Performance and Cost Sensitivities for Post-Combustion Membrane Systems

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NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

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Scope of Study

Presentation Objective

- Provide guidance, based on NETL perspective, to developers of membrane materials and CO_2-membrane capture systems for post-combustion CO_2 capture
- Summarize results: details in supporting documentation

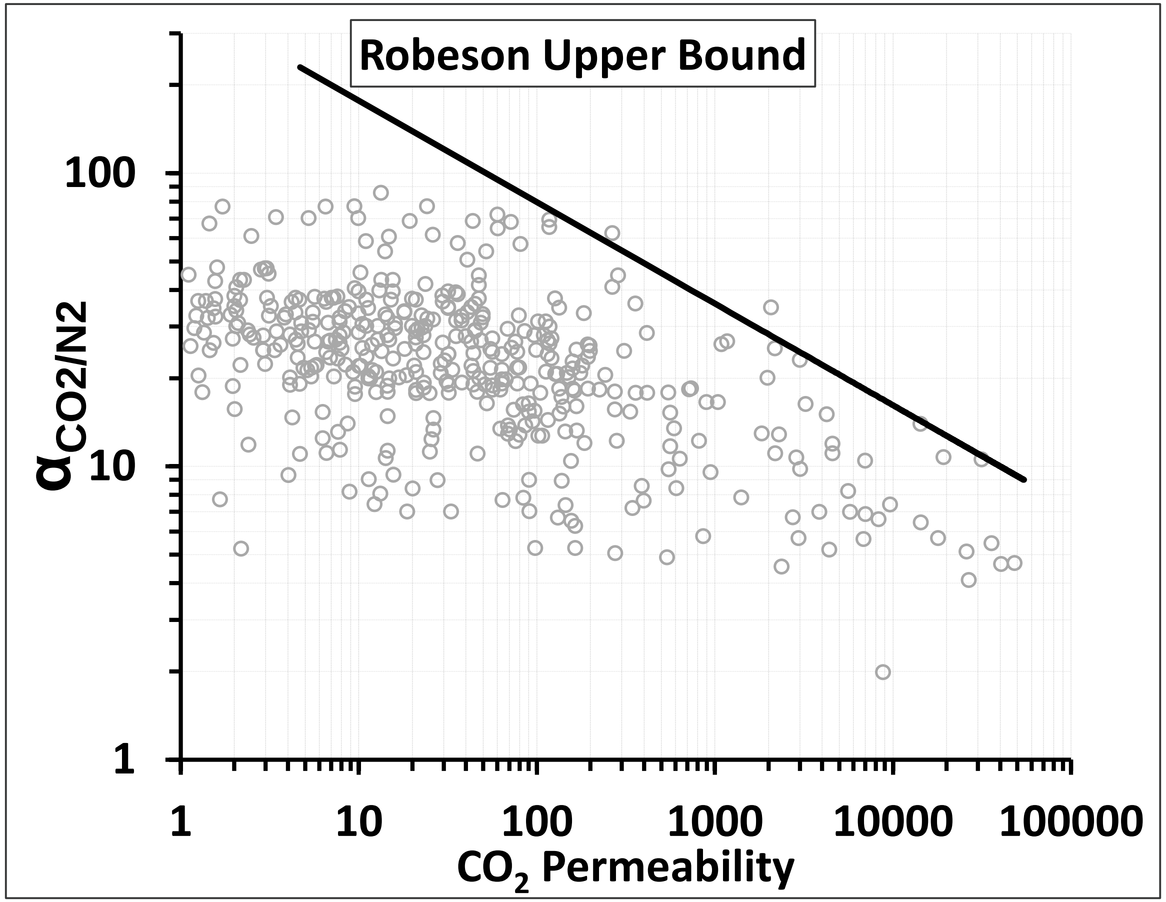
- Review polymeric CO_2-membrane current and potential performance characteristics
- Consider the influences of alternative PC power plant CO_2-membrane process configurations and operating conditions
- Estimate PC power plant CO_2-membrane post-combustion performance factors: membrane area, permeate CO_2 purity, power plant efficiency
- Generate cost of electricity results that inform the potential impacts of the membrane material performance, and process configurations

Background

- **Potential benefits of membrane-based post-combustion CO_2 capture**
  - No power plant steam extraction is needed
  - No circulating medium is needed (solvent, adsorbent, sorbent)
  - Low-cost, polymer-based membrane materials are commercially available for small-scale applications
- **Goals of membrane-based post-combustion CO_2 capture development**
  - Reduce the large membrane surface area currently needed
  - Reduce the large number of membrane modules currently needed
  - Improve the low CO_2-permeate purity that results for high (90%) CO_2 separation efficiency
  - Eliminate the need for process enhancement by an air-sweep membrane, and/or minimize the negative impacts on the PC furnace performance that may result

