Air Liquide
creative oxygen

Hydrogen Production through SMR with CCS

2021 ARPA-E Methane Pyrolysis Annual Program Review Virtual Meeting

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Agenda

1 Air Liquide and CCS

2 SMR with CCS Options

3 Port-Jerome Demonstration

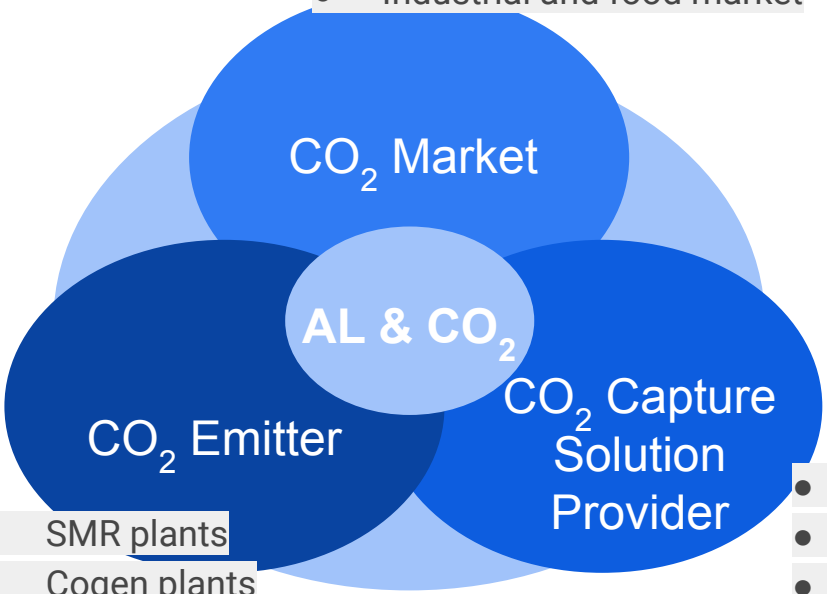
4 Hybrid Technologies

Air Liquide and CCS

01

Air Liquide and CCS

- CO_2 plants
- Industrial and food market



- SMR plants
- Cogen plants
- Electricity for ASU

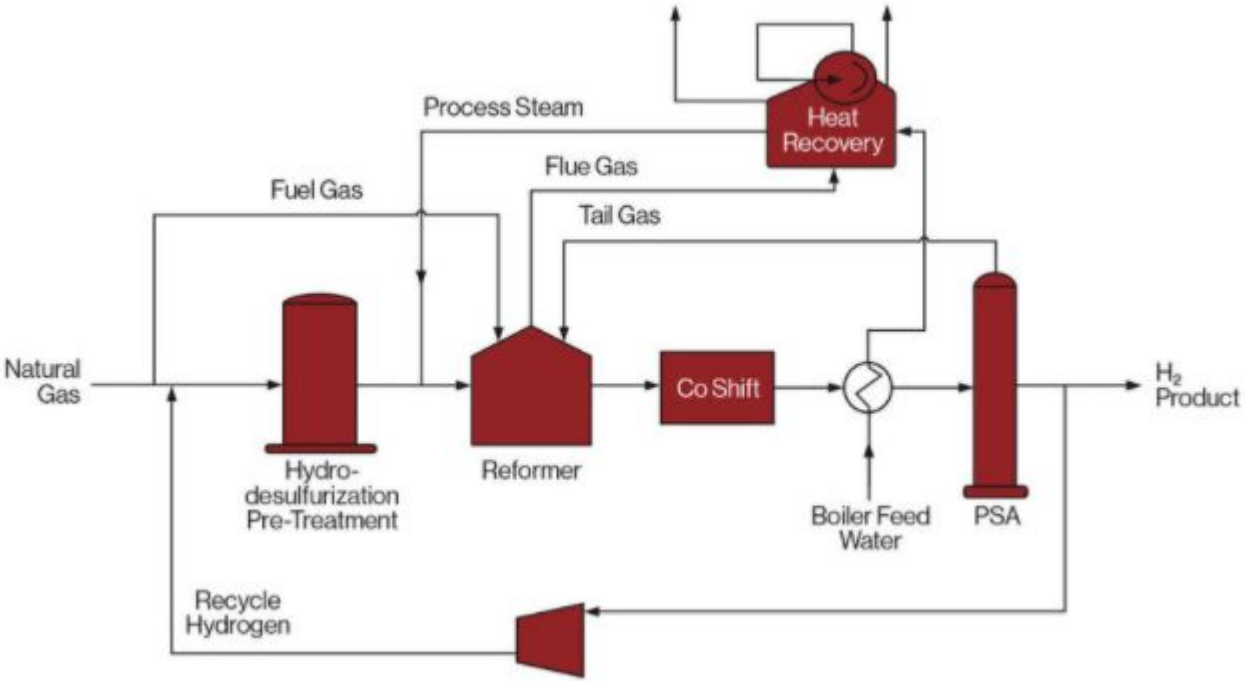
- All CO_2 capture technologies
- Any CO_2 source
- Any CO_2 product purity

