CO_2 CAPTURE: HONEYWELL H_2 & CO_2 SOLUTIONS

JM H2 & SYNGAS TECHNICAL TRAINING SEMINAR

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30 November 2023

Honeywell
UOP

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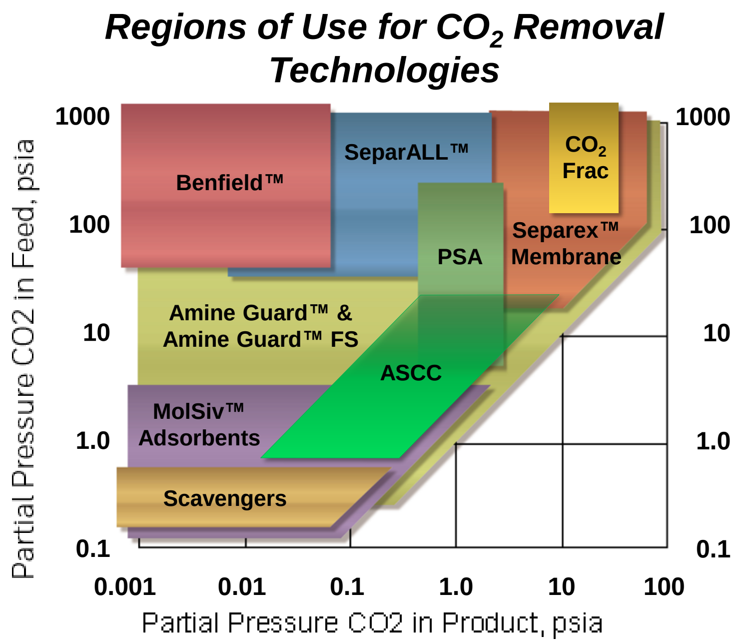
UOP CO2 CAPTURE PORTFOLIO

HONEYWELL CO_2 SOLUTIONS



Chemical Solvents

- **Amine Guard^{TM} & Amine Guard FS Process**
  UOP is largest licensor of high concentration MEA-based systems; formulated solvents have lower Opex vs. MEA (> 600 units)
- **Benfield^{TM}**
  Totally inorganic solvent for pressurized flue gas & industrial processes (> 650 units)
- **Advanced Solvent for Carbon Capture**
  Direct CO_2 capture from flue gas for refining, power, steel, cement, and natural gas industries (seeking first commercial scale application)

Physical Solvents

- **SeparALL^{TM} Process**
  H_2S/CO_2 selectivity using Selexol solvent for sources containing sulfur or in oxidative conditions (>50 units)

Note: Solvent processes can be used in hybrid cycles with other technologies like PSA, membranes, and cryogenics to optimize CO_2 capture

Adsorbents

- **Polybed^{TM} Pressure Swing Adsorption (PSA) System**
  Optimized adsorbents and cycles for CO_2 rejection (>1,150 units, 3 operating in CO_2 application)

Cryogenics & Membranes

For capture of CO_2 at higher partial pressure

- **Separex^{TM} Membrane Systems**

Significant experience in offshore capturing & sequestering CO_2 (>300 units)

- **Ortloff CO_2 Fractionation**
  Not only captures but also provides CO_2 as a high purity liquid product (2 operating units)

UOP is leveraging existing technologies and expertise to deliver differentiation in new applications

Proven Technologies can be used for CO_2 Capture

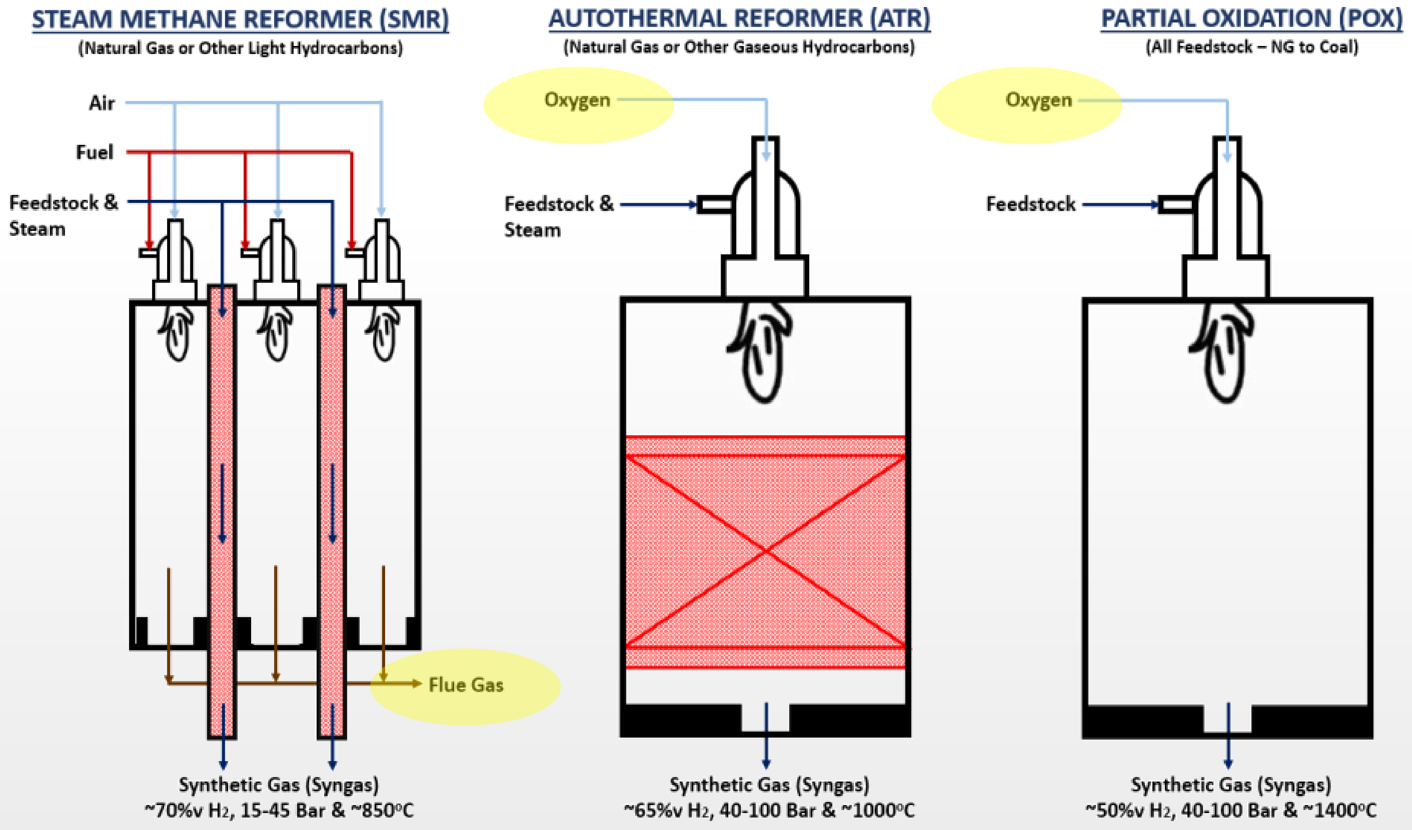
LOW CARBON H2
ATR SOLUTIONS

H2 GENERATION PROCESS

Steam Methane Reforming (endothermic)
$CH_4 + H_2O \rightarrow CO + 3H_2$
$\Delta H = 206$ kJ/mol

Partial Oxidation of Methane (exothermic)
$CH_4 + 1/2\ O2 \rightarrow CO + 2H_2$
$\Delta H = -36$ kJ/mol

Water Gas Shift (exothermic)
$CO + H_2O \leftrightarrow CO_2 + H_2$
$\Delta H = -41$ kJ/mol