CO_2-Membrane Characteristics

- Important CO_2-membrane material characteristics are the CO_2 permeance, K_{CO2}, and the selectivity, α, of CO_2 relative to the other gas constituents (N_2, H_2O, O_2, and Ar)
- Robeson [1] provides a correlation relating membrane permeability and selectivity, based on collected test data
- Performance data for membranes assumed in this study is characterized by the Robeson upper bound



- K_{CO2} is corrected for application at our power plant operating temperature (53-63°C) in this assessment [2]

1. L. M. Robeson, The upper bound revisited, J. Membr. Sci. 320 (2008) 390-400
2. B. W. Rowe, L. M. Robeson, B. D. Freeman, D. R. Paul, Influence of temperature on the upper bound: Theoretical considerations and comparison with experimental results, J. Membr. Sci. 360 (2010) 58-69

CO_2-Membrane Characteristics (cont'd)

Maximum Polymeric Membrane CO_2 Permeance (gpu) from Robeson (at 53-63°C)

Robeson Upper Bound Permeance				
Selectivity ($\alpha_{CO2/N2}$)	Membrane Film Thickness (μm)			
	1	0.5	0.25	0.1
25	2,022	4,044	8,087	20,218
50	273	546	1,092	2,731
100	37	74	148	369
200	5	10	20	50

CO_2-Membrane Study Characteristics

- **PC flue gas contains CO_2, N_2, O_2, Ar, and significant water vapor**
- **Polymeric membranes are generally sensitive to water vapor: Rubbery polymers are less sensitive; glassy polymers are more sensitive (permeance decreases with increased water vapor) [3]**
  - A sensitivity study on the impact of water showed that for a single, counter-current membrane configuration, membrane area requirements per mole of CO_2 to achieve 90% CO_2 capture could vary by as much as 35%, with permeate purity varying by 7%
- **Polymeric membrane K_{CO2} and selectivity assumptions applied in study**
  - $\alpha_{CO2/H2O} = 0.2$ (water vapor permeates rapidly)
  - $\alpha_{CO2/N2} = \alpha_{CO2/O2} = \alpha_{CO2/Ar}$
  - Permeance or selectivity are not influenced by operating pressure, or interactions with other flue gas constituents (including gas contaminants and water vapor)

3. B. T. Low, L. Zhao, T. C. Merkel, M. Weber, D. Stolten, A parametric study of the impact of membrane materials and process operating conditions on carbon capture from humidified flue gas, J. Membr. Sci. 431 (2013) 139-155

CO_2-Membrane Study Characteristics (cont'd)

- **This study considers polymeric membranes having $\alpha_{CO2/N2}$ ranging from 25 to 100**
  - Permeance values above the Robeson upper bound represent advanced membrane materials of unknown properties and cost

