Biogas Upgrading Cycle Options for 2, 3, and 4-stage Designs

Membrane Solutions

Leo Nemetz
Applications Engineer

April 2026

GENERATING A CLEANER FUTURE

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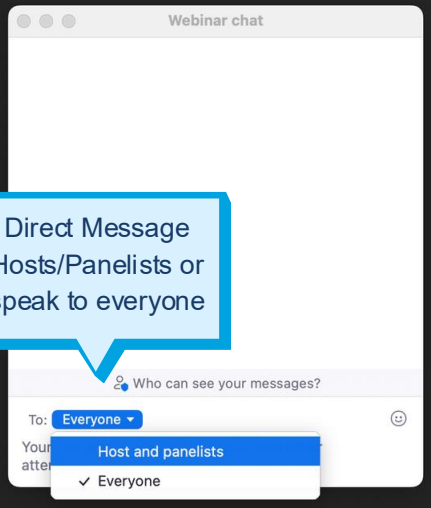
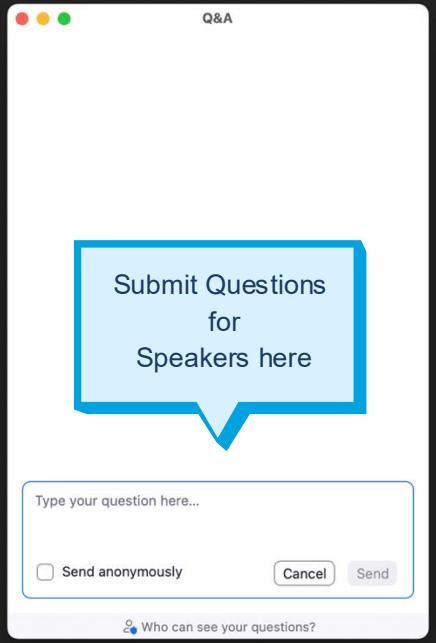


Direct Message Hosts/Panelists or speak to everyone



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GENERATING A CLEANER FUTURE

Air Products

Air Products Today

12.0
Billion dollars in sales

>8
Decades in business

~50
Countries where we operate

1,800
Miles of industrial gas pipeline

750+
Production facilities

30+
Industries served

>250,000+
Customers

Air Products is…
…a leader in the global industrial gas industry

- We are a **Fortune 500 company**, and are traded on the NYSE (APD)
- We provide essential industrial gases, **technologies and applications expertise** that enhance our customers' sustainability and improve their operations.
- As the leading global supplier of hydrogen, **we are accelerating the energy transition** through clean hydrogen megaprojects to decarbonize the hardest-to-abate industrial and heavy-duty transportation sectors.
- Air Products has a proud **history of innovation, operational excellence,** and an unwavering commitment to safety and environmental stewardship.

Total Safety Philosophy

Maintaining a safe workplace is a **fundamental and moral responsibility**.

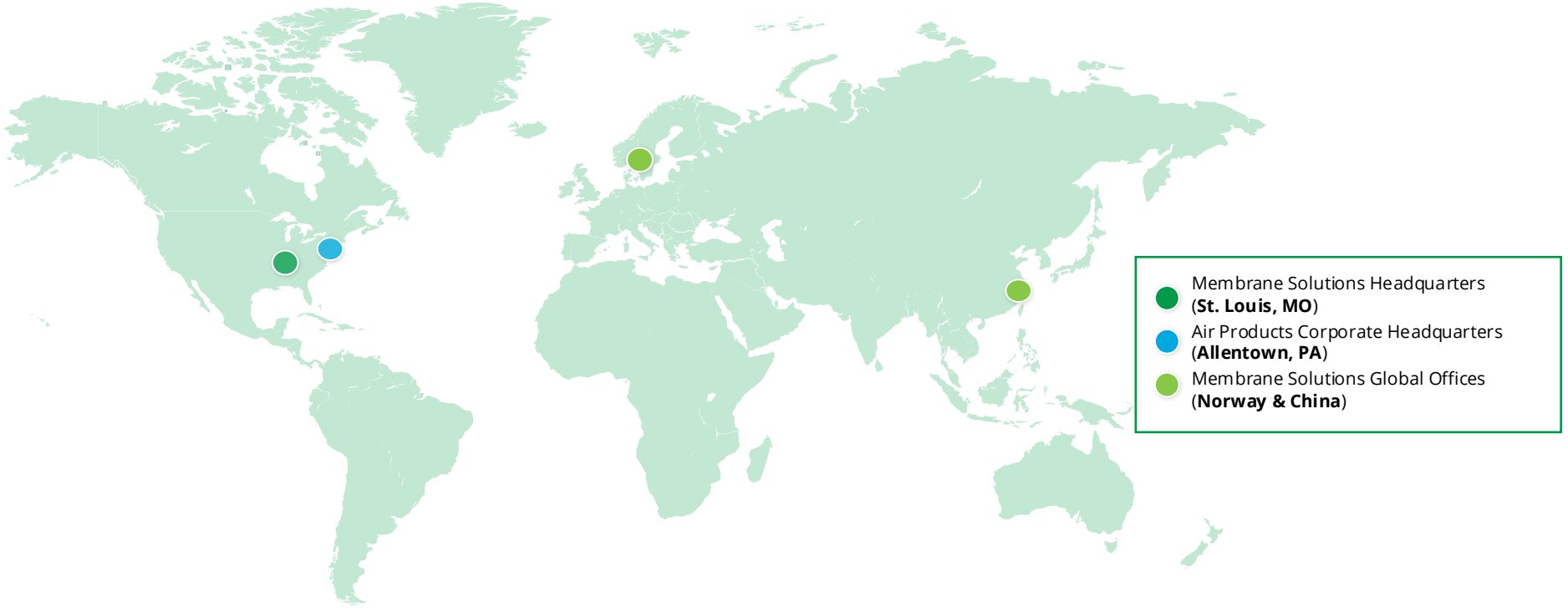
We take the approach that all accidents are preventable. The only acceptable goal is **zero** accidents and incidents. We will strive toward that goal in **every location**, **every day**.