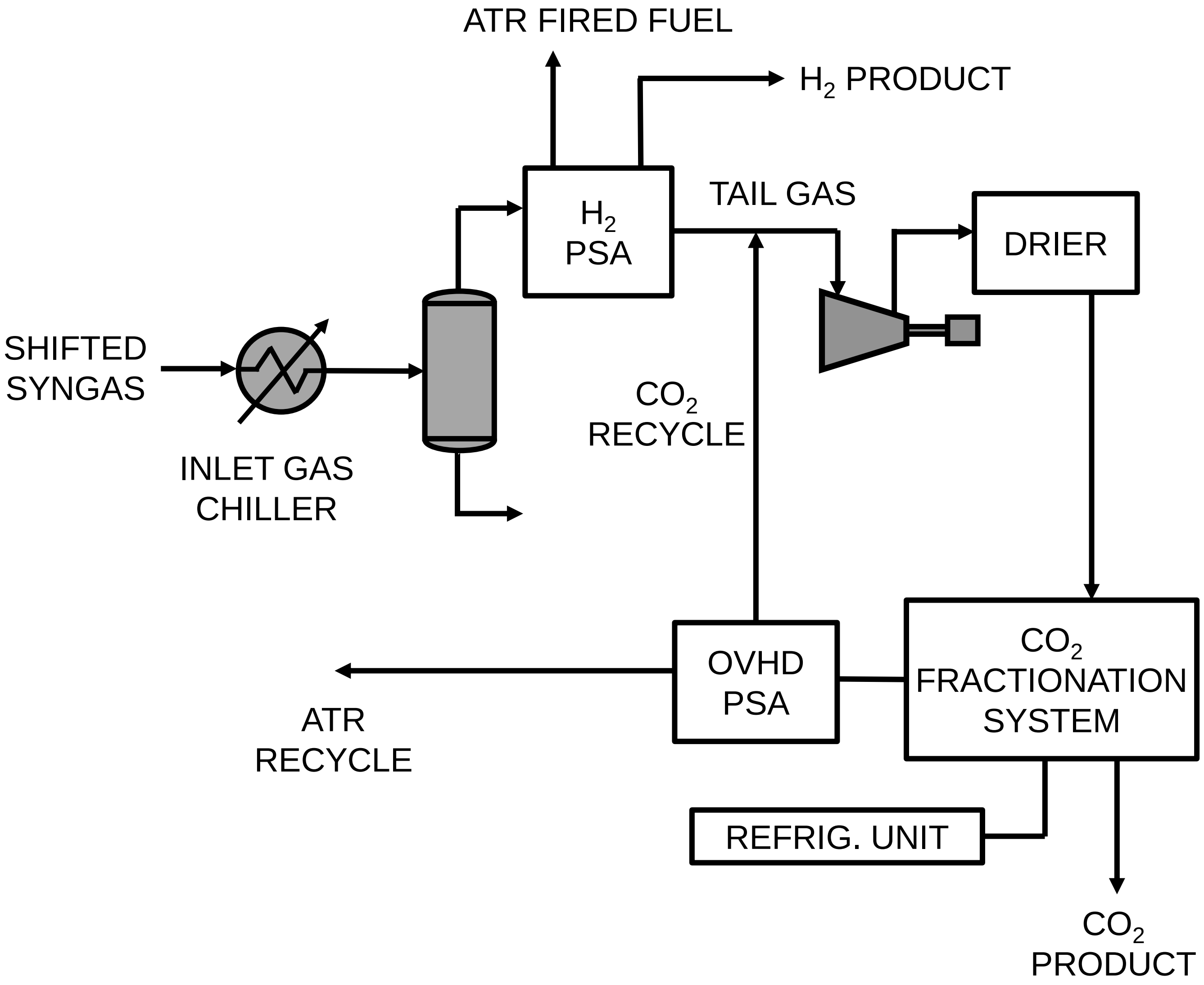
SMR ATR POX

Source: IEAGHG

ATR RECYCLE

CLOSED LOOP CARBON RECYCLE

UOP CO_2 FRACTIONATION SYSTEM



Off-gas Recycle to ATR Feed

- Low Carbon Emissions
- Higher Feedstock Efficiency

Scope 1 Emissions: <0.1 kg CO_2 / kg H_2

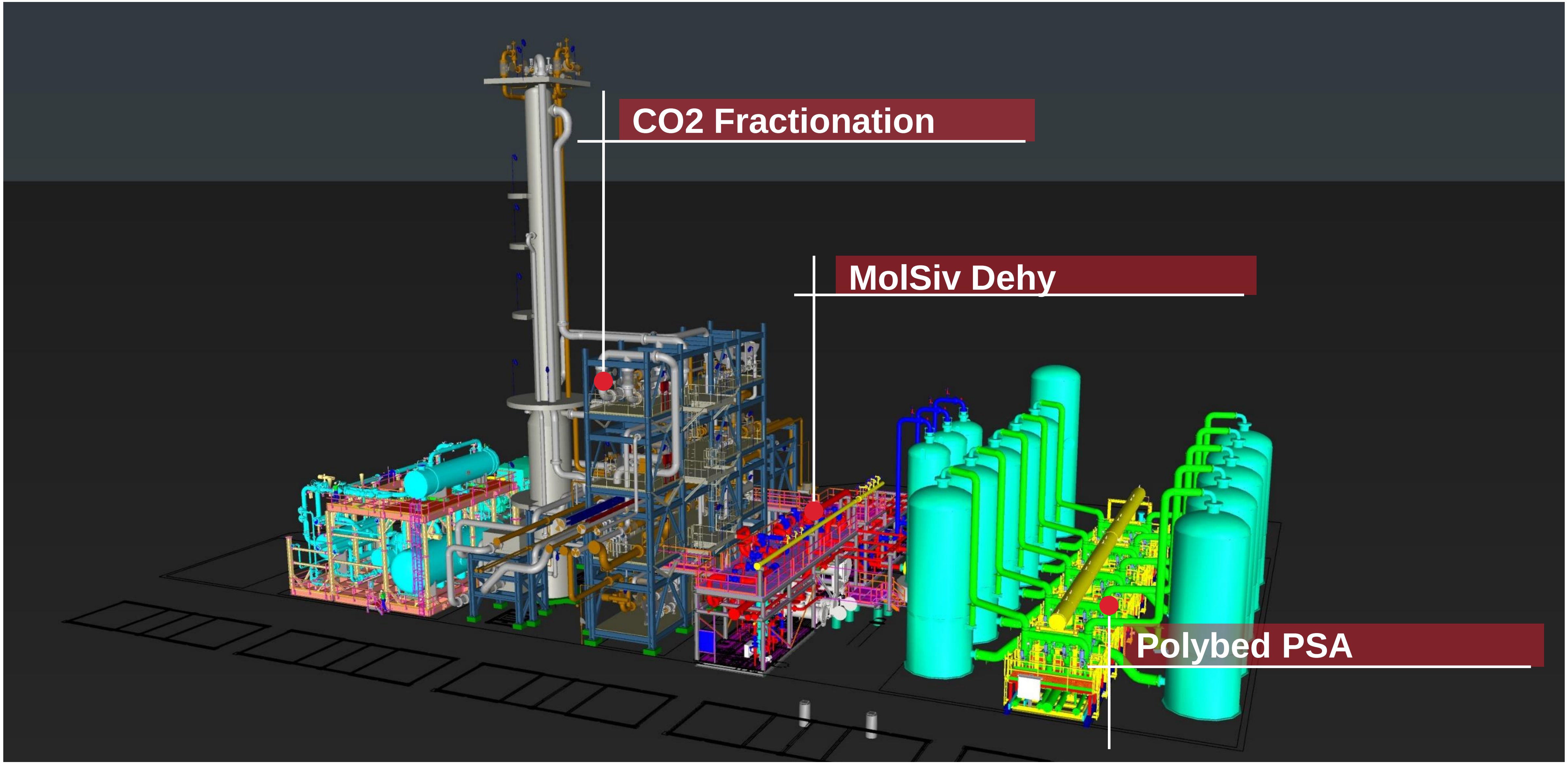
Carbon-free fuel gas stream produced in H_2 PSA

- Selective rejection of inerts
- Approximately 30 psi(g)
- Approximately 90 mol% H_2 and 10% N_2 + Argon

Equal expected OpEx vs. Configuration 1

2% - 5% higher CapEx vs. Configuration 1

CO_2 FRACTIONATION UNIT



VALUE PROPOSITION – INTEGRATION OF AUTO-THERMAL REFINING AND CRYOGENIC FRACTIONATION TECHNOLOGIES

- **Scope 1 emissions can be reduced to <0.1 kg of CO_2 per kg of H_2** by recycling Carbon molecules to the ATR and purging inerts. Overall carbon intensity will be driven by fugitive emissions upstream of the process and the carbon footprint of the electricity consumed from the grid
- **Lower Natural Gas consumption but more Electrical Power consumption.** Potential for Scope 2 emissions to be reduced over time as the grid power leverages renewable energy sources
- Scope 3 emissions driven by fugitive emissions upstream
- H_2 product is at 99.9+% purity
- **No C and no inerts (Ar and N) to H_2 Product Stream** (C recycled, inerts purged in other streams)
- UOP's flow scheme has different battery limits, and this provides **more flexibility** to adapt to the needs of the Customer while optimizing performance
- **Liquid CO_2 product stream is inherent to process** and is ready for storage and shipping, and would save CAPEX and energy in case CO_2 needs to be compressed for high-dense pipeline transportation
- Reliability: **H_2 product supply can be delivered even when CO_2 capture system is shutdown**
- Equipment count of UOP Cryo fractionation system is about 2/3 that of an amine system, which helps **reduce Plot Area required and reduces maintenance requirements**

HONEYWELL IS WINNING WABASH VALLEY RESOURCES

Overview

UOP selected as technology provider for carbon capture and H_2 purification for clean H_2 production from gasifier at **Wabash Valley Resources (WVR)** in West Terra Haute, Indiana

Why it Matters

- One of the largest **CCS projects** (1.65 Mt/yr CO_2)
- Second US project to sequester CO_2 in permanent geologic storage
- **Demonstrates large-scale commercially viable clean H_2 and CCS project under current regulatory and policy framework**

Technology

Integration of Modular MOLSIV, Modular Ortloff CO_2 Fractionation System, Modular PSA

Solution Advantages

- Commercially proven technologies
- Lower Capex / Opex
- Faster modular execution
- Parallel on-site and module fabrication execution
- High-quality shop-fabricated equipment
- Efficiency: single supplier for technology and equipment allows for less handoff
- Bankability: well-recognized in the market for both technology licensing and modular equipment

One of the largest carbon capture and clean H_2 production facilities in the US to date

