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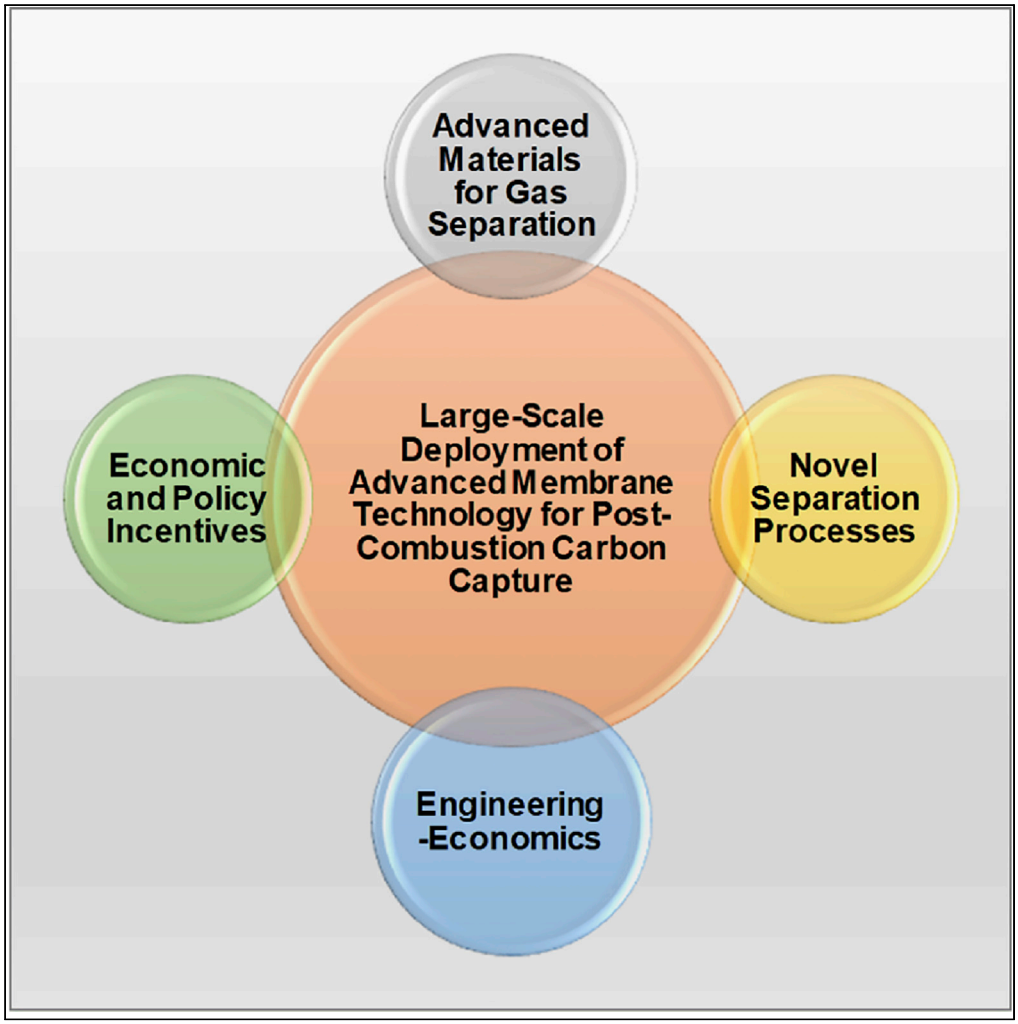

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HIGHLIGHTS

A forward-looking assessment is provided for advanced membrane technology

Major material property targets are identified for advanced membranes

This study demonstrates the evolutionary trend of advanced membrane technology

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Advanced Membranes and Learning Scale Required for Cost-Effective Post-combustion Carbon Capture