AIR PRODUCTS Membrane Solutions

Moving Forward

Air Products Membrane Solutions

Air Products Membrane Solutions
Global Presence



AIR PRODUCTS Membrane Solutions

Air Products Membrane Solutions
Decades of Experience

- **1975 – 1990**: Monsanto owned the original membrane technology (marketed as PRISM® under the company name Permea Inc.)
- **1970s & 1980s**: **Permea commercialized membrane separation systems**
- **1985**: Permea acquired the marine systems business unit, based in Norway
- **1991**: **Air Products acquired the business including the PRISM® trademark**
- **2002**: OBIGGS product commercialization
- **2010s**: **Expansion into Biogas Upgrading market via OEM network**
- **2021**: Rebranded as Membrane Solutions
- **2024**: **Broke ground on our expanded manufacturing facility in St. Louis**

Saint Louis, Missouri USA

Kristiansand, Norway

Yantai, China

Air Products Membrane Solutions
Overview

Air Products Membrane Solutions designs, engineers, manufactures, and services a portfolio of PRISM® Membrane Separators, Marine Systems, and Engineered-to-Order Systems globally.

PRISM® Membrane Separators

Marine Systems

Engineered-to-Order Systems

Global Services & Support

AIR PRODUCTS Membrane Solutions

Membrane Solutions | PRISM® Membrane Separators

Biogas Upgrading

Used for biogas upgrading, dehydration, and simplified bio-LNG production

Onsite Nitrogen

Generate high-purity, ready-to-use nitrogen from compressed air

Dehydration Separators

Remove water vapor from compressed air, gas, or biogas streams

Onboard Inert Gas Generation

Create an inert environment to prevent fuel vapor combustion

High-Altitude Oxygen Generation

Generate a reliable oxygen-enriched air supply

Air Products Membrane Solutions Today
Proven Performance

Biogas Membrane System References

Process Gas Membrane Systems

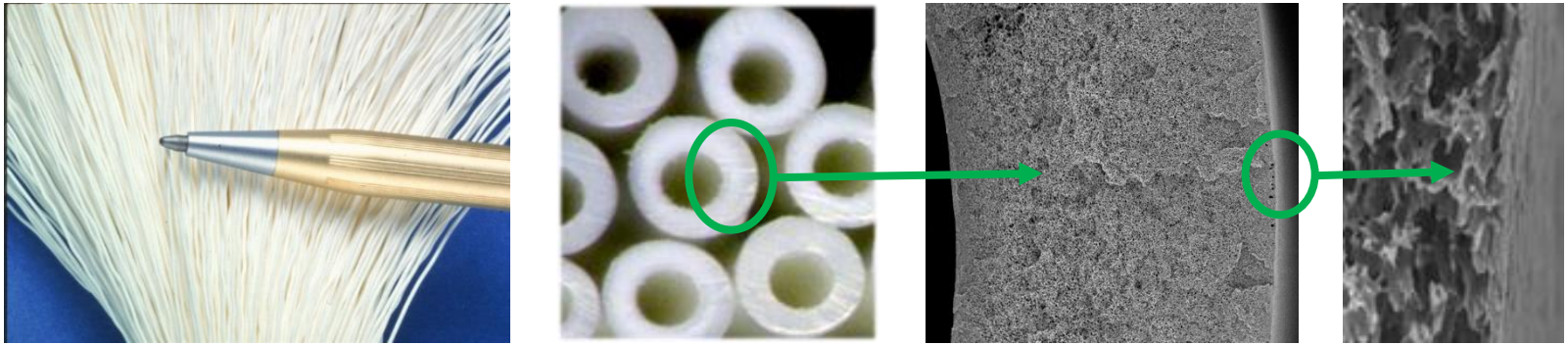
Engineered-to-Order Nitrogen Membrane Systems

Marine Nitrogen Membrane Systems

AIR PRODUCTS Membrane Solutions

What are Membranes?