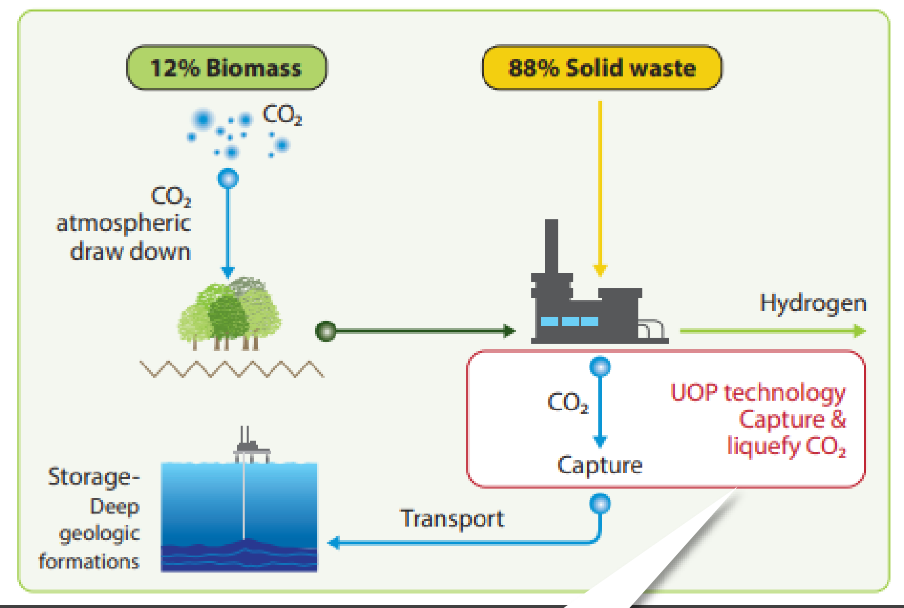


Figure 1: Overall flow scheme

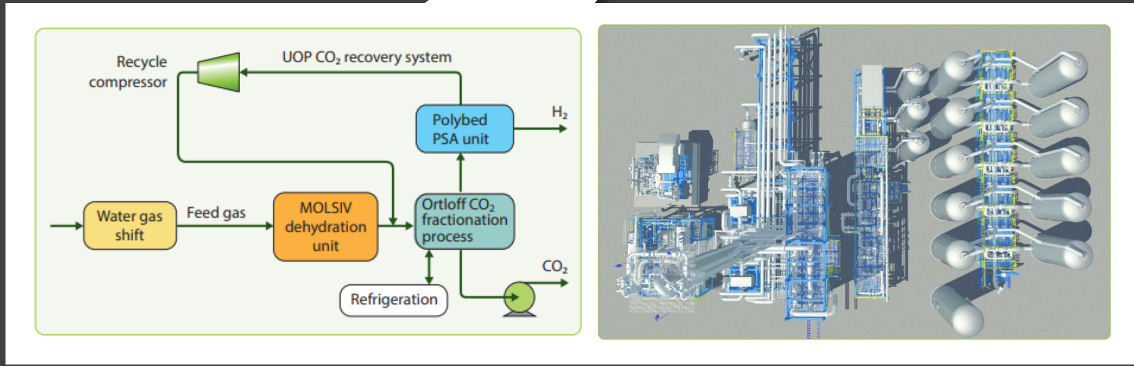
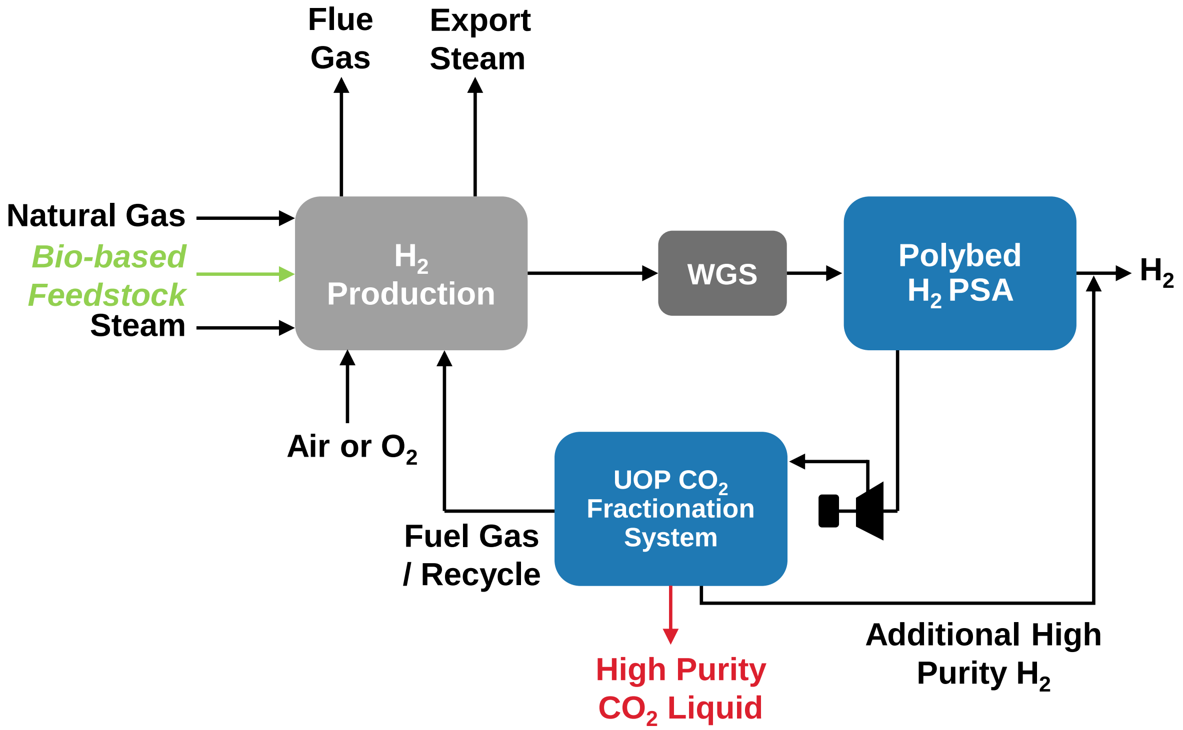


Figure 2: Honeywell CO_2 capture solution

LOW CARBON H2
SMR RETROFIT SOLUTIONS

SMR RETROFIT

UOP CO_2 FRACTIONATION SYSTEM



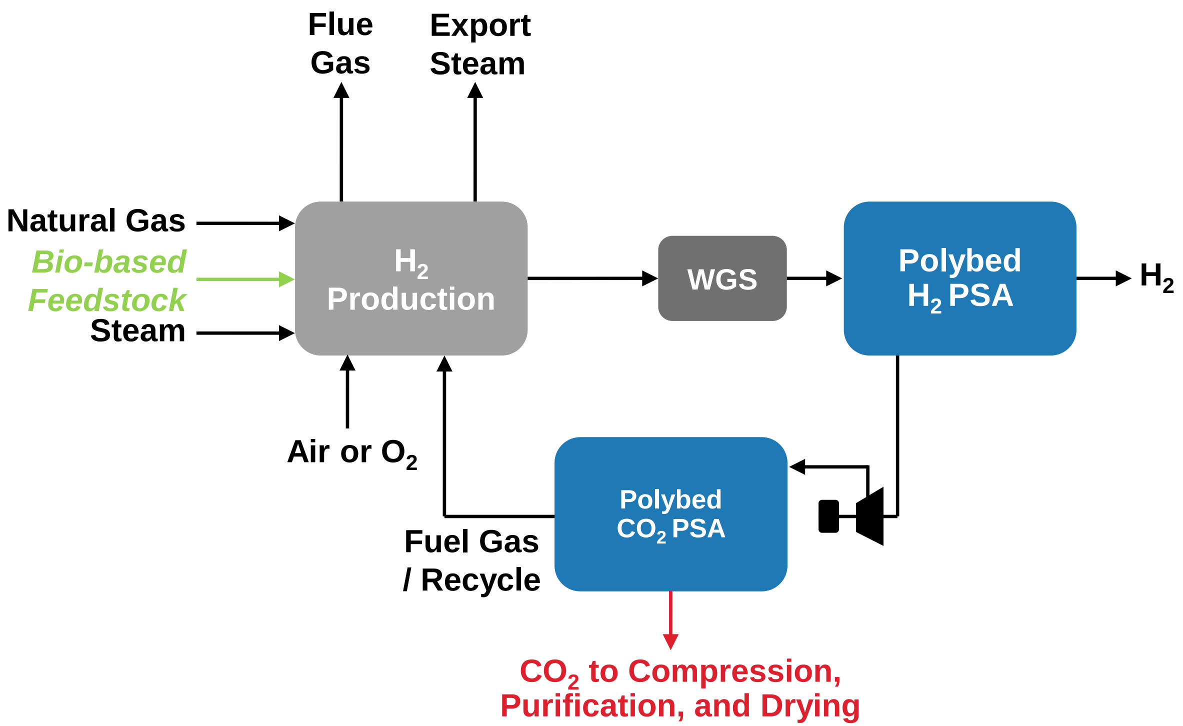
- Up to 20% additional H_2 yield from SMR**
- >99% CO_2 recovery from PSA tail gas (~60% overall direct CO_2 emissions reduction in typical existing SMR)
- CO_2 liquid purity of 99-99.9+ mol%
- Food-grade CO_2 can be produced if required
- Liquid CO_2 product ideal for rail or ship transport
- No steam usage for carbon capture
- “Bolt-on” system
- $20–40/MT CO_2 captured with H_2 credit*

* Cost of CO_2 captured includes operating costs, fixed costs, USGC basis annualized capital costs (10%/yr), and product value for additional H_2 production where applicable. Low end of range shown is for $3/GJ (LHV) and high end of range is for $6.6/GJ (LHV) natural gas price. CO_2 is provided as high-pressure product at plant battery limits and does not include CO_2 sequestration costs or any tax or credits for CO_2. Cost of CO_2 captured is subject to key variables - stream composition, CO_2 delivery requirement (pressure, purity, phase), utility price set, price of H_2, and geographic location; and is calculated based on internally developed models.

** 90% H_2 recovery from existing PSA tail gas proven in pilot plant testing and commercial plants. Overall H_2 yield increase depends on the performance of the existing PSA, and is maximized by retrofitting an asset with a low H_2 recovery existing PSA.

SMR RETROFIT

CO_2 POLYBED™ PSA

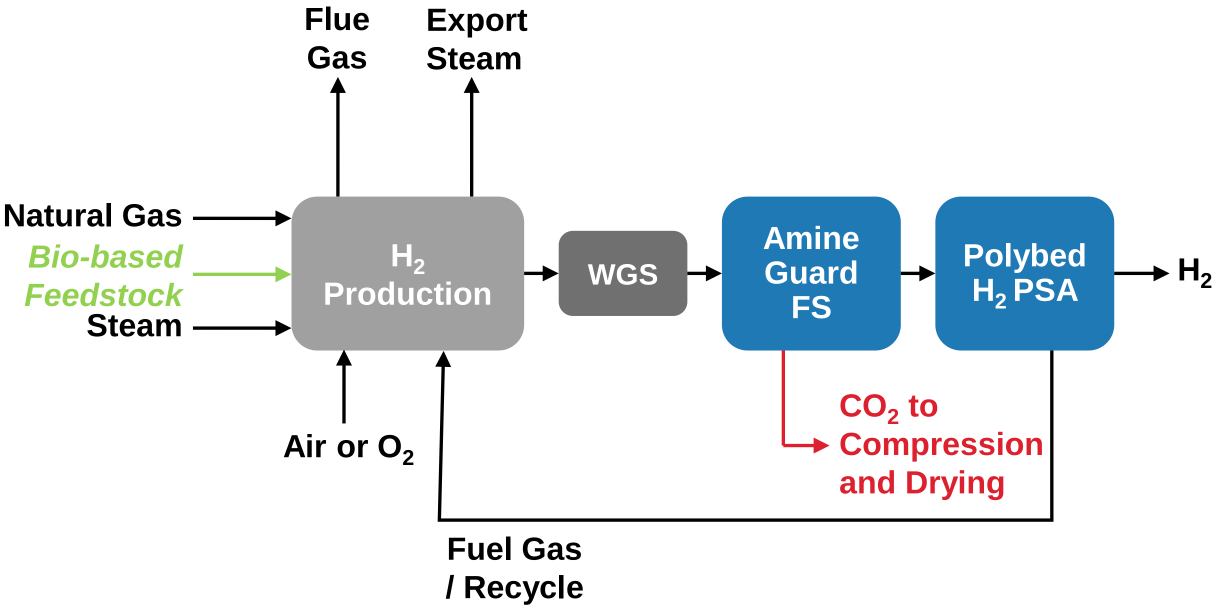


- Lowest capex and opex compared to solvent and cryo systems
- 90-98% CO_2 recovery from PSA tail gas (~50-60% overall direct CO_2 emissions reduction in typical existing SMR)
- >95 mol% CO_2 gas purity
- Optimal when lower purity or lower recovery of CO_2 is acceptable
- No steam usage for carbon capture
- “Bolt-on” system
- $35–50/MT CO_2*