Committed to reducing carbon intensity by 30% by 2025

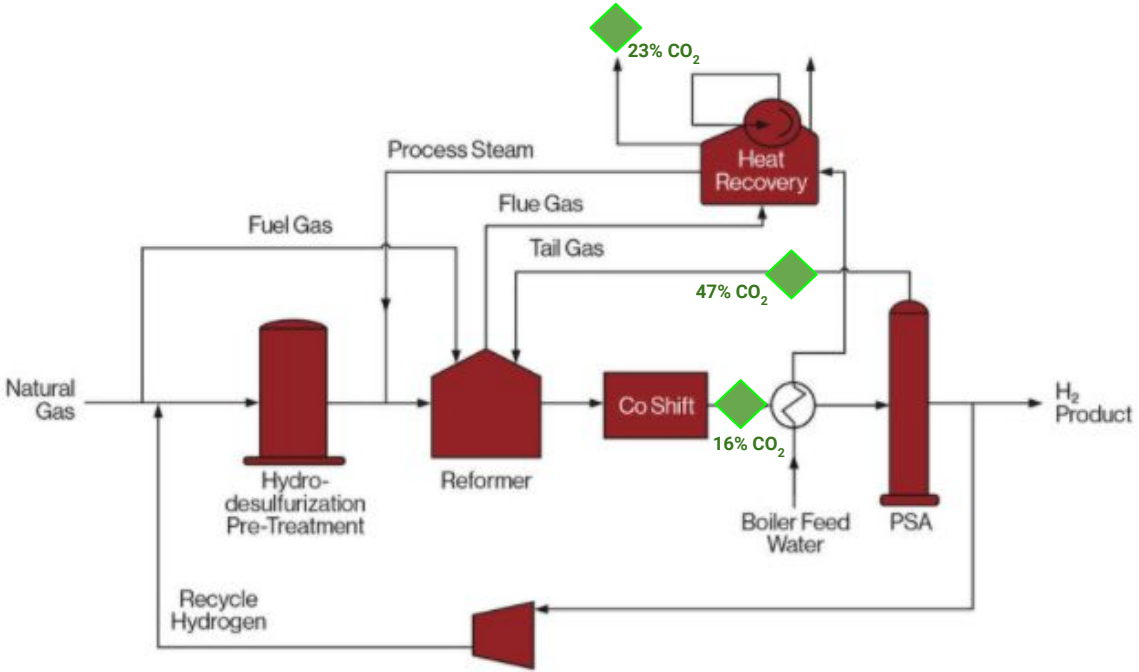
SMR with CCS Options

02

H_2 Production through SMR



H_2 Production through SMR

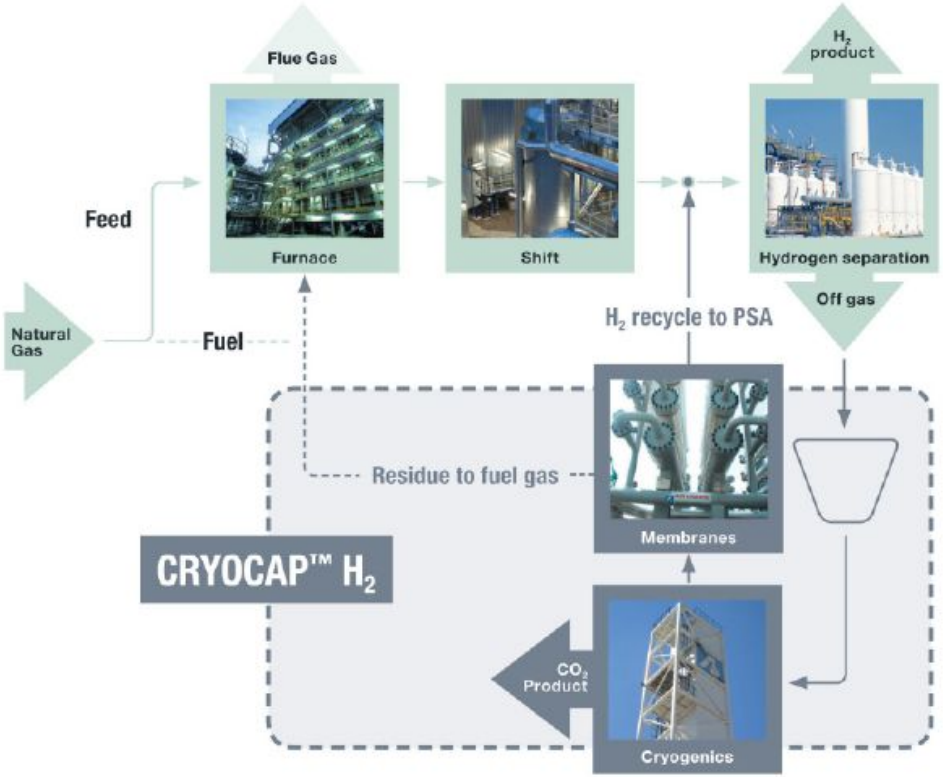


CO_2 can be captured at three locations

The flue gas is 23% CO_2 with nitrogen, but the other two locations are CO_2 with hydrogen

CO_2 capture points and concentrations

Cryocap™ H_2 Process



- More than 97% of CO_2 from syngas can be captured
- Hydrogen production increase ranges from 10 to 15%