- A membrane is:
  - **"a discrete, thin interface that moderates the permeation of chemical species in contact with it."** (R.W. Baker, Membrane Technology and Applications, 2004)
- Different chemical species move through at different rates:
  - Dimensional differences
  - Varying interactions between chemical species and membrane material



Applications of Membranes

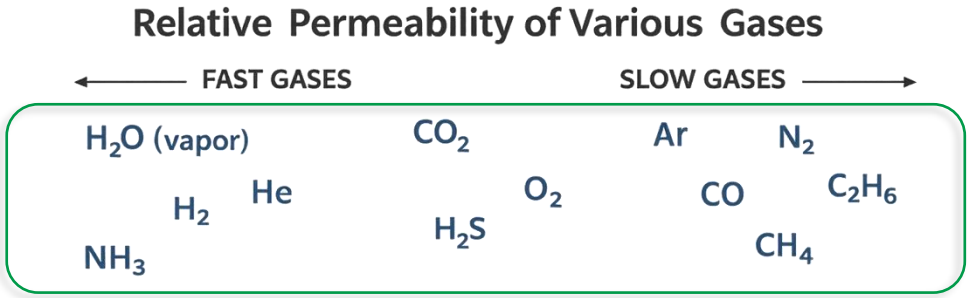
- Membranes can be made of many materials and come in different forms:
  - **Polymers**, metals, ceramics, glasses, carbon, etc.
  - Flat sheets, spiral wound, **hollow fibers**

- **Gas separations**:
  - N_2 production, CO_2 capture, H_2 recovery, **Biogas Upgrading**
- Water treatment:
  - Reverse osmosis, ultrafiltration
- Dialysis, Fuel cells, Gas/liquid contactors

Gas Permeability and Solution-Diffusion

$$P_i = D_i \times S_i$$

- P_i = Permeability coefficient of gas i through membrane
- D_i = Diffusion coefficient of gas i through membrane
  - Diffusion is primarily a function of molecule size
  - Smaller molecules will diffuse more quickly than larger molecules
- S_i = Solubility coefficient of gas i through membrane
  - Solubility is how much gas/vapor can "dissolve" in the membrane
  - Gases can interact differently with different materials



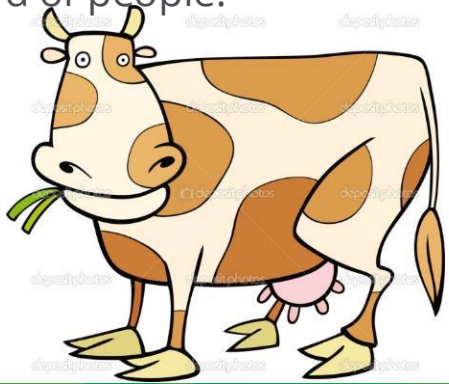
Diffusion of Gases

- Diffusion is primarily a function of molecule size
- Smaller molecules will diffuse more quickly than larger molecules

Gas	He	H_2O	H_2	CO_2	Ar	O_2	N_2	CH_4
Diameter (nm)	0.26	0.265	0.289	0.33	0.34	0.346	0.364	0.38

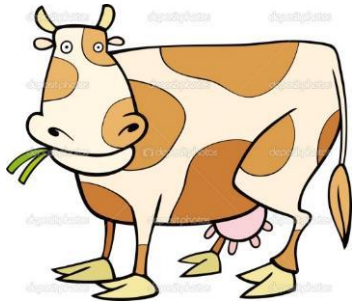
- Who could move more easily through a crowd of people?

A mouse can get through easier!



Solubility of Gases in Polymers

- Gases can interact differently with different materials
  - Polar vs non-polar
  - Hydrophilic vs hydrophobic (water-loving vs oil-loving)
- Temperature can also play a role
- Sometimes the solubility of a gas is more important than the size of a gas
- Now who do you think will run the fastest through a crowd?



The bull's horns changes the interaction with the crowd

Permeation via Solution-Diffusion

The Science

1. Molecules sorb onto upstream face of membrane
2. Molecules diffuse across membrane
3. Molecules desorb at downstream face of membrane

High pressure feed gas
p_{feed}

Low pressure permeate gas
$p_{permeate}$

$$J_A = P_A \frac{(p_{feed_A} - p_{permeate_A})}{L}$$

$$\alpha_{A/B} = \frac{P_A}{P_B}$$

Real World Solution-Diffusion

Sorption

Diffusion

Desorption

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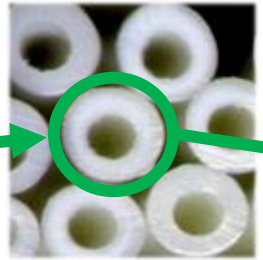
Membrane Fundamentals