*Cost of CO_2 captured includes operating costs, fixed costs, USGC basis annualized capital costs (10%/yr), and product value for additional H_2 production where applicable. Low end of range shown is for $3/GJ (LHV) and high end of range is for $6.6/GJ (LHV) natural gas price. CO_2 is provided as high-pressure product at plant battery limits and does not include CO_2 sequestration costs or any tax or credits for CO_2. Cost of CO_2 captured is subject to key variables - stream composition, CO_2 delivery requirement (pressure, purity, phase), utility price set, price of H_2, and geographic location; and is calculated based on internally developed models.

SMR RETROFIT

AMINE GUARD™ FS

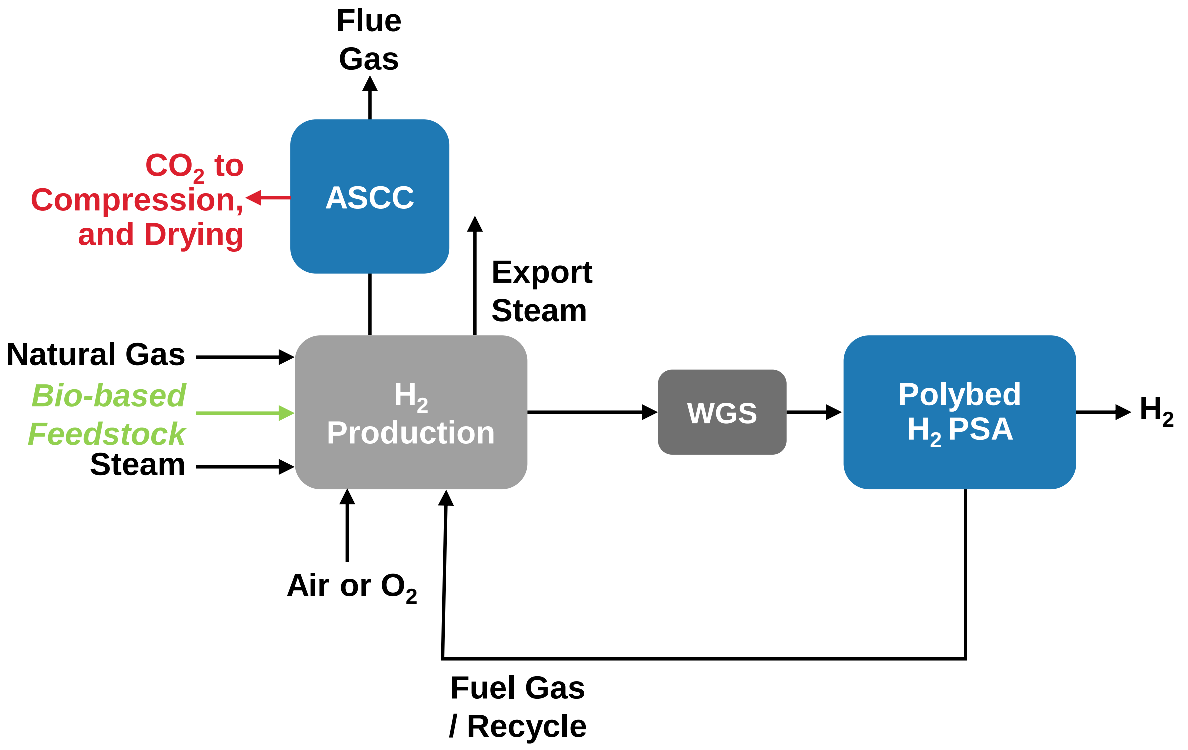


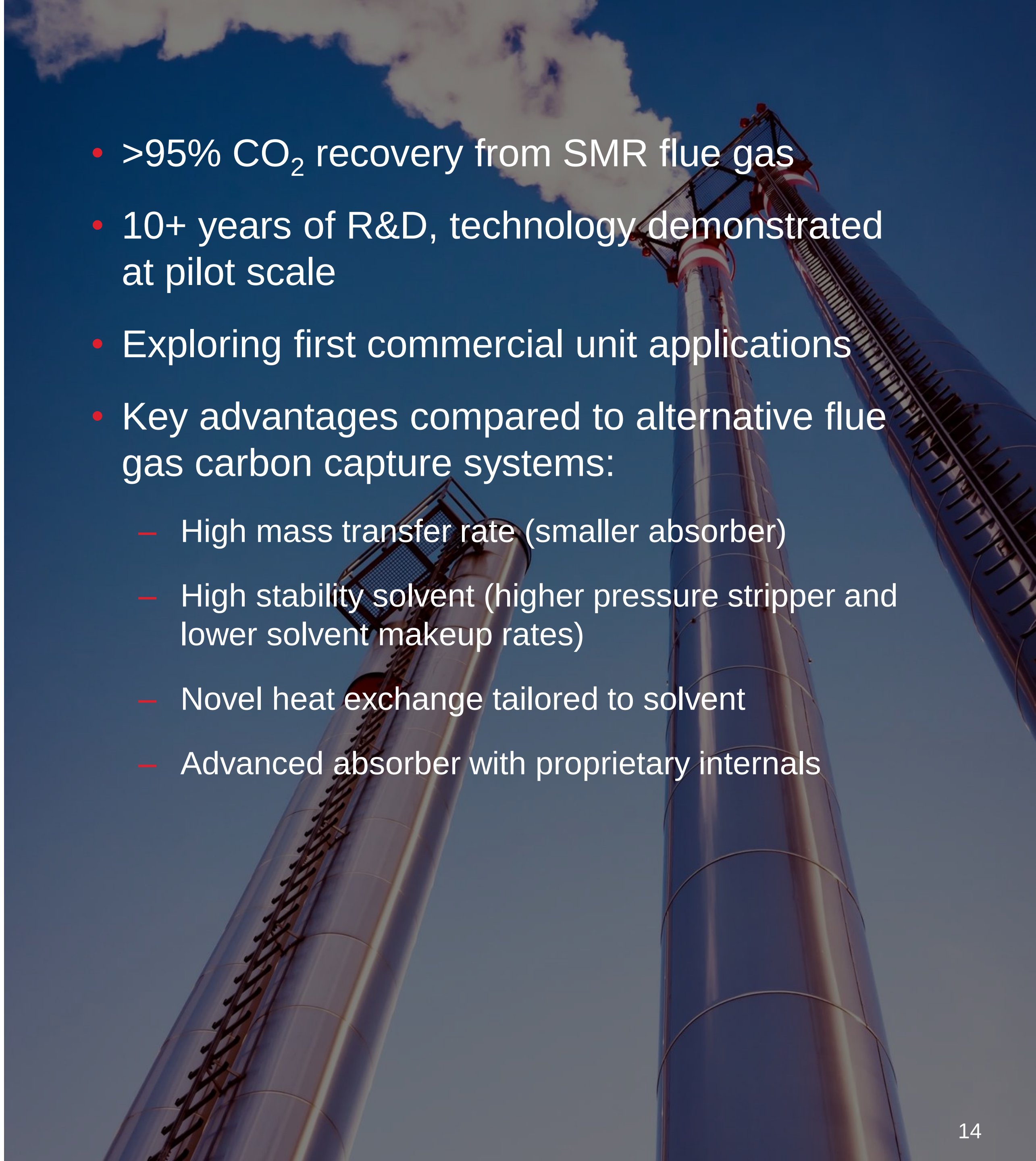
- Lower electricity requirement compared to cryo or PSA systems, but requires steam and does not provide additional hydrogen recovery
- >99% CO_2 recovery from SMR syngas (~60% overall direct CO_2 emissions reduction in typical existing SMR)
- 99 mol% CO_2 gas purity
- Revamp of H_2 PSA may be required
- Extensive commercial experience in natural gas treating, synthesis gas treating, direct iron ore reduction, and ammonia plants
- $45–60/MT CO_2*

* Cost of CO_2 captured includes operating costs, fixed costs, USGC basis annualized capital costs (10%/yr), and product value for additional H_2 production where applicable. Low end of range shown is for $3/GJ (LHV) and high end of range is for $6.6/GJ (LHV) natural gas price. CO_2 is provided as high-pressure product at plant battery limits and does not include CO_2 sequestration costs or any tax or credits for CO_2. Cost of CO_2 captured is subject to key variables - stream composition, CO_2 delivery requirement (pressure, purity, phase), utility price set, price of H_2, and geographic location; and is calculated based on internally developed models.