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SUMMARY

This study offers an integrated vision for advanced membrane technology for post-combustion carbon capture. To inform development of new-generation materials, a plant-level techno-economic analysis is performed to explore major membrane property targets required for cost-effective CO_2 capture. To be competitive with amine-based nth-of-a-kind (NOAK) technology or meet a more ambitious cost target for 90% CO_2 capture, advanced membranes should have a higher CO_2 permeance than 2,250 GPU and a higher CO_2/N_2 selectivity than 30 if their installed prices are higher than \$50/m^2. To assess learning experience required for advanced technology using such high-performance membranes toward commercialization, a hybrid approach that combines learning curves with the techno-economic analysis is applied to project the cumulative installed capacity necessary for the evolution from first-of-a-kind to NOAK systems. The estimated learning scale for advanced membrane technology is more than 10 GW, depending on multiple factors. Implications for research, development, and policy are discussed.

INTRODUCTION

Carbon capture and sequestration (CCS) is a key technology for significantly reducing carbon dioxide (CO_2) emissions from fossil-fuel-fired power plants to stabilize global climate (Intergovernmental Panel on Climate Change, 2014). To remarkably reduce energy and cost penalties for large-scale deployment when compared with current amine-based CCS, a variety of novel materials have been under development, including solvents, sorbents, and membranes (Rubin et al., 2012; Figueroa et al., 2008). To make fossil-based power generation systems competitive beyond 2035, the US Department of Energy has proposed a capture cost target for transformational post-combustion capture technologies: \$30 per ton of CO_2 (U.S. Department of Energy, 2013).

Membrane-based capture systems have engineering and economic advantages over absorption-based CO_2 capture that requires unavoidable pressure or temperature swing for solvent regeneration (Brunetti et al., 2010; Shelley, 2009). To be viable, membranes should possess some favorite features: high CO_2 permeability and permeance, good CO_2 versus nitrogen (N_2) selectivity, thermal and chemical resistance, plasticization resistance, low cost, and ease of fabrication (Du et al., 2012; Brunetti et al., 2010). Recent developments in high-performance materials have enhanced the feasibility of membrane technology for CO_2 capture (Khalilpour et al., 2015; Luis et al., 2012). Multiple review studies consistently speak of several important classes of highly permeable polymeric membranes, including polymers with intrinsic microporosity (PIMs), thermally rearranged polymers (TRs), poly(ethylene oxide) (PEO)-based polymers, and polyimides (Liu et al., 2016; Wang et al., 2016; Du et al., 2012; Luis et al., 2012). Although significant progress in materials has been made, polymeric membranes are generally governed by a trade-off relationship between permeability and selectivity, which is called the Robeson upper bound: highly permeable membranes with low selectivity, and vice versa (Robeson, 2008). Thus emerging materials like facilitated transport membranes and mixed matrix membranes are of interest as they may achieve both high permeability and high selectivity via improved gas transport mechanisms (Tong and Ho, 2017; Vinoba et al., 2017; Rafiq et al., 2016; Wang et al., 2016; Dong et al., 2013).

Gas transport properties are crucial to the performance of membrane separation processes and largely influence their feasibility for CO_2 capture. Data of membrane properties of advanced polymeric membranes are assembled from recent review studies and presented in Figure 1 (Liu et al., 2016; Wang et al., 2016; Du et al., 2012), which exhibits the distributions of CO_2 permeability and CO_2 versus nitrogen (N_2) selectivity

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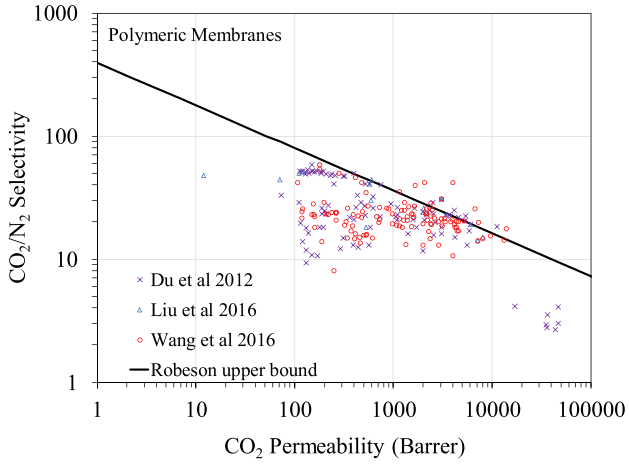