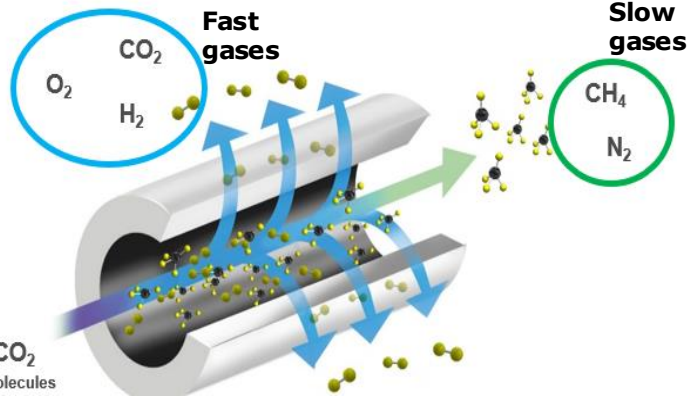
Relative Permeability of Various Gases

FAST GASES ← → SLOW GASES

H_2O (vapor)			CO_2		Ar	N_2
	H_2	He		O_2	CO	C_2H_6
NH_3			H_2S			CH_4



Mixture of Fast + Slow gases



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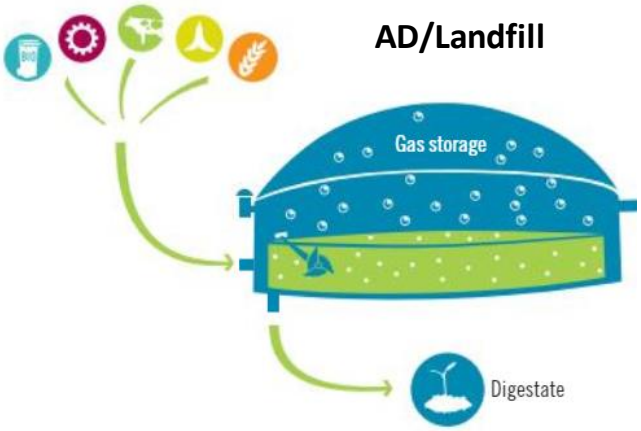
Biogas Basics

Feedstocks



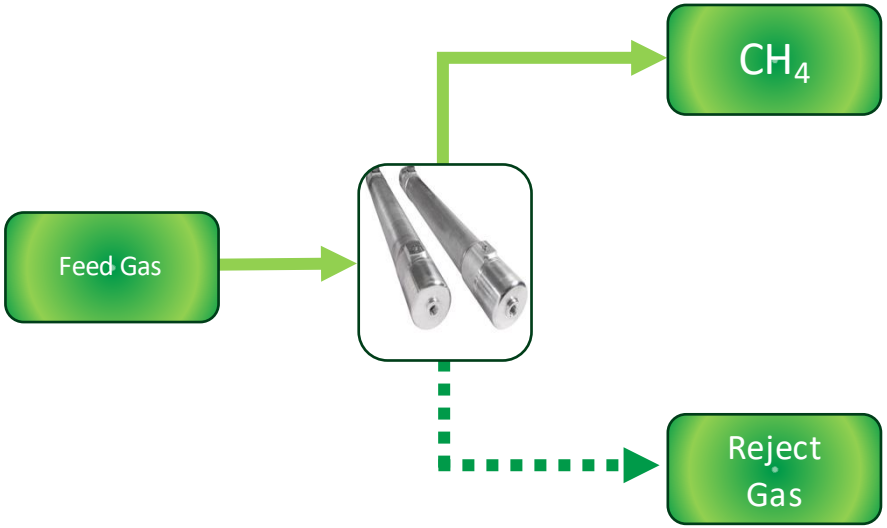
Raw biogas

- 45-85 vol% CH4
- 25-50 vol% CO2
- Byproducts: H_2O, H2S, NH3, O2, N2, VOC's, Siloxanes, Particles, amines, oil, etc.

Correct pretreatment gives:

- Extended lifetime & reduced maintenance
- No unpredicted downtime
- Performance upkeep
- Corrosion & deposits prevention

