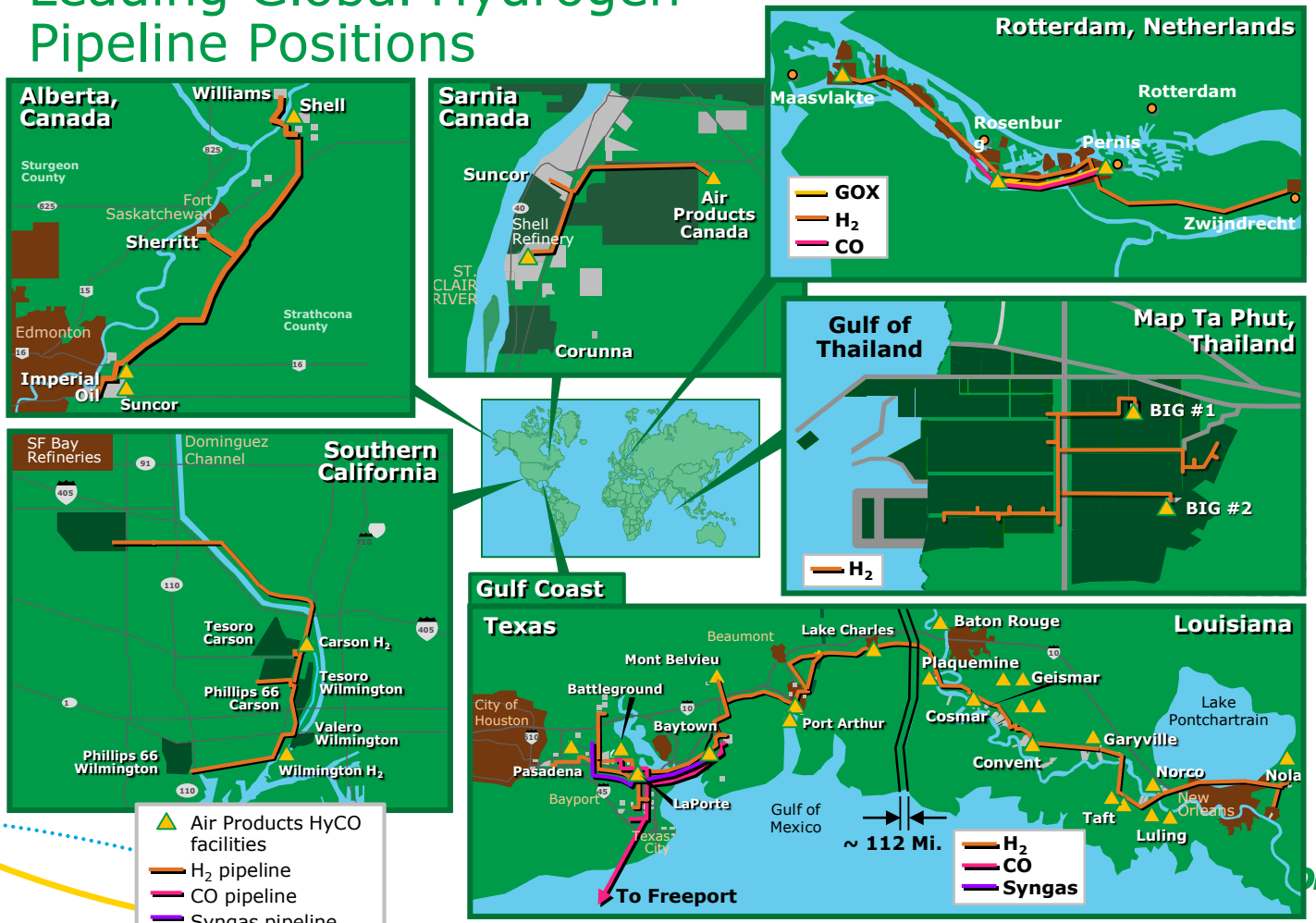
Leading Global Hydrogen Pipeline Positions



Hydrogen Fueling

- Unique product offerings for H_2 fueling
- Projects since 1993
  - 225 hydrogen station projects
  - 1,500,000 fuellings/yr
  - ~7 million fuellings total
  - Stations in 20 countries
  - 50+ patents
  - SAE J2601 Fueling Standard based on AP technology

Summary

- Large scale hydrogen production from steam methane reforming is widely practised
- CO_2 capture from SMRs is possible and demonstrated, but ATRs are better suited to high levels of CO_2 capture
- Piping hydrogen is well understood: 100s miles of hydrogen pipelines around the world, connecting dozens of hydrogen plants with many customers
- Gasification (of bottom of the barrel, petcoke, coal) could play a part in a hydrogen-with-CO_2-capture world, even in the UK

Thank you
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