SMR
RETROFIT

ADVANCED SOLVENT FOR CARBON CAPTURE





- >95% CO_2 recovery from SMR flue gas
- 10+ years of R&D, technology demonstrated at pilot scale
- Exploring first commercial unit applications
- Key advantages compared to alternative flue gas carbon capture systems:
  - High mass transfer rate (smaller absorber)
  - High stability solvent (higher pressure stripper and lower solvent makeup rates)
  - Novel heat exchange tailored to solvent
  - Advanced absorber with proprietary internals

SUMMARY OF OPTIONS

	Pre-Combustion			Post-Combustion
	UOP CO_2 Fractionation System on Tail Gas	CO_2 Polybed PSA on Tail Gas	AmineGuard FS on Syngas	Advanced Solvent System on Flue Gas
CO_2 Recovery from Stream	>99% Liquid product	90-98% Gas phase product	>99% Gas phase product	>95% Gas phase product
Overall CO_2 Capture	Depends on configuration of H_2 plant and % of total CO_2 in pre-combustion stream			95%+
Additional H_2 Yield	10-20%	NO	NO	NO
Ultra High CO_2 Purity	YES	NO	NO	NO
Steam Usage	NO	NO	YES	YES
Retrofit	Bolt-on	Bolt-on	May require main PSA retrofit	Bolt-on
Commercial Experience	YES, ref. units in similar applications	YES, ref. units in similar applications	Extensive	Exploring first commercial applications
Cost of CO_2 Captured*, $/MT	**20–40 (includes H_2 credit)**	**35–50**	**45–60**	**55-70**

*Cost of CO_2 captured includes operating costs, fixed costs, USGC basis annualized capital costs (10%/yr), and product value for additional H_2 production where applicable. Low end of range shown is for $3/GJ (LHV) and high end of range is for $6.6/GJ (LHV) natural gas price. CO_2 is provided as high-pressure product at plant battery limits and does not include CO_2 sequestration costs or any tax or credits for CO_2. Cost of CO_2 captured is subject to key variables - stream composition, CO_2 delivery requirement (pressure, purity, phase), utility price set, price of H_2, and geographic location; and is calculated based on internally developed models.

Best option depends on project requirements

ASCC TECHNOLOGY

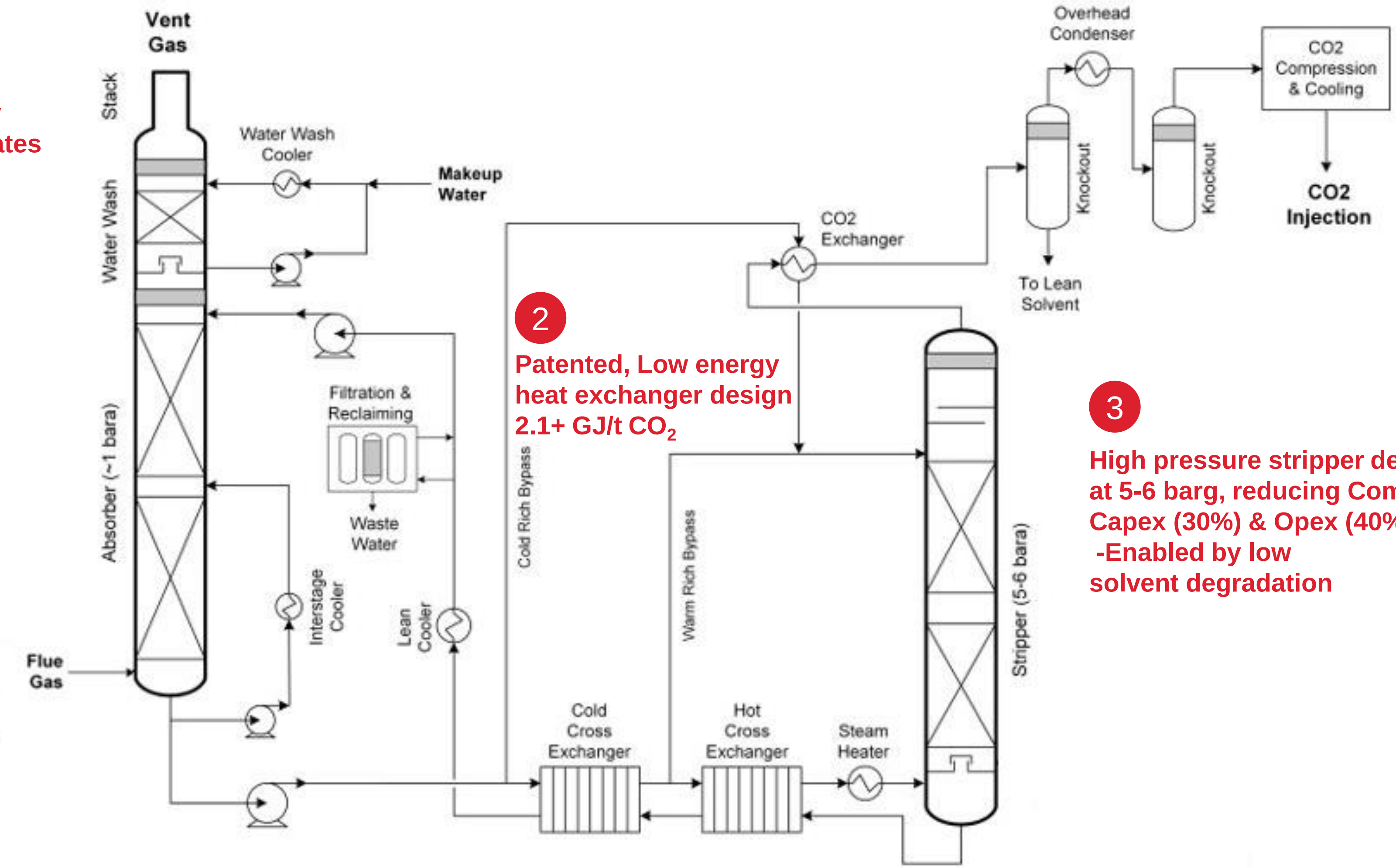
ADVANCED SOLVENT
CO_2 CAPTURE PROCESS

Commercial Ready offering targeted for Flue Gas Applications:
Refining & Petchem, Power, Steel, Cement

1. Advanced Solvent /w high mass transfer rates – Shorter Absorber – 30% cost savings

2. Patented, Low energy heat exchanger design 2.1+ GJ/t CO_2

3. High pressure stripper delivers CO_2 at 5-6 barg, reducing Compressor Capex (30%) & Opex (40%) -Enabled by low solvent degradation



Advanced Solvent Offering Reduces overall CAPEX and OPEX

ASCC DEVELOPMENT & TESTING

- On-going development over the past 20 years
- Culmination of 42 PhD dissertations and three MS theses
- >1,200 hours Pilot Plant testing (on 17” absorber) since 2006
- CO_2 concentrations 3-20%
- Flue Gas flow rates of 350-600 CFM

ASCC NCCC DEMONSTRATION

- NCCC facility located at Alabama Gaston Power Plant
- 0.5 MW coal-fired flue gas, 1500 CFM Flow with 8 TPD CO_2 Capture
- CO_2 concentrations tested @ 12% (2018) and 4% (2019) and 2023 (on-going thru early Aug– available to host Customers)
- Each campaign operated for 2000+ hours – a total of over
  4000 hours to date and counting
- Oxygen content tested up to 15%