One- Stage Systems
Ideal for 85-90% CH_4 Recovery



↑ CH_4 Purity	↓ Recovery
↓ CH_4 Purity	↑ Recovery

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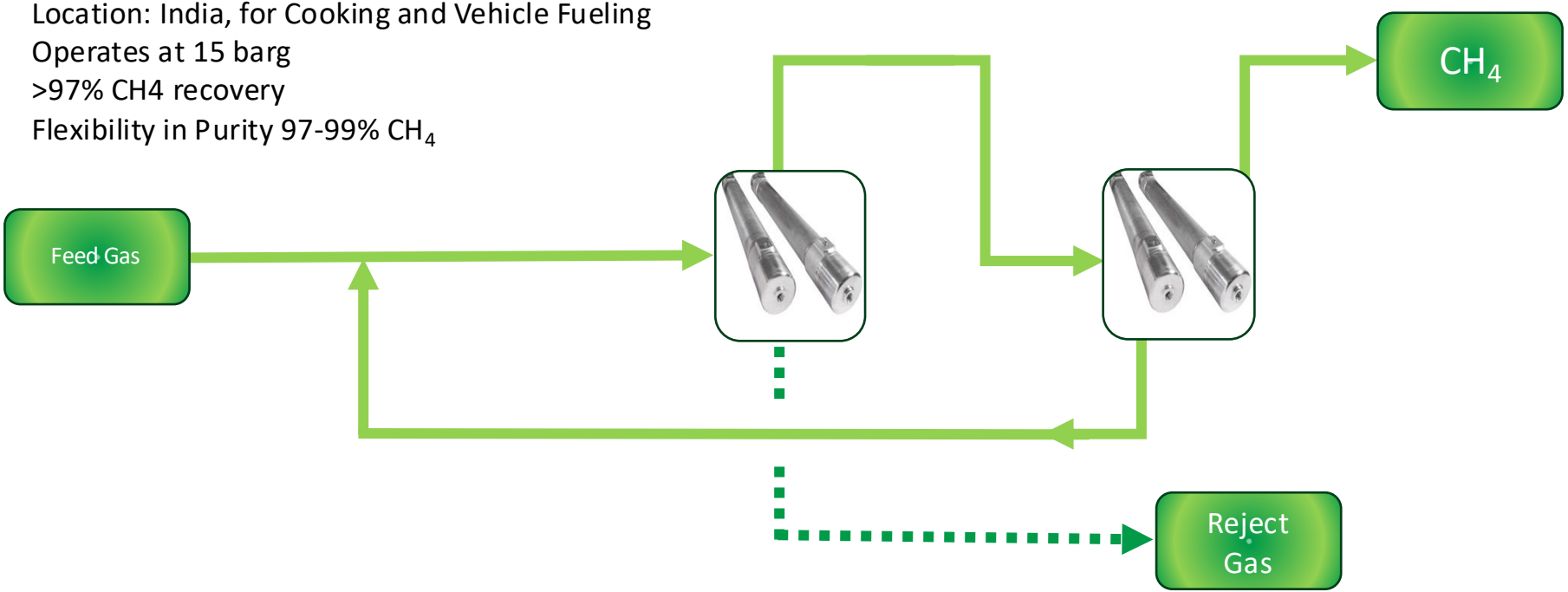
Moving Forward

Biogas Upgrading Options

Two-Stage Systems
Ideal for 93-97% CH_4 Recovery

Reference

- Location: India, for Cooking and Vehicle Fueling
- Operates at 15 barg
- >97% CH4 recovery
- Flexibility in Purity 97-99% CH_4



Two-Stage Systems
Design Comparisons

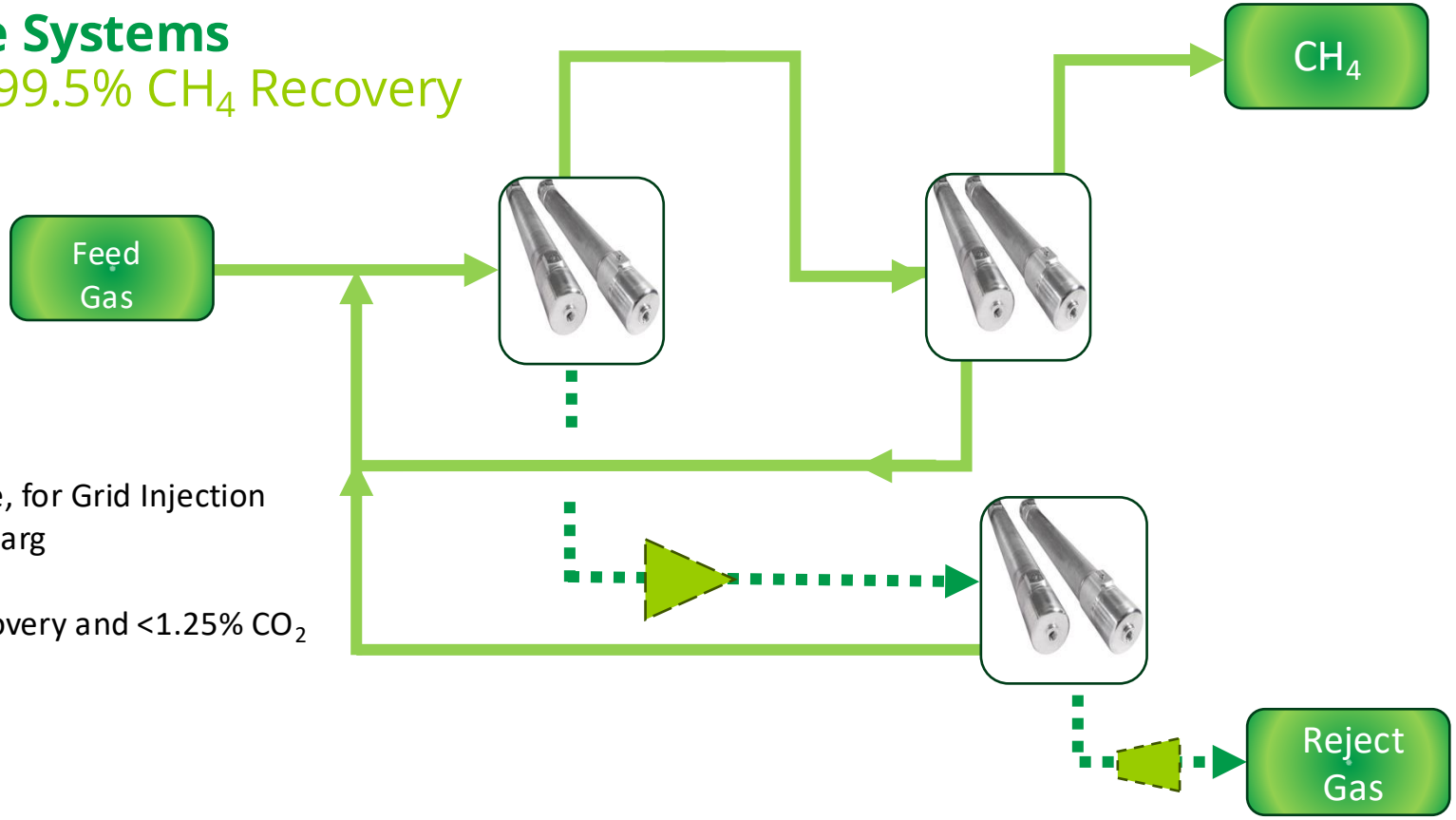
Constant Variables
Feed: 60 mol% CH4 and 40 mol% CO2
Operating Temp: 20°C
Inlet Pressure: 16 barg