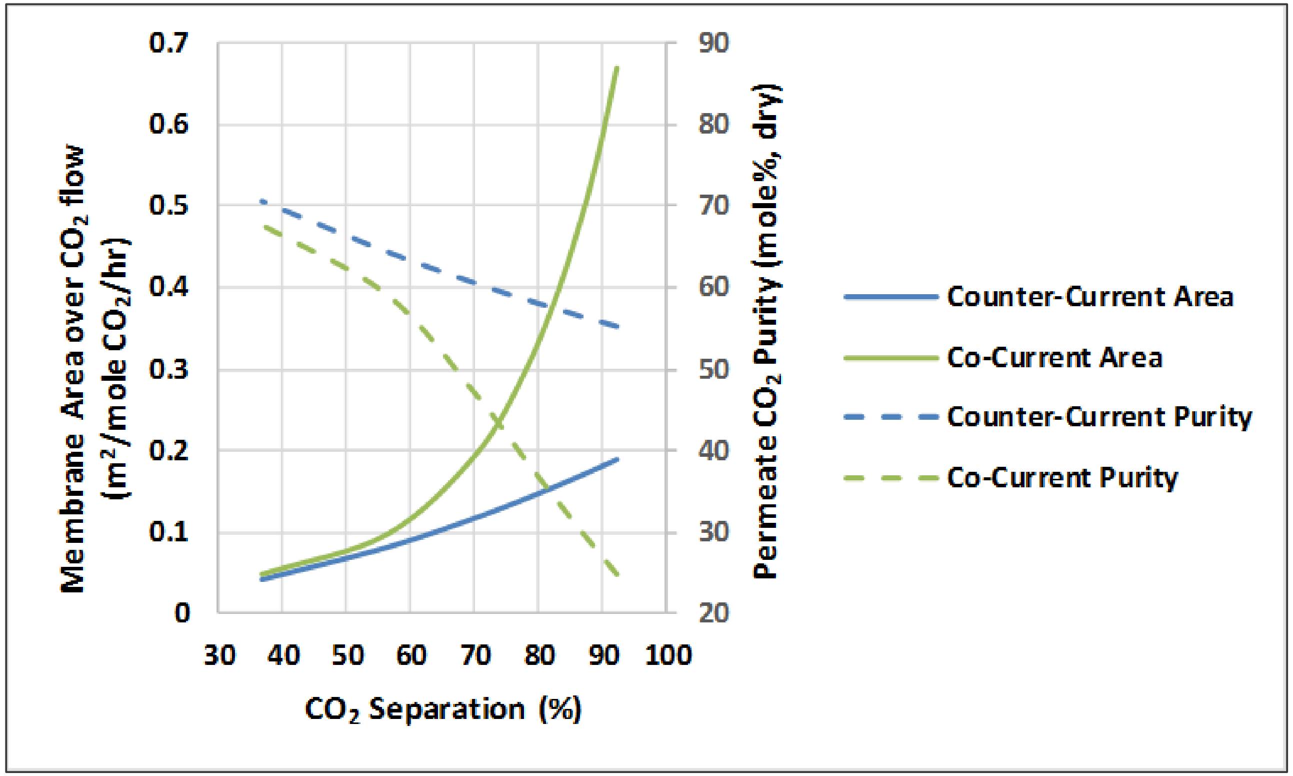
Membrane-Module Design

- **The "membrane-module" is a commercial packaging of membrane surface (hollow fiber bundles, spiral-wound units, flat plate units, tubular units) within a containment structure**
- **These would be deployed as a large array of parallel membrane-modules (possibly hundred to thousands, depending on the membrane-module gas flow capacity)**
- **The array of membrane-modules requires a distribution system of headers, manifolds, valves, and piping to transition the gas flows between the membrane-module array and the large power plant gas ducting**
  - We account for this membrane-module sub-system cost in a simplified manner

Membrane-Module Performance Modeling

Membrane-Module Flow Configuration and Surface Configuration

- Any membrane-surface configuration (spiral-wound, hollow fibers, plate, tubular) can be used so long as it can promote counter-current contacting, can operate with acceptable pressure drop, can tolerate the membrane-surface pressure difference, and can be housed as a sufficiently large membrane-module



PC Power Plant Assessment Basis

- **The DOE/NETL baseline conventional PC power plant with conventional capture serves as the reference plant for this study [4]**
- **The DOE/NETL baseline flue gas flow, composition, temperature, and pressure (using a fixed coal feed rate for all cases) are applied in the study**
- **CO_2 capture process performance requirements**
  - Net CO_2 capture: 90% of coal feed carbon
  - CO_2 product minimum purity: 95 vol% CO_2 with ≤10 ppmv O_2
  - CO_2 product delivery pressure: 2200 psig
  - PC furnace secondary air O_2 content: 18 vol% [5] (for air-sweep membrane applications)
- **Range of membrane CO_2 permeance and selectivity considered: 500 to 20,000 gpu; $\alpha_{CO2/N2}$ 25 to 100**

4. National Energy Technology Laboratory (NETL). Cost and Performance Baseline for Fossil Energy Plants, Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3. Pittsburgh, PA : DOE/NETL 2015/1723, April 2015
5. Babcock & Wilcox Company Power Generation Group, Effect of CO_2-enriched Air on Combustion Performance: Pilot-scale Evaluation, DOE Contract No. DE-NT0005795, December 17, 2013