ASCC RECENTLY COMPLETED DESIGNS

460 MW CCGT

CO_2 Capture: 1600 KMTA

Customer: Mustang Power Station, TX

Design Status: FEED COMPLETED 2022

300 MW PFBC

CO_2 Capture: 3100 KMTA

Customer: Consol 21st Century Power Plant

Design Status: PRE-FEED COMPLETED 2022

Simple Cycle Turbine

CO_2 Capture: 10 KMTA

Customer: Confidential

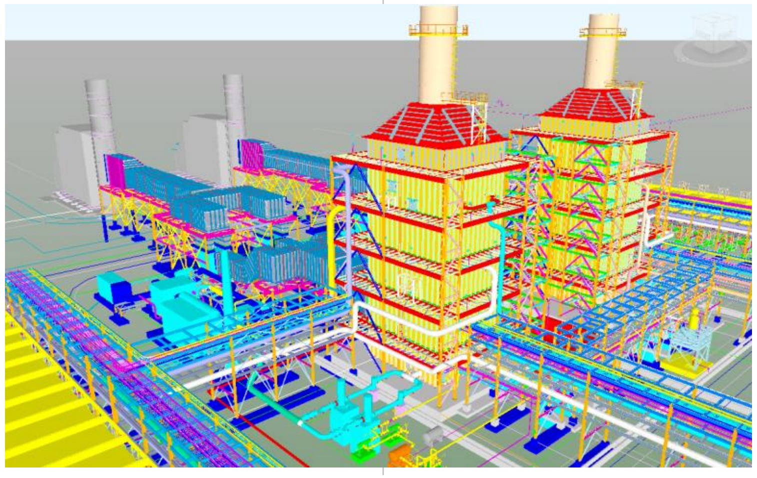
Design Status: PRE-FEED COMPLETED 2022

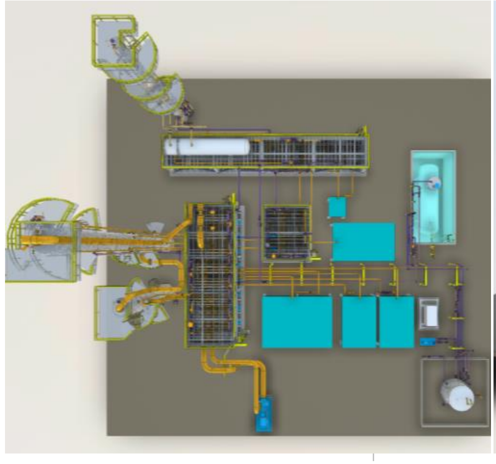
FCC Flue Gas

CO_2 Capture: 10 KMTA

Customer: Ecopetrol

Design Status: PRE-FEED COMPLETED, 2023

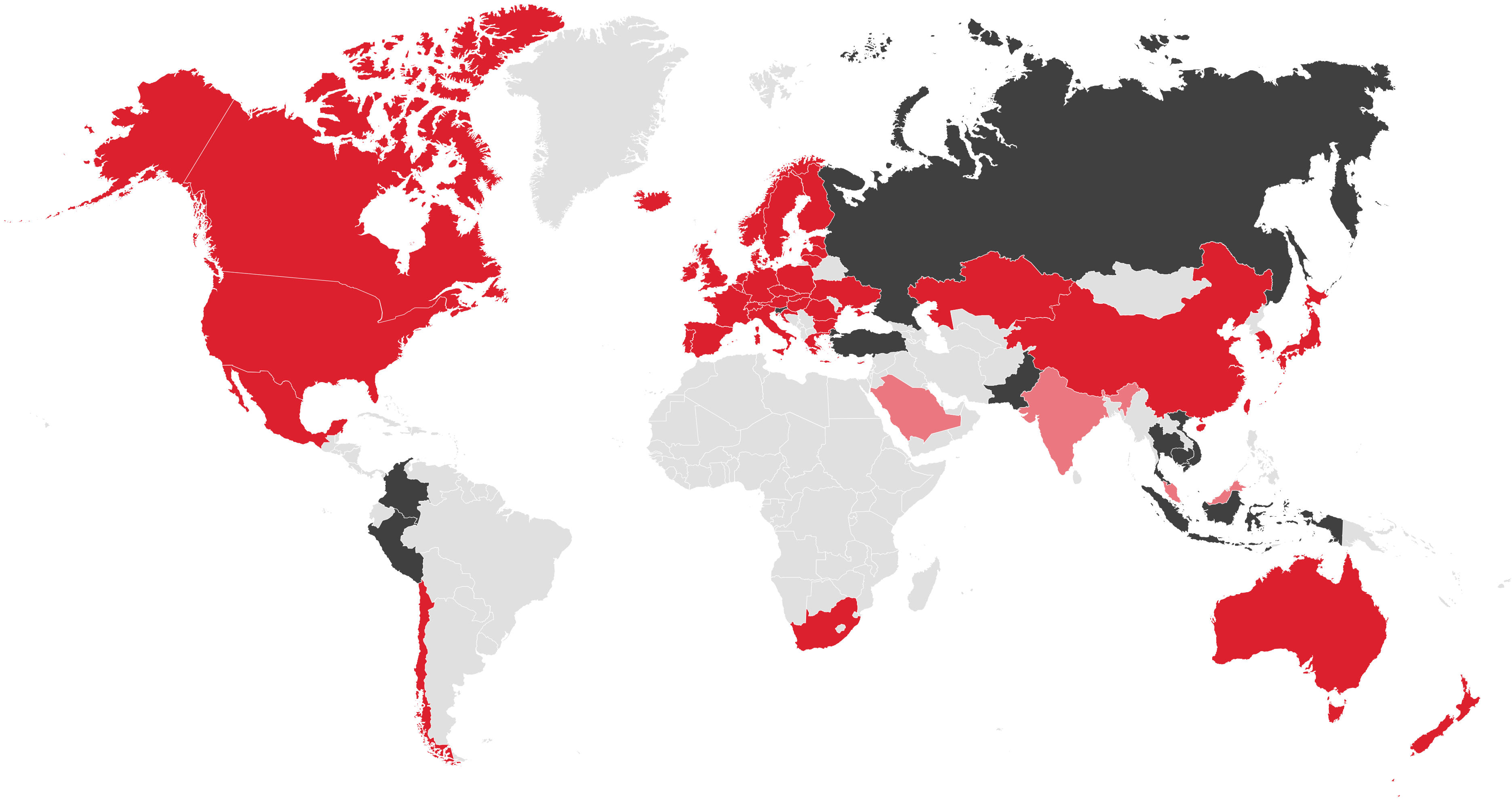




Advancing ASCC Across Diverse Application Set

H2 AND CO2 SOLUTIONS
POLICY UPDATE

GLOBAL
CO_2 POLICY



Key: Implemented CO_2 pricing + RD&D | Proposed CO_2 pricing + RD&D | Public RD&D programs

CO_2 PRICING:

- Emissions Trading Schemes (45 countries)
- Carbon intensity/ LCA credits
- Tax Credits
- Capex Credits

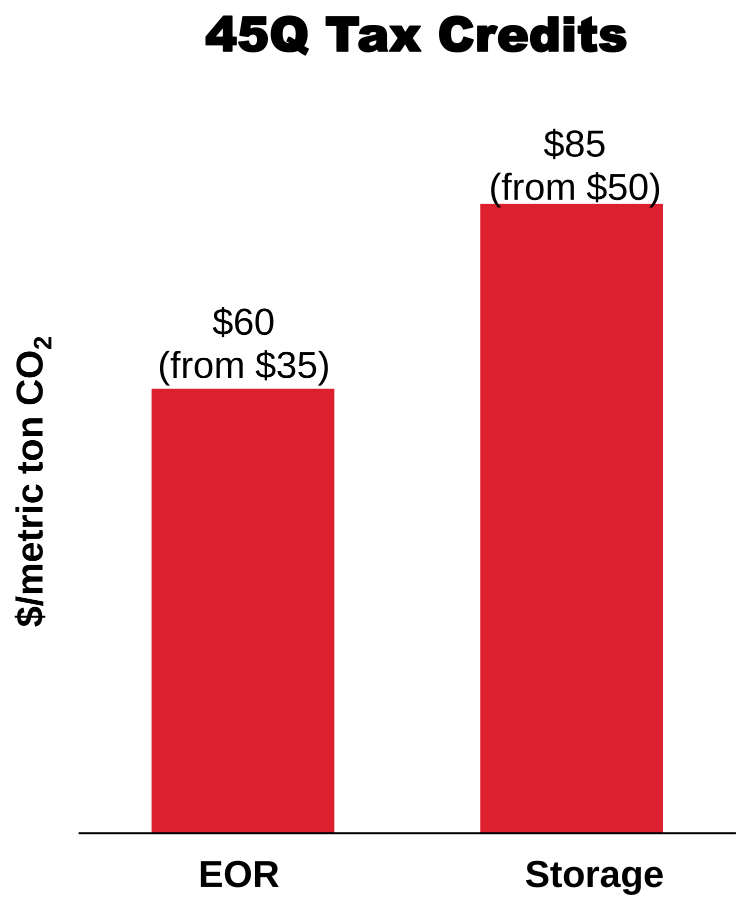
RD&D

- Public funding for research, development, and **demonstration**

Source: Global Carbon Capture Institute, S&P, UOP Analysis

USA POLICY UPDATE
CARBON CAPTURE

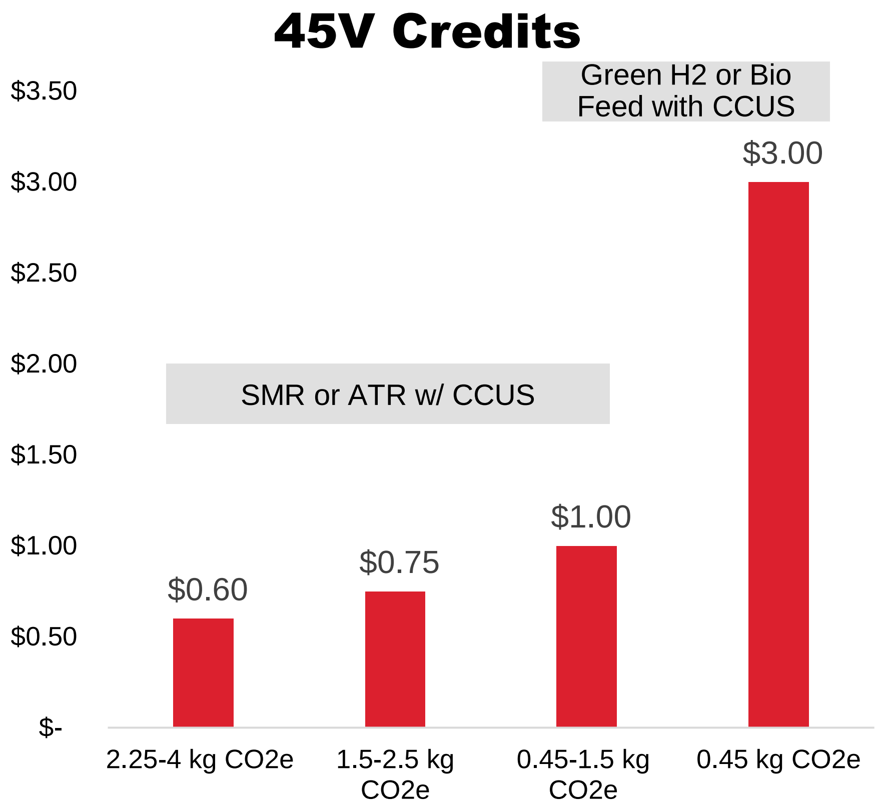
- USA Tax Code - 45Q Tax Credit (performance-based); incentives updated 2022 via the Inflation Reduction Act (IRA) – **signed into law on 8/16**
- Increased $/ton credits – see chart at right
- Project Thresholds:
  - Power Generation must capture greater than 18,750 metric tpy & more than 75% removal of baseline CO_2 production (Previously 500,000 tpy)
  - Industrial Requirements, must capture a minimum of 12,500 metric tpy (Previously 100,000 tpy)
  - Must begin construction before **JANUARY 1, 2033**, and can claim the credit for up to 12 years after being placed in service (previously 2026)
- Included Direct pay provisions
  - Allow projects to receive direct pay for first 5 years of operation, while non-profits and co-ops can receive direct pay for full 12 years of credit payout



Policy support has strengthened to increase project development

USA POLICY UPDATE
HYDROGEN PRODUCTION

- USA Tax Code – 45V Tax Credit (performance-based); Creates new clean hydrogen production incentive with direct pay provisions
  - Qualified facility means a facility that is
    - (1) owned by the taxpayer
    - (2) which produces qualified clean hydrogen, and
    - (3) the construction of which begins before January 1, 2033
  - Qualified Clean H_2 is H_2 produced with lifecycle GHG rate of not greater than 4 kg CO_2/kg H_2 produced
  - Credit value ranges from \$0.12/kg to \$3.00/kg max, if Prevailing wage and labor requirements are met (5x multiplier from base)
  - Credit increases in value as the lifecycle emissions decrease



UOP analysis; CO2 intensity considers upstream emissions of 1.8 kg CO2 / kg H2 as well as estimated H2 plant emissions after carbon capture. Bubbles are indicative to show where production methods may qualify for credits.