Table 1: Two-Stage Solutions for Various Methane Recovery and Purity*

	97% CH_4 Recovery 99 mol% CH_4	97% CH_4 Recovery 98 mol% CH_4	98% CH_4 Recovery 99 mol% CH_4	98% CH_4 Recovery 98 mol% CH_4
Relative Membrane Quantity†	100%	88%	111%	94%
Power Consumption (kW/Nm³/hr of raw gas)	0.23	0.22	0.27	0.26

* Performance is based on the constant variables listed for temperature, pressure, and composition.
†Relative membrane quantity is compared to the green column

Three-Stage Systems
Ideal for 98-99.5% CH_4 Recovery



Reference 1 of >200

- Location: Europe, for Grid Injection
- Operates at 17 barg
- ~55% Recycle
- >99.5% CH4 recovery and <1.25% CO_2

Three-Stage Systems
Design Comparisons

Constant Variables
Feed: 60 mol% CH4 and 40 mol% CO2
Operating Temp: 20°C
Inlet Pressure: 16 barg
Recovery: 99.5% CH4
Product Purity: 98.75 mol% CH4

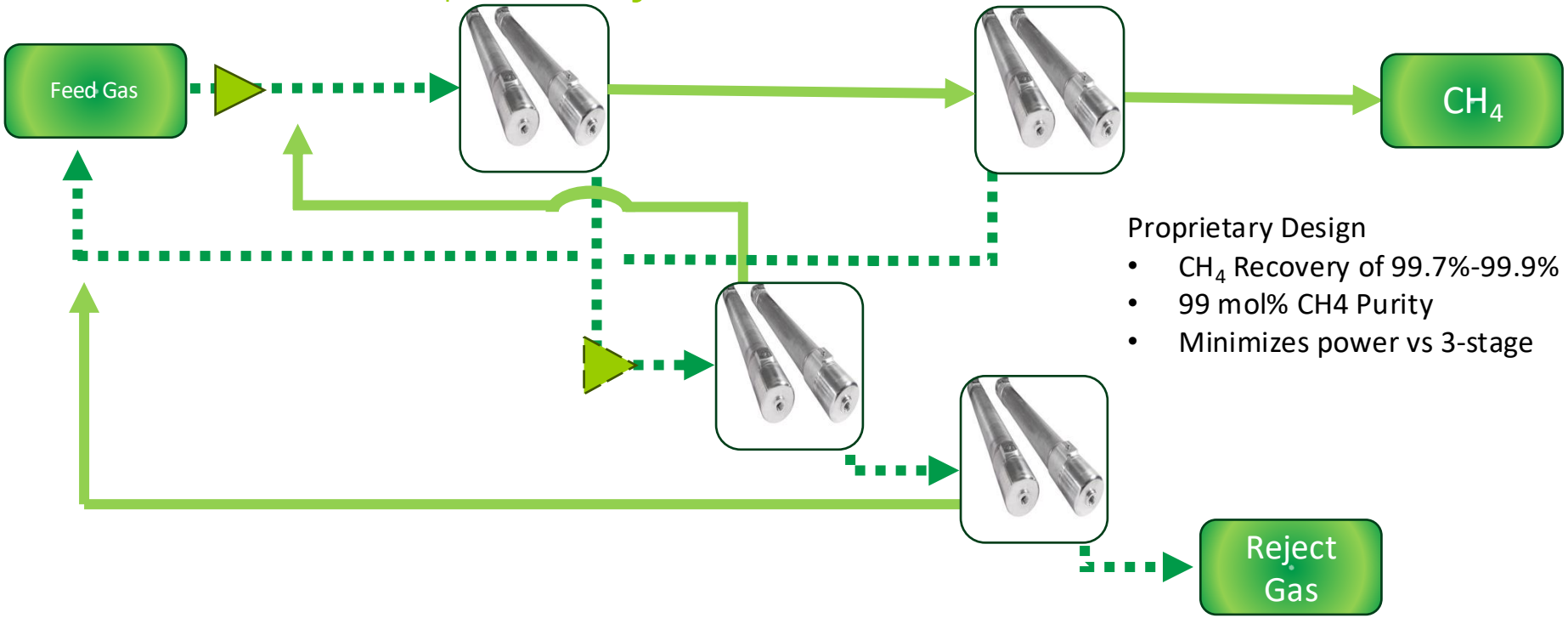
Table 2: Three-Stage Solutions with Equipment Variations*