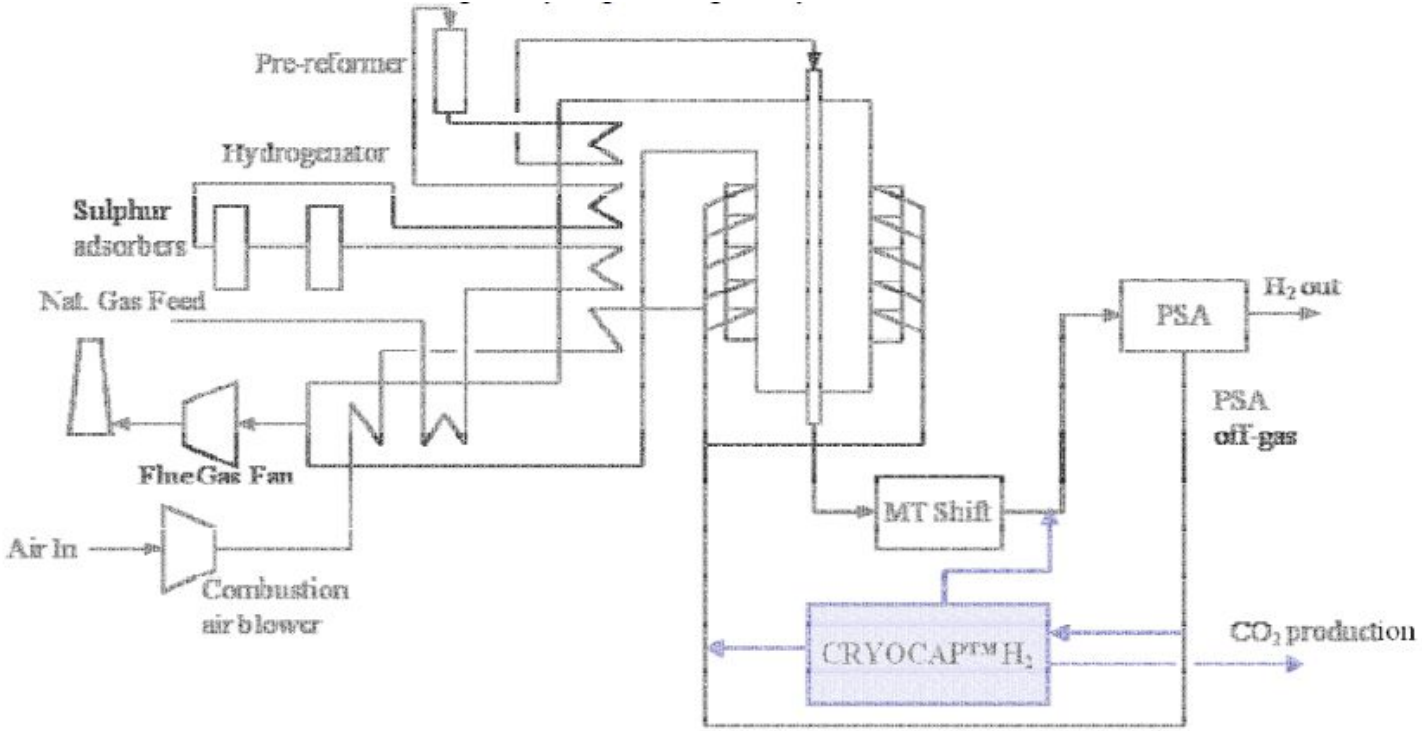
Port-Jerome Demonstration

03

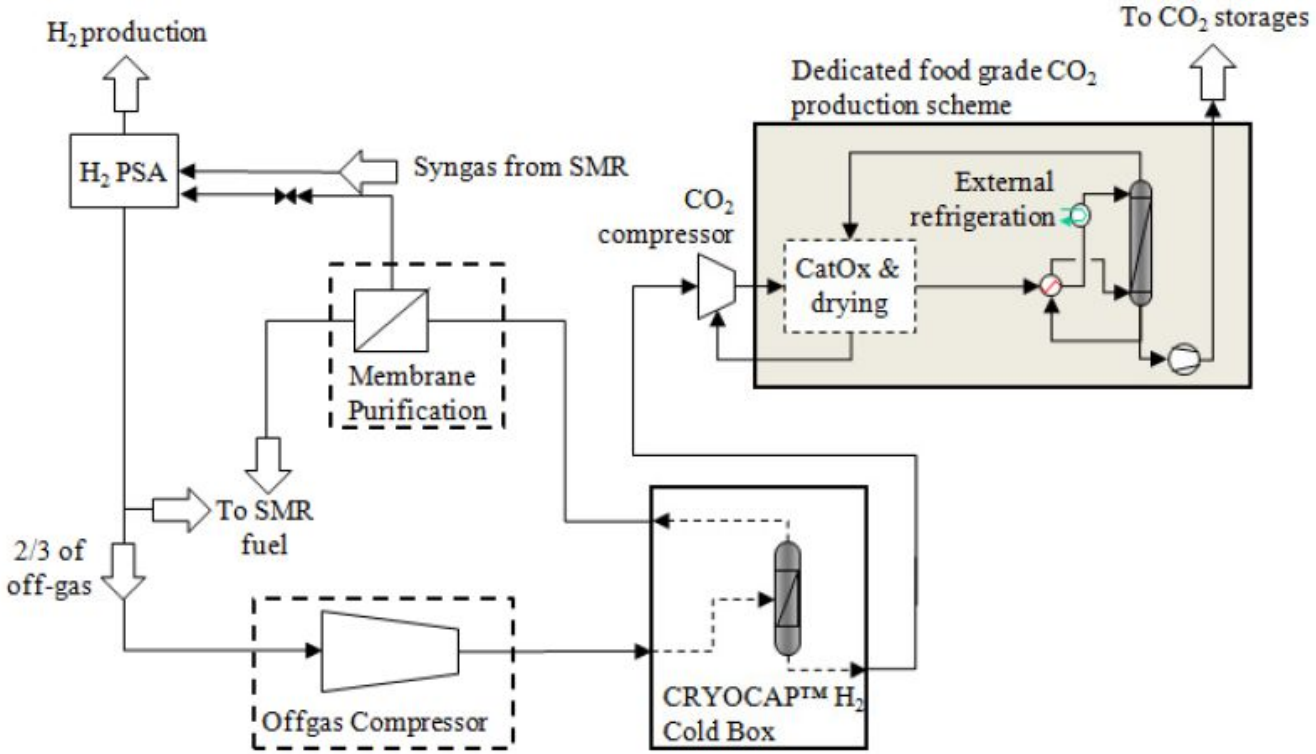
Commercial Scale Demonstration at Port-Jérôme SMR

This Cryocap™ unit has an annual capture capacity of **100 000 tonnes of CO_2 at this site**.

Simplified Scheme at Port-Jerome



Process Flow Diagram



Commercial Operation

Increased H_2 production coupled with industrial scale CO_2 production

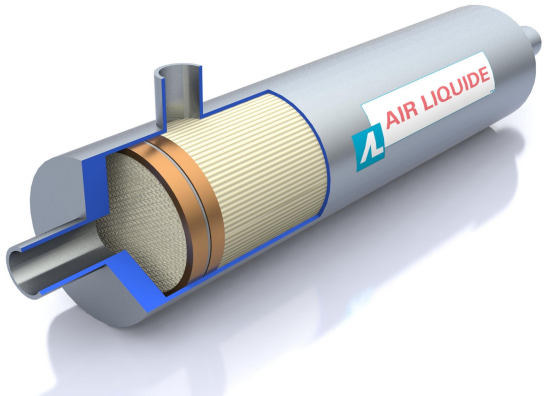
Case	SMR only	SMR + CRYOCAP™ H_2 *Partial CO_2 capture (Port-Jérôme unit)*	SMR + CRYOCAP™ H_2 *Full CO_2 capture*
H_2 production	47 000 Nm^3/hr	50 155 Nm^3/hr	52 480 Nm^3/hr
Additional H_2 production	-	+7%	+12%
H_2 recovery from PSA offgas	0%	87%	87%
Overall H_2 recovery from syngas	88.0%	93.9%	98.3%