Policy support has strengthened to increase project development

REGIONAL POLICY HIGHLIGHTS

EUROPE

European Union
- ETS with cap and annual rate of reduction, ~$80/tonne in Nov '22

United Kingdom:
- ETS covering power gen & industry, $90/tonne in Nov '22

Denmark:
- 5 billion Euro investment over 10 years for CCUS projects; 70% emission reduction by '30, most aggressive in Europe

Netherlands:
- Sustainable Energy subsidy fund increased from 5 to 13 billion, ½ to Porthos CO_2 storage project

ASIA PACIFIC

China:
- Cap and trade based on emission intensity, starting with coal and gas power plants '(<$10/tonne)

Australia:
- Large emitters (>100KMTA) exceeding baseline must offset thru purchased credits; CCU allows credit generation

Thailand, Malaysia, Indonesia, Korea:
- Early stages of policy development
- Major O&G evaluating hubs in Singapore, Malaysia, Indonesia

REST OF WORLD

Middle East:
- Most countries have climate policies, but not CCS specific. Growth being led by vision of governments focused on decarbonization as growth opportunity. Voluntary markets in KSA, UAE, Egypt.

LATAM:
- Very early stages of policy development;
- Brazil on track to inject 40 Mt CO2 from Petrobras project by '25

Canada:
- Investment credit available for up to 50% capex; Alberta province supporting hub development

Global policies developing in support of projects

Source: Global Carbon Capture Institute

THANK YOU

Honeywell

HON ASCC TECHNOLOGY EVALUATION

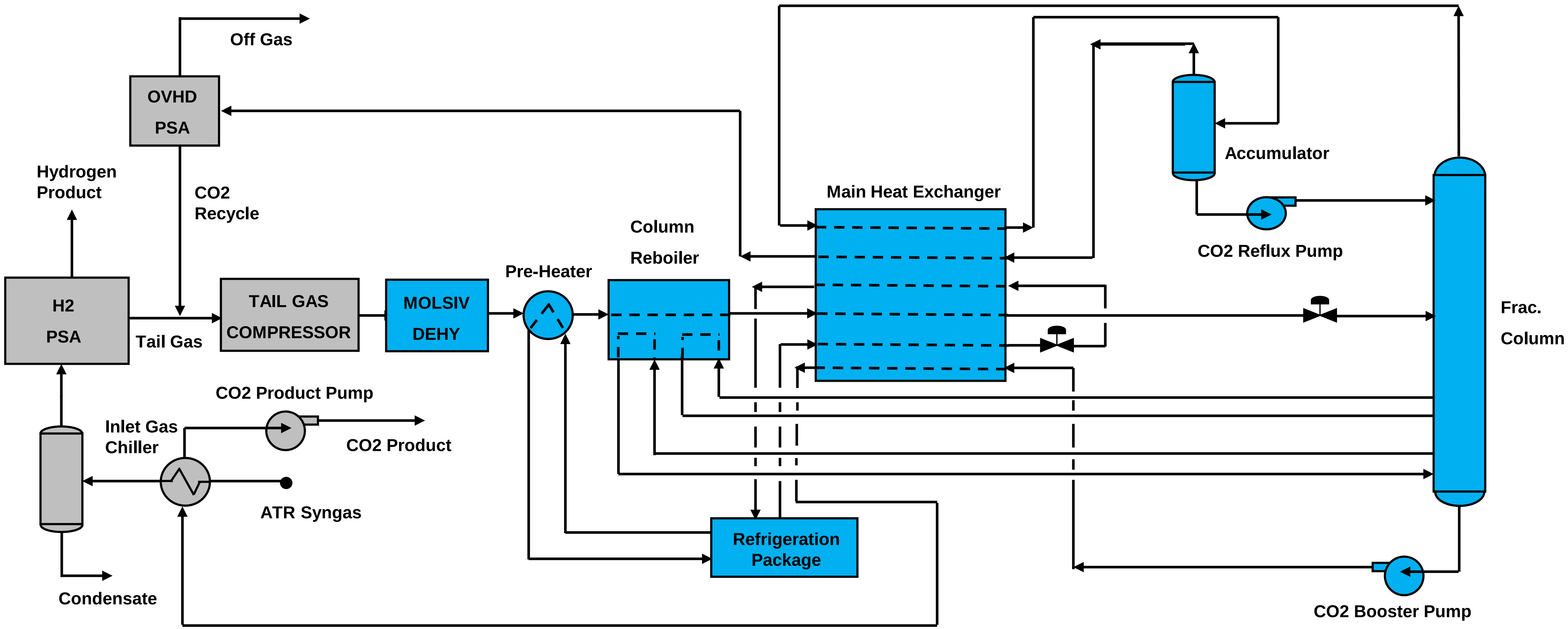
HON UOP ASCC offers significant advantages over legacy MEA technology and commercially available 2nd gen solvents

Basis: Typical values across flue gas ranges (100-1500 MMSCFD) and Concentrations (3.5% - 18% CO2); 200KMTA – 1000 KMTA CO2 capture

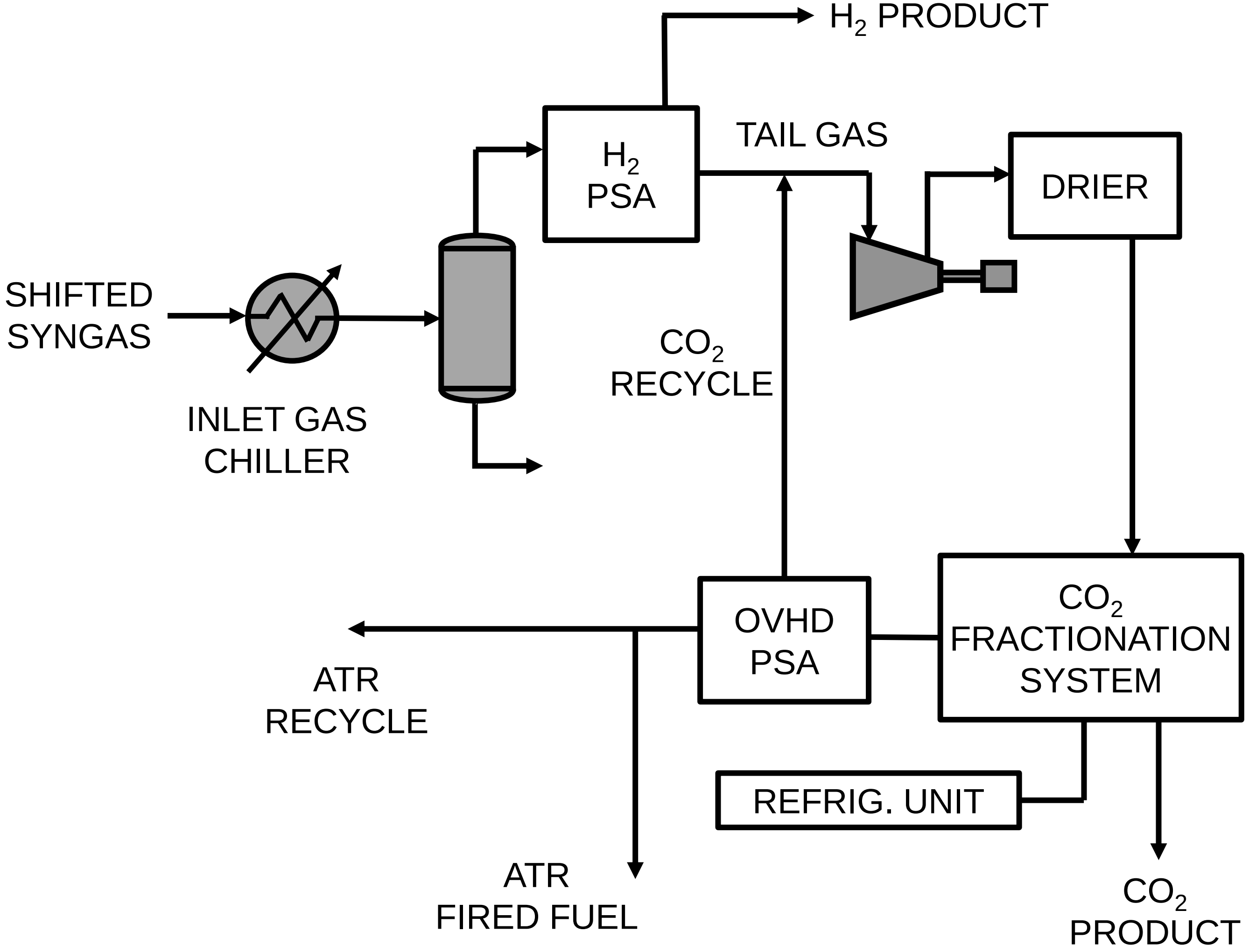
	HON ASCC	Competitor A[(2)] (30% MEA+)	Competitor B[(2)] (2nd Gen Solvent)	Value from HON ASCC
CO_2 Capture rate (%)	95-99 [(1)]	90 (typ.)	95 (typ.)	Maximum CO2 capture to maximize credits / minimize penalties
Quench Column	Not Required for low CO_2, low water (<10%), & low temp (< 120C) – ideal for CCGT	Required	Required	When applicable, enables: 11% reduction in installed equipment cost 18% reduction in cooling water
Absorber Height (ft) Packing Height (ft)	110 – 130 50 [(3)]	+>20% Shell Height +40-50% Packing Height[(4)]	+>20% Shell Height +40-50% Packing Height[(4)]	30% savings in absorber equipment cost
CO_2 Stripping Pressure (psig)	65-85	<10	<10	30% Compressor Capex Savings [(5)] 40% Compressor Opex Savings [(5)]
Steam Consumption (GJ / t CO_2)	2.1 – 2.6	3.3-3.7	2.4-3.3	10-30% Opex Savings
Solvent Loss (kg/tonne CO_2)	<0.1 – 0.5	8x	1x – 2x	Equivalent or Lower annual opex using ASCC

1. Recovery estimates based on varying temperatures over summer/winter seasons
2. All data above sourced from publicly available information.
3. Including water wash section
4. Estimate based on T-T
5. Assuming 2000 psig injection pressure