	Basic Three-Stage Design	Three-Stage Design with Vacuum Pump on Vent	Three-Stage Design with Interstage Blower
Relative Membrane Quantity†	100%	97%	71%
Power Consumption (kW/Nm³/hr of raw gas)	0.23	0.21	0.22

* Performance is based on the constant variables listed for temperature, pressure, recovery, and composition.
†Relative membrane quantity is compared to the green column

Four-Stage Systems

Ideal for 99.5%+ CH_4 Recovery



Proprietary Design

- CH_4 Recovery of 99.7%-99.9%
- 99 mol% CH4 Purity
- Minimizes power vs 3-stage

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Four-Stage Systems
Design Comparisons

Constant Variables
Feed: 60 mol% CH4 and 40 mol% CO2
Operating Temp: 20°C
Recovery: 99.8% CH4
Product Purity: 98.75 mol% CH4

Table 3: Four-Stage Solutions with Condition and Equipment Variations*

	Three-Stage Design 14 barg	Four-Stage Design with One Compressor 14 barg	Four-Stage Design with One Compressor 16 barg	Four-Stage Design with Two Compressors 14 and 15 barg
Relative Membrane Quantity†	100%	109%	100%	116%
Power Consumption (kW/Nm³/hr of raw gas)	0.28	0.28	0.28	0.23

* Performance is based on the constant variables listed for temperature, recovery, and composition.
† Relative membrane quantity is compared to the green column

Process Variables and System Impact

↑ Biogas Flow		↑ Membrane Quantity
↑ CH4 in Biogas	↓ Recycle Ratio	↓ Membrane Quantity
↑ CH4 Recovery	↑ Recycle Ratio	↓ Membrane Quantity
↑ Biomethane Purity	↑ Recycle Ratio	↑ Membrane Quantity
↑ CO2/CH4 Sel.	↓ Recycle Ratio	↑ Membrane Quantity
↑ CO2 P/L		↓ Membrane Quantity
↑ Pressure	↓ Recycle Ratio	↓ Membrane Quantity
↑ Temperature	↑ Recycle Ratio	↓ Membrane Quantity