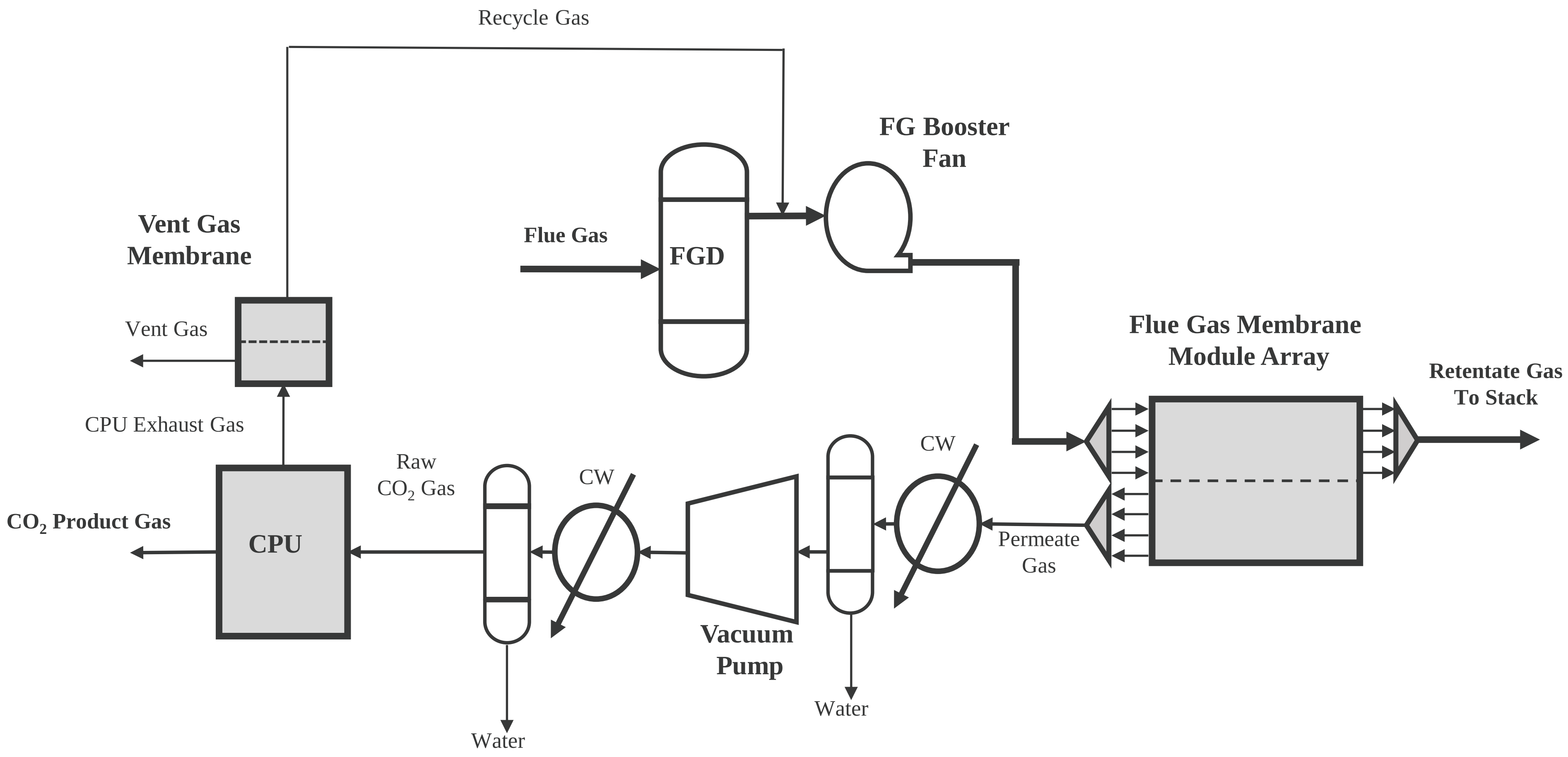
PC Power Plant Assessment Basis: CO_2 Capture Process Alternatives

Five CO_2 Separation Process Configurations Considered

- Independent flue gas membrane modules with low-pressure flue gas and permeate-side vacuum ("independent FG membrane" configuration)
- Flue gas membrane modules coupled with air-sweep membrane modules, with low-pressure flue gas and permeate-side vacuum ("combined air-sweep" configuration)
- Both configurations above with flue gas pressurization
- Independent FG membrane modules with added membrane module stages for permeate-side enrichment, with low-pressure flue gas