Hybrid Technologies

04

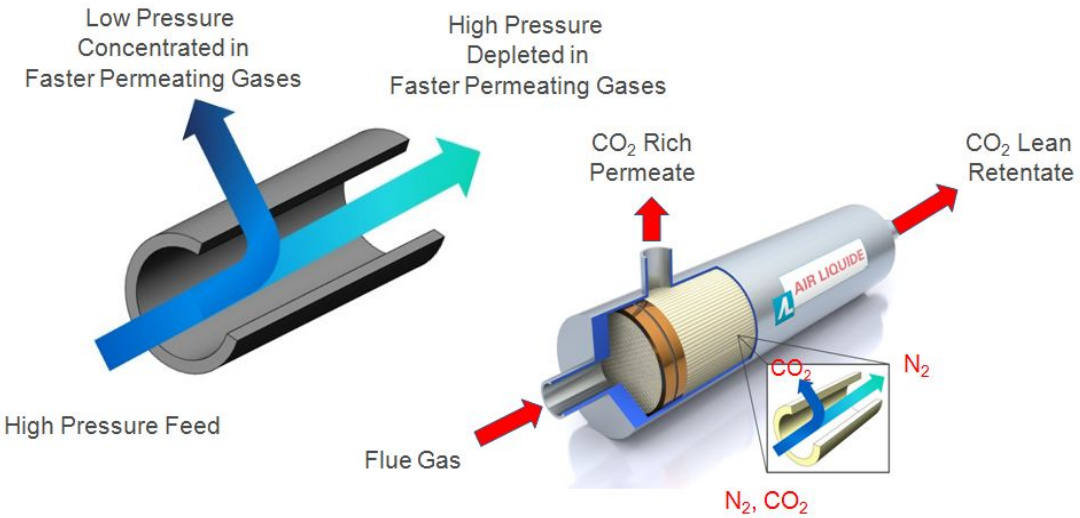
Hybrid Systems

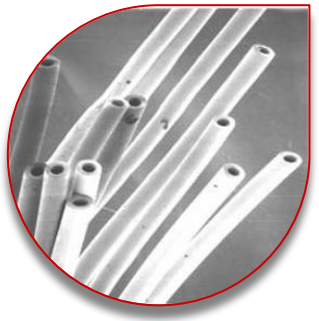
- Cryogenic solutions have two advantages:
  - High purity of the CO_2
  - Liquid CO_2 Product



- Hybridization of the process to achieve high recovery of CO_2
- Recovery with PSA or Cold Membranes

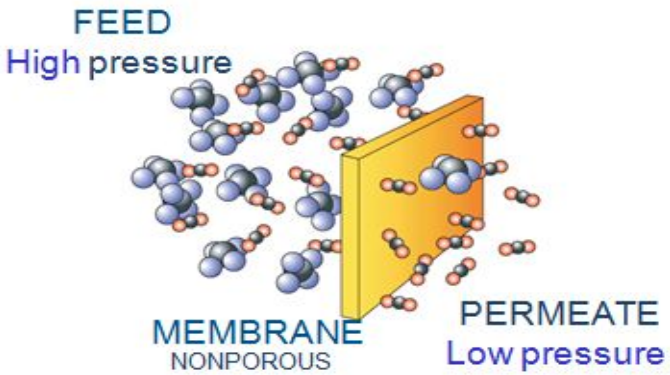
Hollow Fiber Membranes



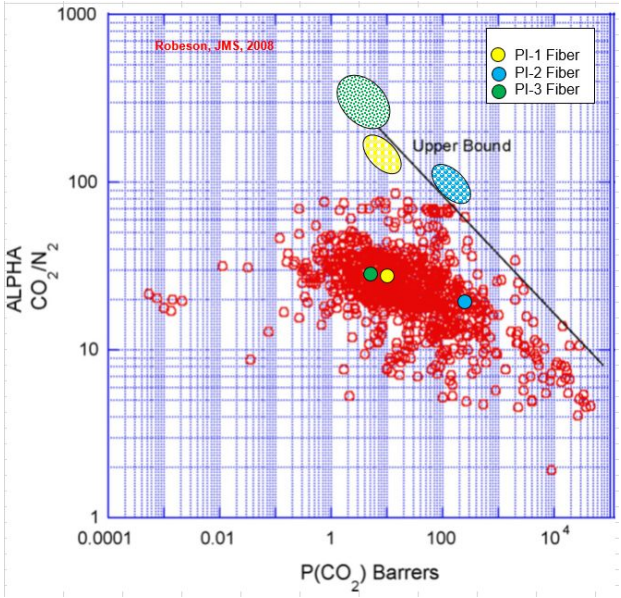


Hollow fibers allow low cost manufacture of membranes with high surface area per unit volume. Large natural gas installations have been installed at membrane costs of ~$20/m^2.