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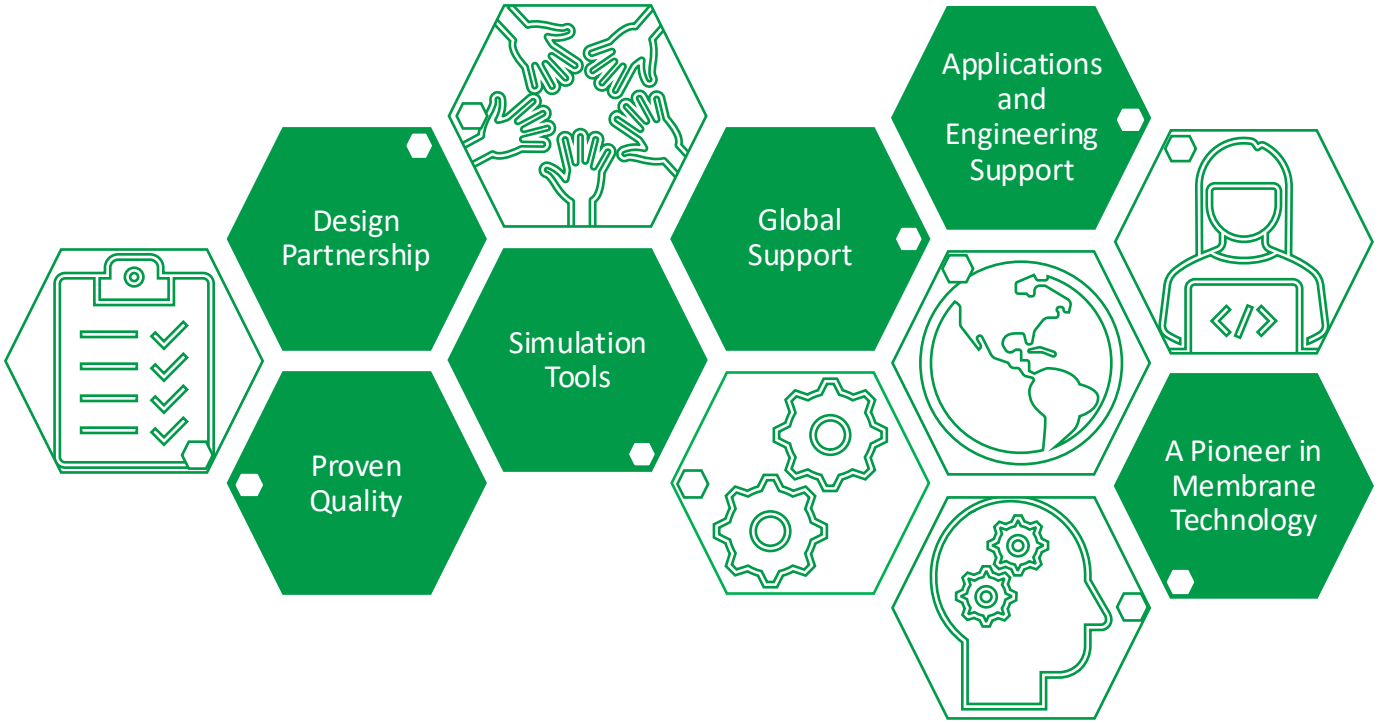
Key Differentiators



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Thank you

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Learn More at https://membranesolutions.com

Membrane Solutions

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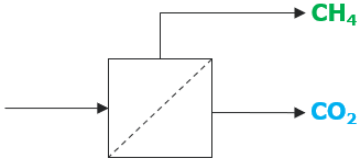
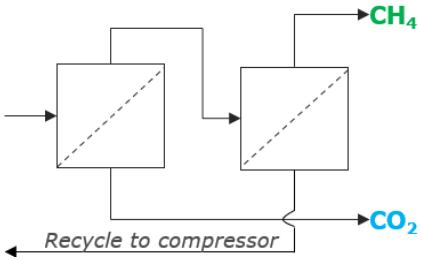
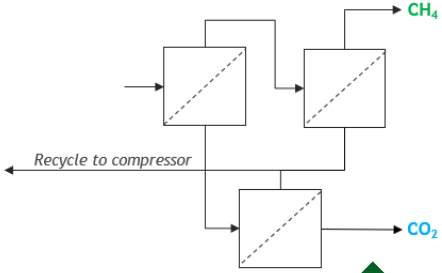
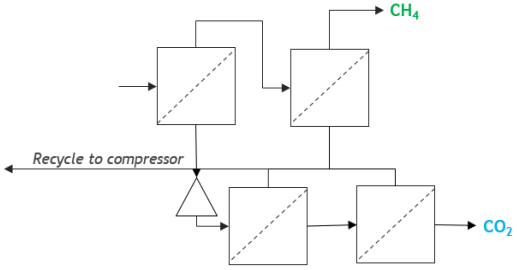
Appendix

Summary of Membrane Cycle Options









Functions of each separation stage:

- Stage 1 (Feed Stage): Initial bulk separation – must permeate almost all the CO2 in the raw biogas
- Stage 2 (Stripping Stage): Final polishing step - determines CH4 purity
- Stage 3: (Enriching Stage): Final CO2 enriching step (also must permeate nearly all the CO2 in the raw biogas) - determines CH4 recovery
- Additional stages: increase CH4 recovery

3+ stages systems

3 stages systems

2 stages systems

1 stage system

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Air Products Membrane Solutions Biogas Product lines

PRISM® GreenSep

Upgrade biogas to generate biomethane for grid injection or local vehicle refueling.

- Remove CO_2, hydrogen sulfide, and water vapor from biomethane
- Three sizes, two fiber configurations, modular designs
- Recovery range up to 99.95%
- High-purity methane up to 99.5%
- H_2S tolerance up to 5000ppm

PRISM® GreenDry

Remove water vapor from biogas with reliable, easy-to-maintain system configurations.

- The industry's first dehydration membrane separator designed for biogas processing
- Flexible design, upstream or downstream, while minimizing methane slip

PRISM® GreenSep LNG

Meet strict CO2 requirements associated with bio-LNG.

- Static robust membrane design allows for a reliable and consistent flow of nearly 100% biomethane to be fed directly into the liquefaction process
- Streamline design and reduce capital expenses by eliminating the need for a TSA unit

Membranes: A versatile and proven technology

Field Proven

Cost Savings

Easily Expandable

Lightweight & Compact

Minimal Maintenance

No Moving Parts

Ideal for Remote Locations

Long-lasting Performance

AIR PRODUCTS Membrane Solutions