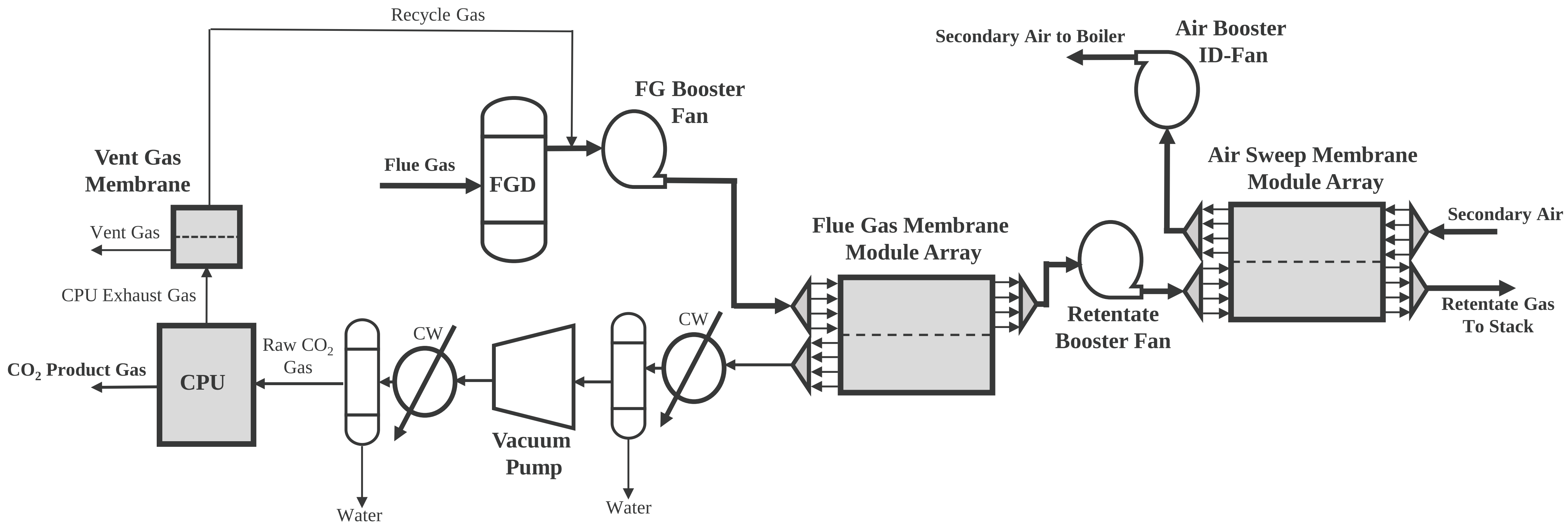
Processes with Low-Pressure Flue Gas

Independent FG Membrane Configuration with Low-Pressure Flue Gas



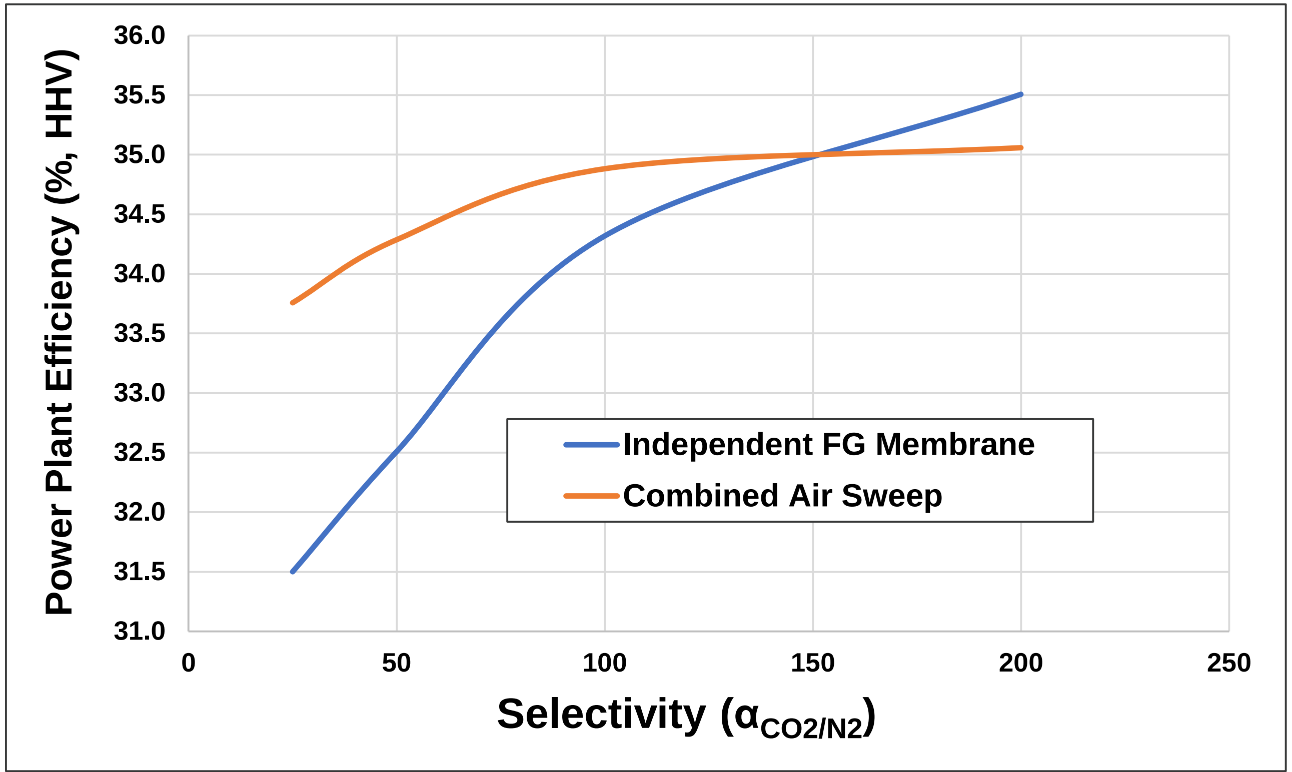
Processes with Low-Pressure Flue Gas (cont'd)

Combined Air-Sweep Configuration with Low-Pressure Flue Gas



Processes with Low-Pressure Flue Gas (cont'd)

Configuration Influence on Power Plant Efficiency Results



- CO_2 permeance does not influence the power plant efficiency
- Increased selectivity increases the power plant efficiency
- The combined air-sweep configuration results in higher power plant efficiency than the independent FG membrane configuration
- Advanced membrane materials having very high selectivity (>100) might minimize this difference

Processes with Low-Pressure Flue Gas (cont'd)