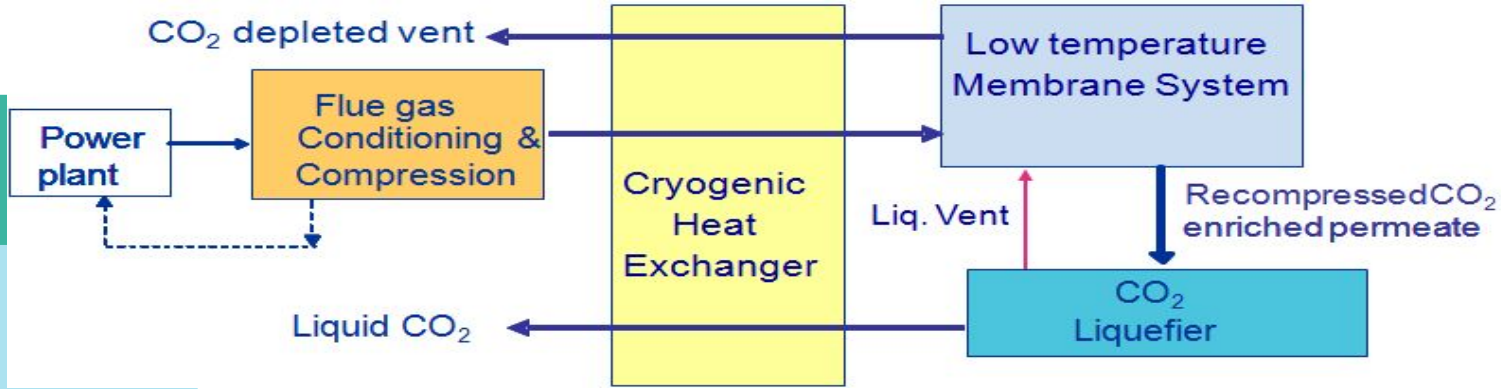
Air Liquide Cold Membrane Technology



- **Why Cold? -- Improve selectivity without loss of productivity**
  - Discovered by Air Liquide R&D in 2008: Improved CO_2 selectivity at T below ambient
- **Why PI-2? -- Improved productivity lowers cost**
  - 4-5 X higher CO_2 productivity/bundle