Figure 1. CO_2 Permeability and CO_2 versus N_2 Selectivity of Advanced Polymeric Membranes

against the Robeson upper bound for advanced membranes, including high-permeability polyimide, TR, PEO, and PIM. Figure 1 shows that advanced polymeric membranes generally agree with the Robeson relation, except for some advanced PIMs; most advanced polymeric membranes have a high CO_2 permeability ranging from 100 to 1,000 Barrer and a good CO_2/N_2 selectivity ranging from 10 to 60, whereas some substituted polyacetylenes have a higher permeability than 1,000 Barrer but a lower selectivity than 5. Among the several classes, many PIM and PEO membranes and some TR membranes appear closer to the Robeson upper bound. In addition to the CO_2 permeability and CO_2/N_2 selectivity, membrane thickness is also important because it affects the permeance, which largely determines the required area of membrane gas separation. The effective thickness generally falls within the range of 0.1–1.0 μm, whereas the effective thickness of state-of-the-art membranes can reach 50 nm (Rafiq et al., 2016).

Computational systems research has been conducted increasingly to examine and improve the viability of membrane-based CO_2 capture systems (Diego et al., 2018; Giordano et al., 2017; Mat and Lipscomb, 2017; Turi et al., 2017; Binns et al., 2016; Roussanaly et al., 2016; He et al., 2015; Brunetti et al., 2014; Shao et al., 2013; Zhai and Rubin, 2013; Hasan et al., 2012; Merkel et al., 2010, 2012; National Energy Technology Laboratory, 2012; Hussain and Hägg, 2010; Zhao et al., 2010). Membrane gas separation has the potential to compete with other capture technologies. Multi-stage membrane processes are able to simultaneously achieve high-level separation targets: high CO_2 removal efficiency and high CO_2 purity. To decrease the parasitic load for CO_2 separation, Merkel et al. (2010) raised a design that uses combustion air as a sweep gas in a countercurrent membrane module to recycle the permeated CO_2 and then increase the CO_2 partial pressure in flue gas. However, Franz et al. (2013) further note that the recycled excess CO_2 should not lower the combustion temperature and undermine the stoichiometric reaction, which likely decreases the overall plant efficiency. To take advantage of various capture technologies, increased attention has been paid to hybrid capture processes, especially membrane-cryogenic and membrane-absorption processes (Diego et al., 2018; Scholes et al., 2013; National Energy Technology Laboratory, 2012; Merkel et al., 2010). The overall cost for CO_2 capture varies with separation targets, process configuration and design, membrane properties, and installed membrane module price. The incorporation of a countercurrent or sweep module into membrane-based capture processes can significantly promote their viability for post-combustion carbon capture (Baker et al., 2017; Turi et al., 2017; Scholes et al., 2013; Zhai and Rubin, 2013; National Energy Technology Laboratory, 2012; Ramasubramanian et al., 2012; Merkel et al., 2010). However, installed membrane module prices of \$27/m^2–\$80/m^2 were assumed widely in the literature, which are much lower than current prices of gas separation membranes (up to several hundred dollars per square meter) (Merkel et al., 2010). In addition, low contingencies of 10%–20% were also often assumed. Uncertainty in cost estimates has been ignored widely in the literature. All those techno-economic studies implicitly or explicitly assumed that membrane technology is a mature or nth-of-a-kind (NOAK) technology, which is not the fact. The time-related scale of learning experience necessary to reach the assumed level of maturity widely remains unknown.