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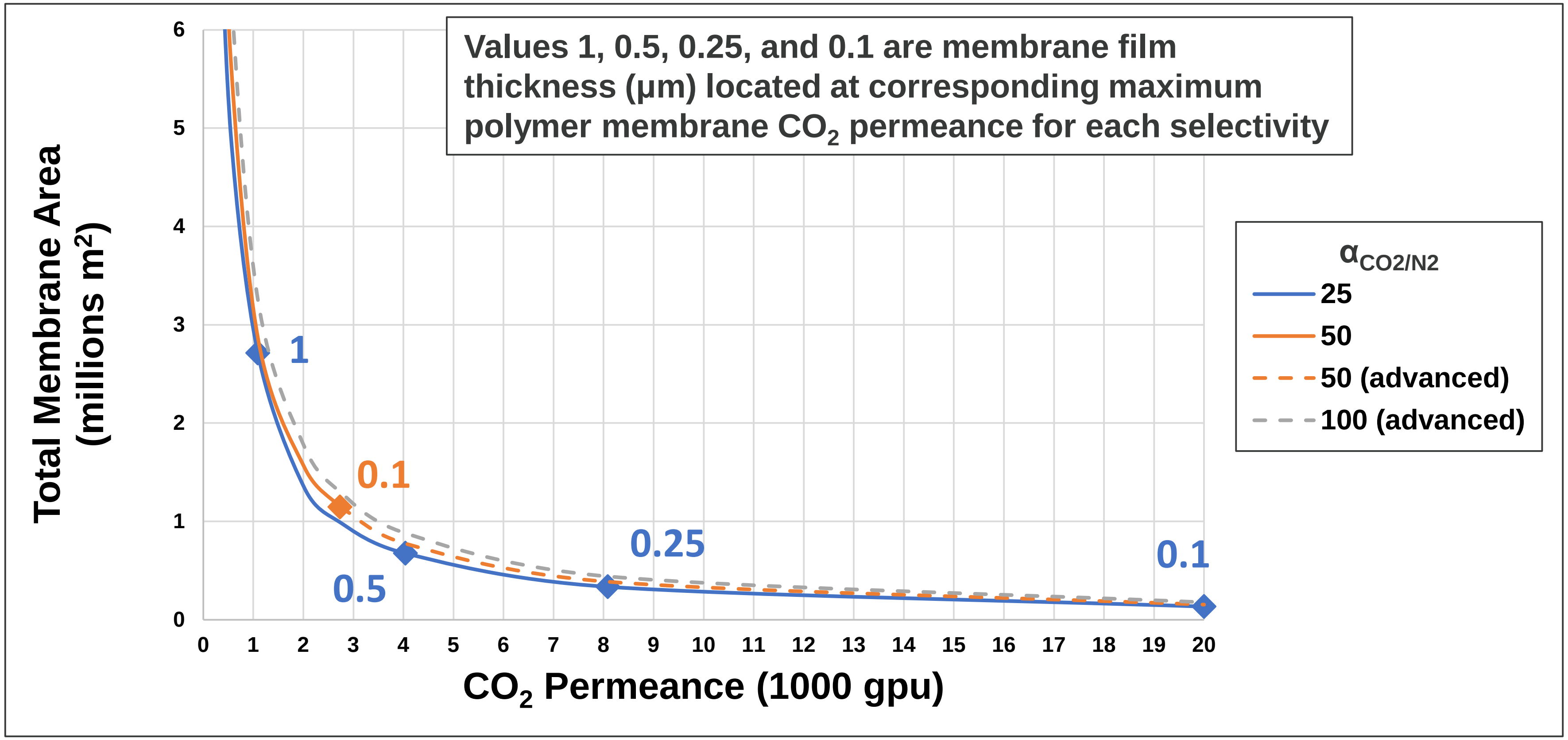
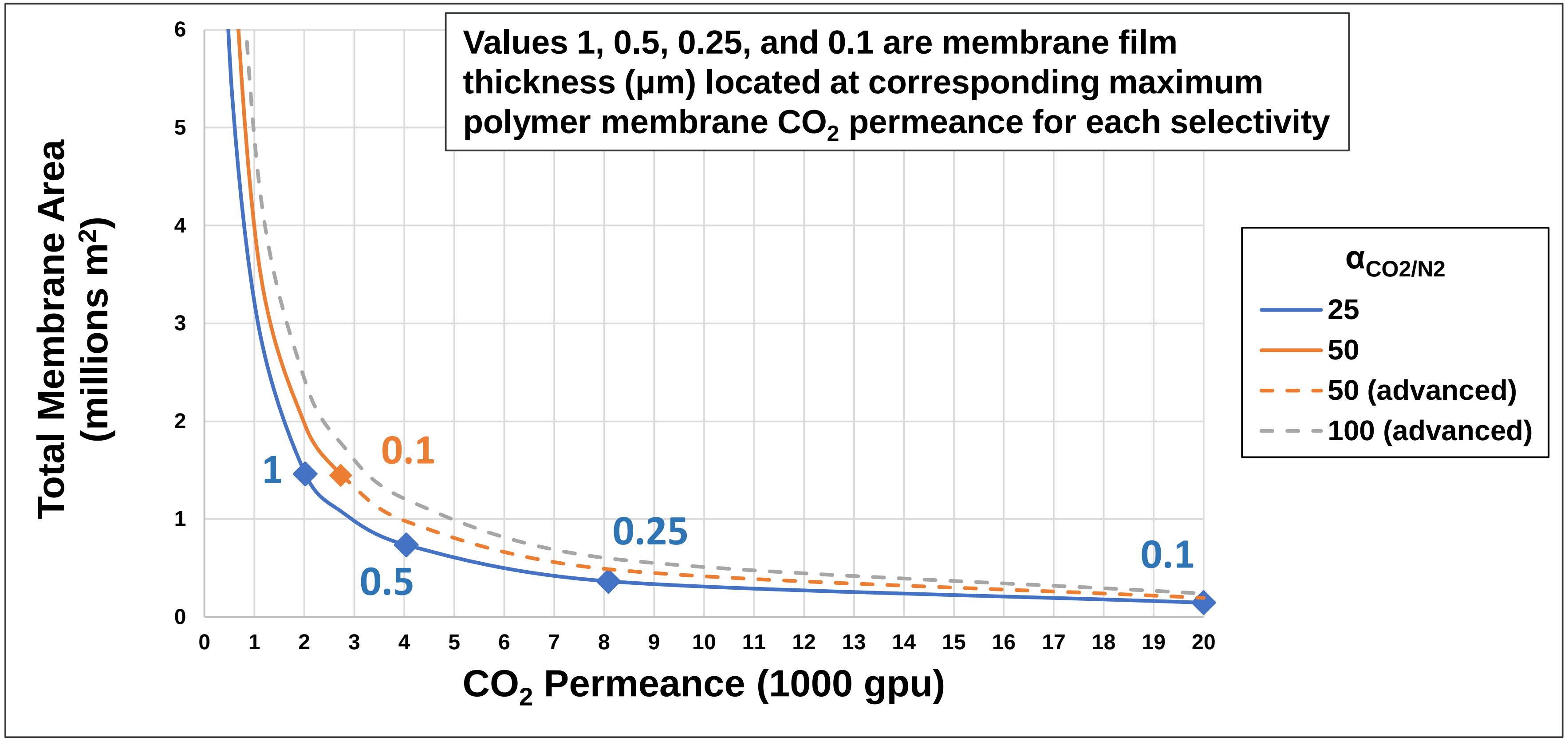
Independent FG Membrane Configuration Area Results