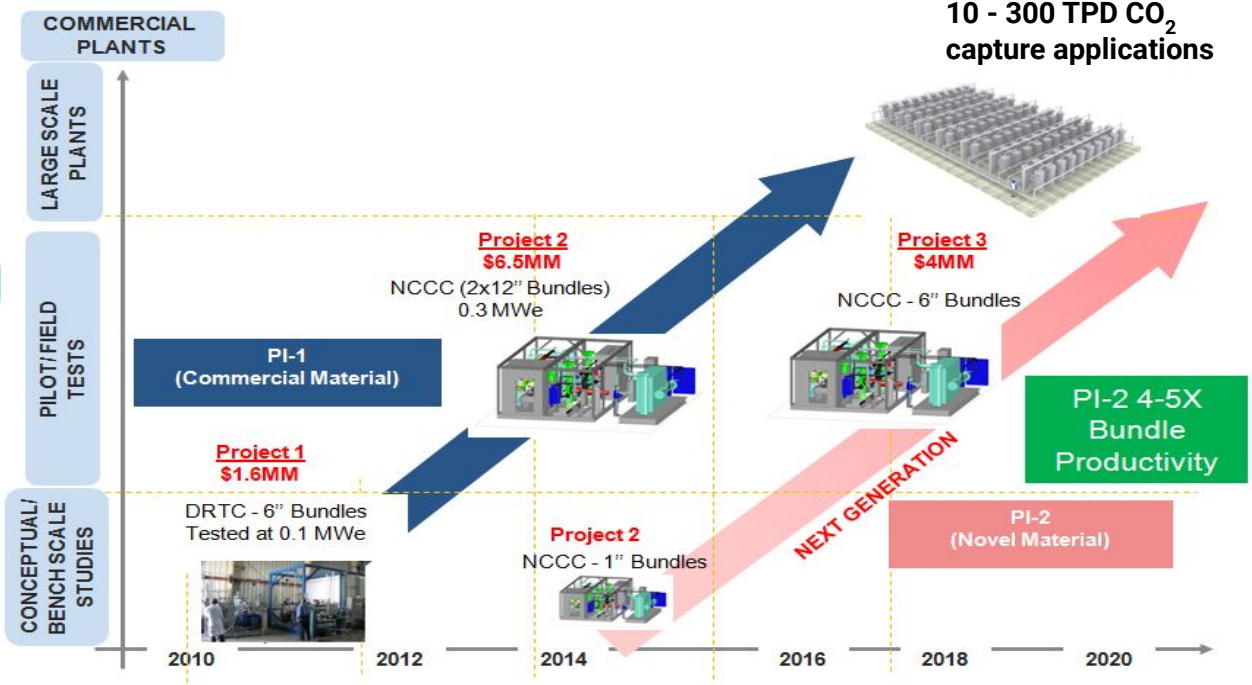


Cold Membrane Process



- Pre-concentration of CO_2 by highly selective membrane before liquefier
- Energy integration between membrane/liquefier through heat exchange
- Efficient recovery of compression energy
- Direct production of liquid CO_2
- High purity suitable for EOR / sequestration / consumer applications

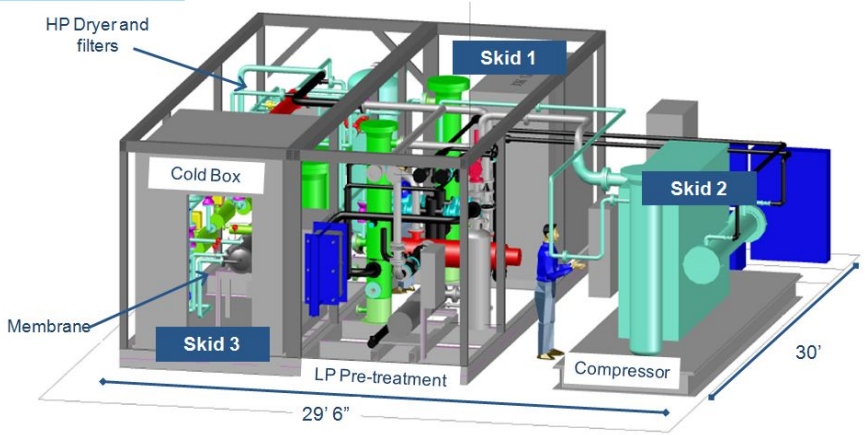
DOE Funded Projects Timeline



Flue Gas Testing - Coal Plant flue gas

0.3MWe / 6 TPD CO_2 (TRL-5) field test unit at the NCCC (Wilsonville, AL)

3,000+ Hours operation PI-1
3,000+ Hours operation PI-2



Summary

- SMR with CCS :
  - Cryocap^{TM} H_2 → Increase in H_2 production while also capturing CO_2
    - Hydrogen production increase ranges from 10 to 15%
    - Partial capture at 60+% CO_2 recovery
  - Hybrid Process can capture 90+% of CO_2 from SMR Flue gas
    - Cold Membrane technology can be implemented in SMR

We are thankful to DOE for a decade of successful partnership with cold membranes

- US DOE: Andrew O'Palko, Sheldon Funk, José Figueroa
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THANK YOU