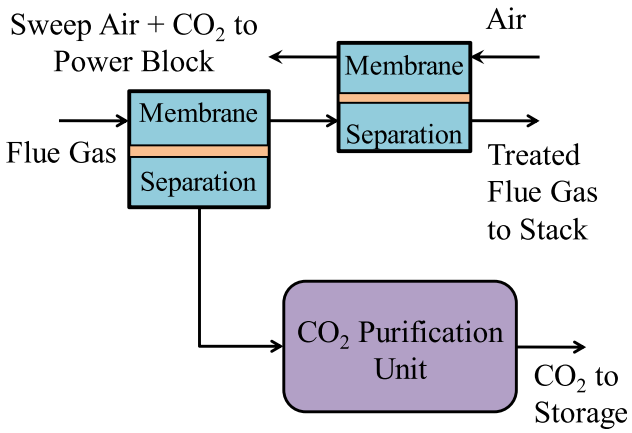

Figure 2. Membrane-Cryogenic Purification for Post-combustion CO_2 Capture

Energy and environmental technologies evolve with progress in numerous areas, such as advanced materials, technical improvements, economies of scale in module manufacturing, and improved productivity in installation and construction, resulting in cost reductions (Rubin et al., 2015; Frankfurt School-UNEP Center/BNEF, 2014). Although considerable advances in membrane technology have been achieved, an initiative that integrates technical and economic aspects with technological learning is needed to accelerate scaling up from laboratory or pilot experiments to industrial applications. Improving understanding of the scale of learning experience required for this emerging technology toward a mature level is of great importance to technology development, investment decision, and policy making. To identify opportunities and challenges for technological innovation and evolution, this study offers an integrated vision for advanced polymeric membrane technology for post-combustion CO_2 capture with respect to materials, engineering economics, and technological learning. Specifically, the major objectives of this study are to (1) determine major membrane property targets required for advanced NOAK membrane technology for cost-effective CO_2 capture at pulverized coal (PC) power plants to inform selection, design, and synthesis of new-generation membranes, which have the potential to compete with amine-based capture technology or meet a more ambitious cost target, and (2) estimate the scale of learning experience required for technological evolution from a first-of-a-kind (FOAK) level toward a mature level and further reveal its dependence on various key factors.

RESULTS

Systems Analysis for Advanced NOAK Membrane Technology

To provide an outlook for advanced membrane technology, a plant-level techno-economic analysis is first conducted to explore the targets of membrane properties necessary to compete with amine-based NOAK technology or to reach the cost target of \$30/ton CO_2 required for transformational capture technologies. The Integrated Environmental Control Model (IECM) was employed for the plant-level analysis to estimate the costs of carbon capture systems at various levels of maturity (Integrated Environmental Control Model, 2018).

Recent progress in process engineering has indicated that hybrid membrane-based capture systems hold significant potential for large-scale applications. The hybrid membrane-CO_2 cryogenic purification configuration shown in Figure 2 is adopted for the analysis (National Energy Technology Laboratory, 2012; Merkel et al., 2010): the first-stage cross-flow module removes part of the CO_2 in flue gas; combustion air is used as a sweep gas in a countercurrent or sweep module to recycle the permeated CO_2, and the permeate gas from the first stage is delivered to a cryogenic CO_2 purification unit (CPU). Systems research for such configurations has shown that to simultaneously achieve a high removal efficiency and a high purity, capture processes should employ membranes whose CO_2 permeance and CO_2/N_2 selectivity are at least 1,000 GPU and 30, respectively, and when the CO_2/N_2 selectivity is higher than 50, increasing the CO_2 permeance appears more important than the CO_2/N_2 selectivity in enhancing the economic viability of advanced capture processes with CO_2 recycling (Zhai and Rubin, 2013; Merkel et al., 2010). So the CO_2 permeance was varied from 1,000 to 4,000 GPU in the IECM simulations, whereas the CO_2/N_2 selectivity was fixed at 40. The major techno-economic performance of the CPU was based on that reported by the National Energy