- CO_2 permeances >1,000 gpu are limited to $\alpha_{CO2/N2}$ of 25 to 50
- Higher selectivity (>50 - 100) will require advanced polymeric materials
- The curves show a trend for increased membrane area with higher selectivity
- Limited area benefit for permeances > 8,000 gpu

Processes with Low-Pressure Flue Gas (cont'd)

Combined Air-Sweep Configuration Area Results

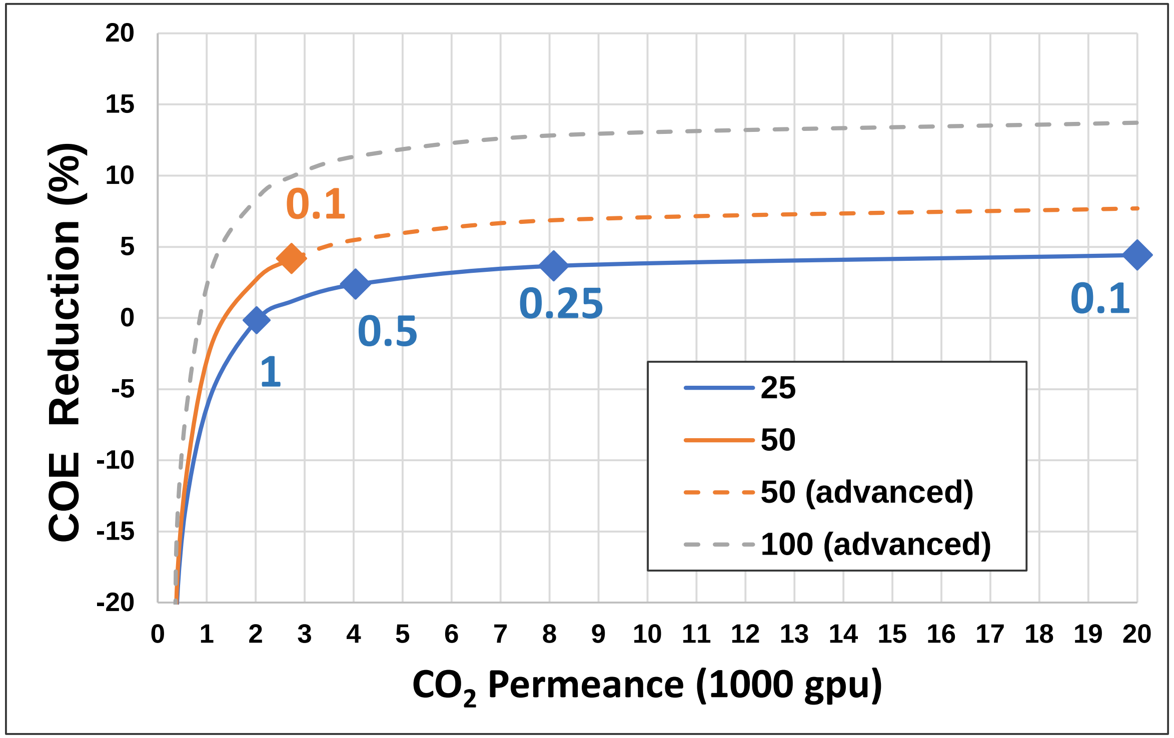


- The curves are similar in trend to the independent flue gas membrane configuration
- The combined air-sweep configuration results in slightly higher total membrane area than the independent FG membrane configuration