CO2 FRACTIONATION SYSTEM



ATR RECYCLE
CONFIGURATION 1
UOP CO_2 FRACTIONATION SYSTEM



Off-gas Recycle to ATR Feed

- Low Carbon Emissions
- Higher Feedstock Efficiency

Recycle Gas Slipstream to ATR Fired Heater

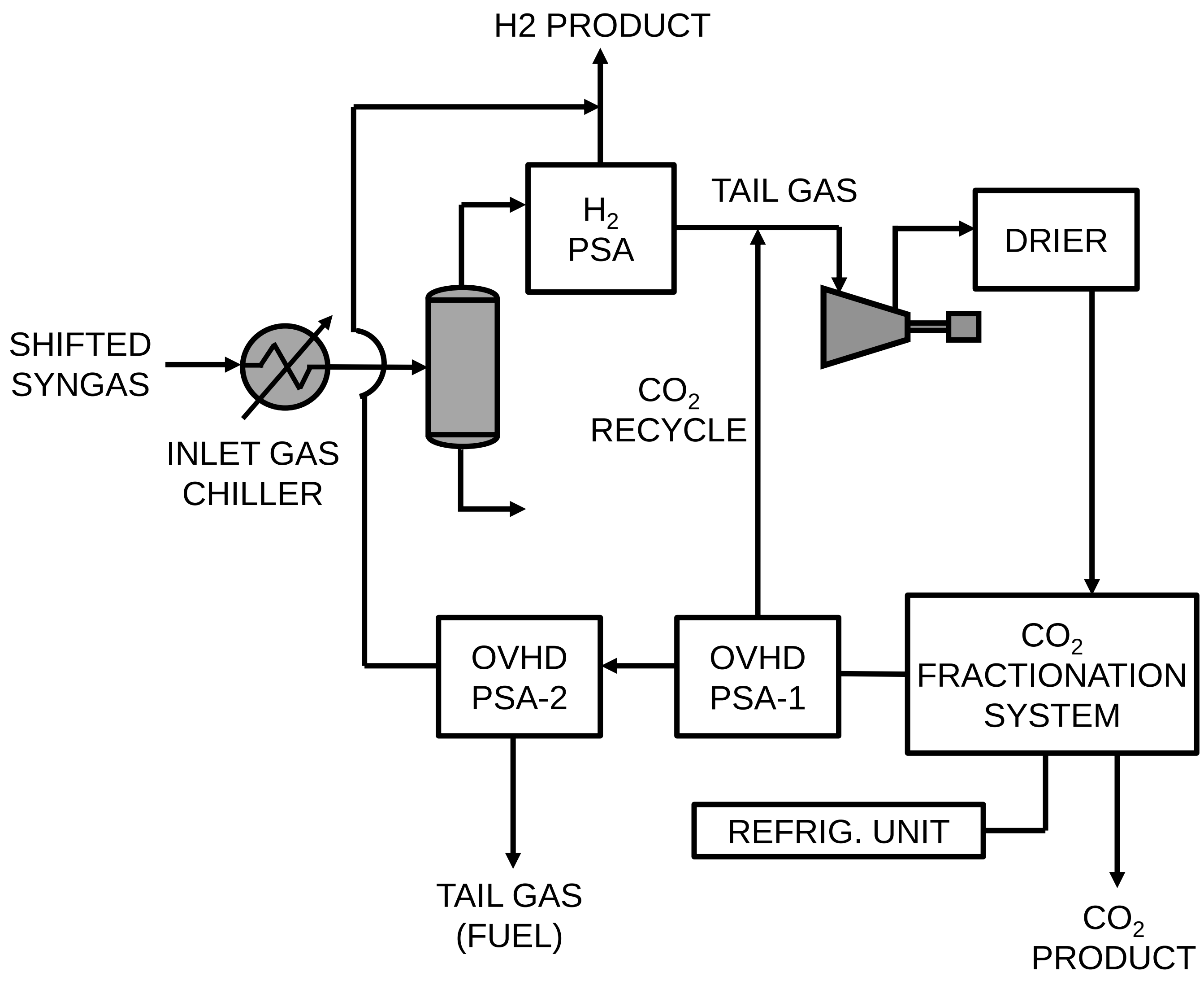
- Steam Generation benefit
- Higher Feedstock Efficiency

Inerts (N_2 + Argon) rejected in ATR Fired Heater

Scope 1 Emissions: 0.1 – 0.3 kg CO_2 / kg H_2

NO ATR RECYCLE

UOP CO_2 FRACTIONATION SYSTEM



Lower Cost Option

- ~10% reduced power consumption

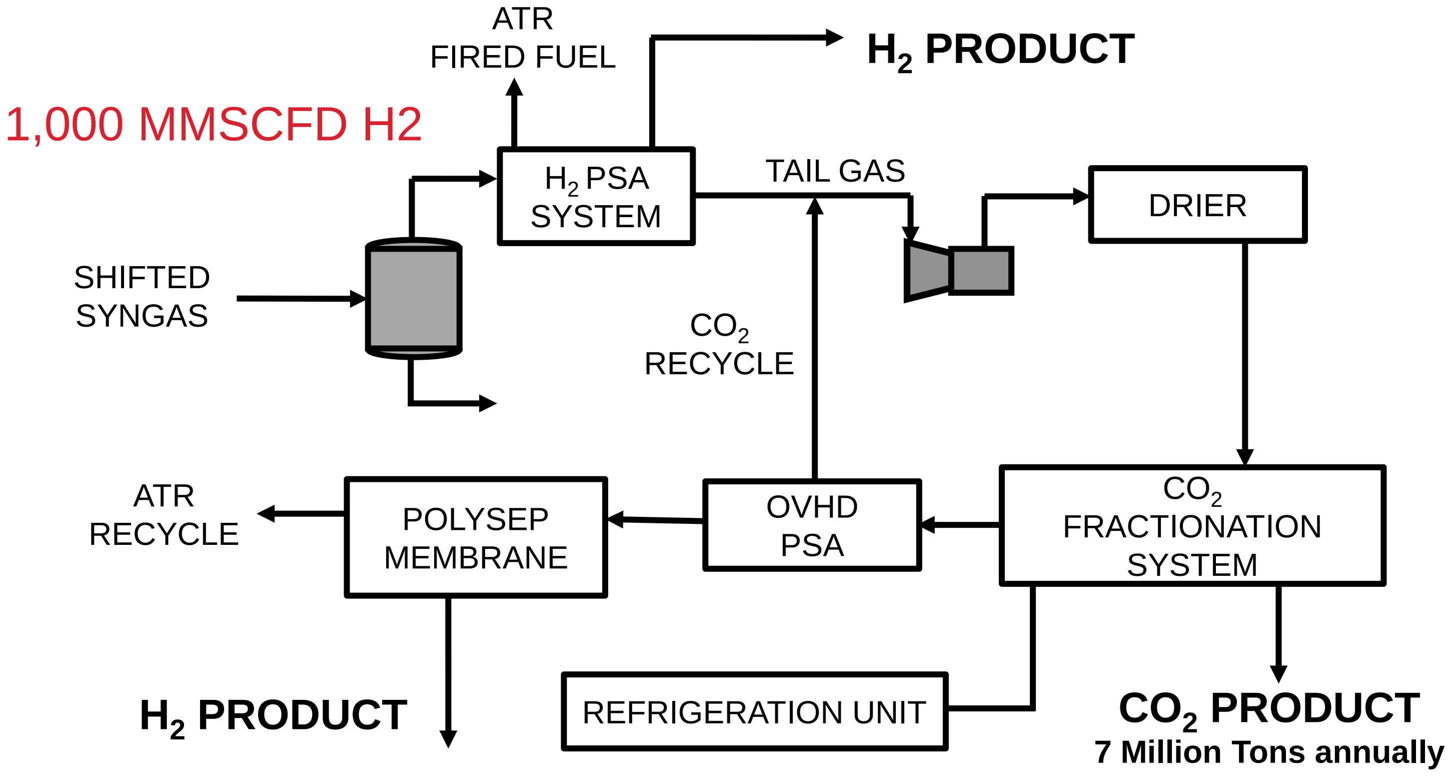
Flexible Uses for Secondary H_2 Product Stream

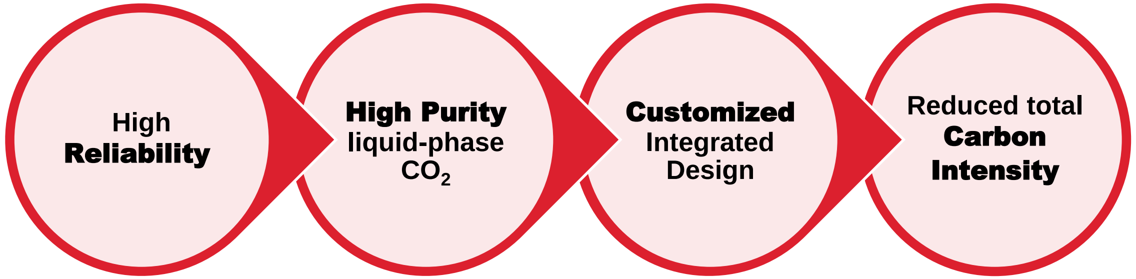
- Fuel-Cell Grade
- Chemical Grade
- Fuel Grade
- Delivery at different pressures

Scope 1 Emissions: 0.3 – 0.5 kg CO_2 / kg H_2

EXXONMOBIL CASE STUDY

UOP H2 PURIFICATION AND CO2 FRACTIONATION





[3] Based on press release issued Feb 15, 2023, announcing HON H2 tech in Exxon Baytown facility. Link

CO_2 Fractionation System

- Enables the capture of about **7 million tons of CO_2 annually**, equivalent to the emission of 1.5 millions of automobiles for one year[1]
- **98% CO_2 emissions captured** across Low-Carbon Hydrogen production facility[2]

H_2 Purification

- **High Purity H_2 produced** from Pressure Swing Adsorption and Polysep™ Membrane technologies
- ExxonMobil's H_2 production project will enable **up to 30% of scope 1 and scope 2 emissions** reduced at their Baytown facility[3]

[1] Based on the EPA's GHG equivalency calculator comparing nearly 7 million tons of CO2 per year with gasoline-powered passenger vehicles on the road.

[2] CO_2 equivalent emissions is a calculated value based on the combined carbon compounds emitted from the Hydrogen production and Carbon Capture equipment plus the combined carbon compounds in the H2 product.