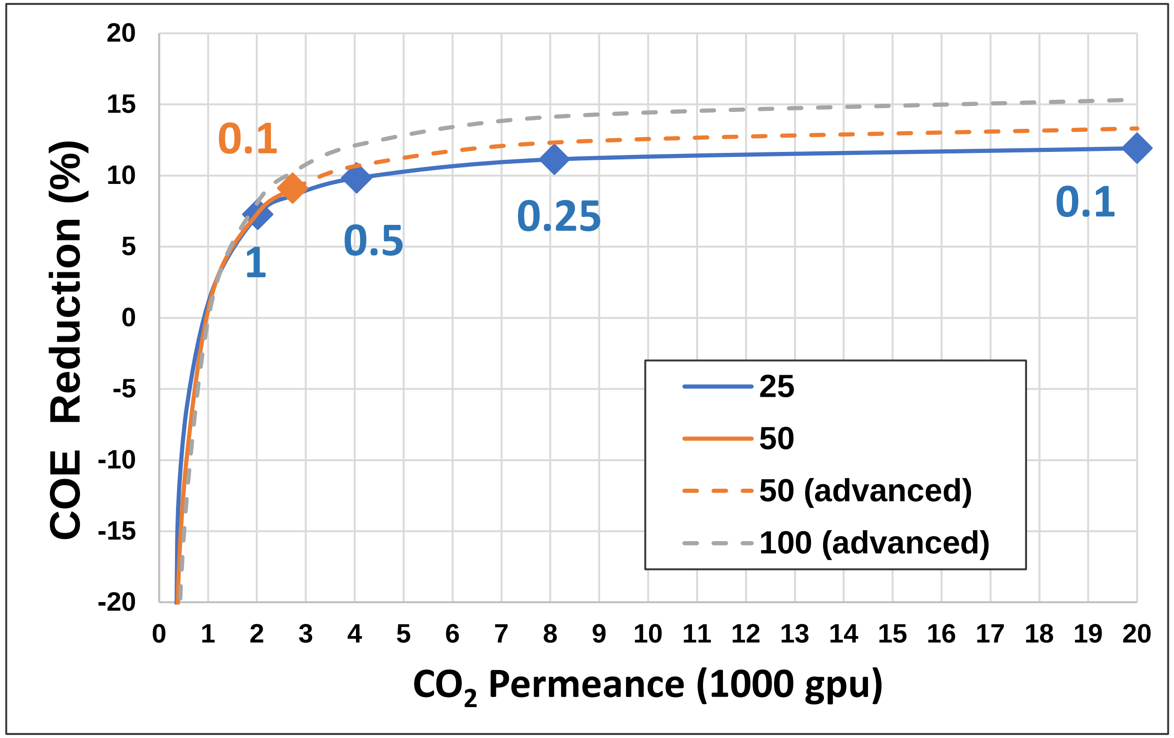
Processes with Low-Pressure Flue Gas (cont'd)

Cost Results

Independent Membrane Configuration



Combined Air-Sweep Membrane Configuration



Membrane module cost 50 $/m^2; Membrane replacement cost 20 $/m^2; Membrane life 5 years

Findings

- **For low pressure operation using current membrane materials, the air sweep configuration offers cost benefits over the independent membrane configuration; as membrane performance improves, the system configuration benefits approach an equivalent cost result**
- **Flue gas pressurization reduces the total membrane area, and plant efficiency; not cost-effective development options**
- **Membrane staging increases permeate purity, gas flow rate to the membrane and the compression work, reducing the power plant efficiency—not a cost-effective development option**
- **Based on the results, developer focus should be on:**
  - Low-pressure membrane CO_2 capture processes
  - Options to eliminate the air-sweep membrane, or to minimize its PC furnace impacts, especially for power plant retrofit applications
  - Development of membrane materials having higher CO_2 permeance (>3,000 gpu) and with selectivity approaching 100

Findings (cont'd)

- **A general COE reduction graph has been developed that allows the COE reduction for low-pressure configurations to be estimated as a function of:**
  - The type of membrane configuration (independent membrane, or combined air-sweep)
  - The cost of the membrane-unit (C_{mem})
  - The cost of membrane-unit replacement ($C_{replace}$)
  - The membrane-unit life (T_{life})
  - The membrane CO_2 permeance (K_{CO2})
  - The membrane selectivity ($\alpha_{CO2/N2}$)
- **This general graph can be applied as a sensitivity study tool**

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