Section	Parameter	Value	
Base plant	Plant type	Supercritical pulverized coal	
	Fuel type	Illinois #6	
	Capacity factor (%)	85	
	Traditional air pollution control systems	SCR/ESP/FGD	
	Cooling system	Wet tower	
	Net power output (MW)	550	
Carbon capture system	Process configuration	Membrane-CPU	
	Driving force for membrane separation	Vacuum pumping	
	CO_2 removal efficiency in cross-flow module (%)	50	
	CO_2 removal efficiency in countercurrent module (%)	90	
	Overall plant CO_2 removal efficiency (%)	~90	
	Membrane CO_2 permeance (GPU)	1,000–4,000	
	Membrane selectivity[a]		
	CO_2/N_2	40	
	CO_2/O_2	40	
	CO_2/Ar	40	
	CO_2/H_2O	0.7	
	CO_2 purification unit (CPU)		
	CO_2 removal efficiency (%)	98	
	CO_2 purity (%)	100	
	CO_2 product pressure (MPa)	15.27	
	Energy use (kWh/ton CO_2)	106.3	
	Process facilities cost (2007, $10^3$$/tonne CO_2)	82.4	
		NOAK	FOAK
	Fixed charge factor (fraction)[b]	0.1128	0.1207
	Construction time (year)	3	5
	Membrane module price ($/m^2)	50	200
	Process contingency (%)[c]	10	35
	Project contingency (%)[c]	10	25
	Membrane material lifetime (year)	5	4
	Membrane replacement Cost ($/m^2)	15	60

Table 1. Major Assumptions and Cost Results of Power Plants and Capture Systems

(Continued on next page)

Section	Parameter	Value	
Overall cost for CO_2 capture[d,e]	Power plant LCOE (2016, constant $/MWh)		
	Case I: 2,500 GPU for CO_2 permeance	85.3	131.2
	Case II: 4,000 GPU for CO_2 permeance	82.6	117.3
	Cost of CO_2 capture (2016, constant$/ton)[d,e]		
	Case I: 2,500 GPU for CO_2 permeance	33.2	87.1
	Case II: 4,000 GPU for CO_2 permeance	30.1	70.9

Table 1. Continued

ESP, electrostatic precipitator; FGD, flue gas desulfurization; NETL, National Energy Technology Laboratory; SCR, selective catalytic reduction; LCOE, levelized cost of electricity.

[a]Referring to the assumption by NETL for advanced membranes based on the test experience (National Energy Technology Laboratory, 2012), N_2, Ar, and O_2 have identical permeance. The permeabilities of Ar and O_2 may be higher than the N_2 permeability, depending on specific materials. However, their fractions in flue gas are much less than the N_2 fraction, and those in the permeate stream out of the cross-flow module can be removed by CPU. This assumption may have no sizable effects on the results.

[b]The fixed charge factor for NOAK is based on the default financial settings in the IECM, whereas that for FOAK is derived in terms of the ratio of NETL's high-risk versus low-risk capital charge factors for the cases with and without CCS (National Energy Technology Laboratory, 2012).

[c]The assumptions of process and project contingencies are made for FOAK and NOAK based on the Electric Power Research Institute's Technical Assessment Guide (Electric Power Research Institute, 1993).

[d]The CO_2 transport and storage costs are not included.

[e]For the reference plant without CO_2 capture, the plant LCOE is $57.0/MWh, which is the IECM modeling result.

Technology Laboratory (National Energy Technology Laboratory, 2012). Table 1 summarizes the major parameters and assumptions of power plants and carbon capture systems. See also Figure S1.

Both membrane and amine technologies had the same assumptions made for fixed charge factor and process and project contingencies at the NOAK level. The other parameters of amine-based CCS were based on the default IECM values. The IECM simulation results show that deployment of amine-based CCS for 90% CO_2 capture decreases the net plant efficiency by approximately 11 percentage points on an absolute basis, compared with the reference PC plant without CO_2 capture; the levelized cost of electricity (LCOE) of a plant with an amine-based NOAK system is estimated to be $92.7/MWh, not including the CO_2 transport and storage (T&S) costs, whereas the LCOE of a plant with an NOAK system capturing CO_2 at the cost of $30/ton is estimated to be $82.6/MWh; the cost of CO_2 capture by amine technology is about $35/ton, whereas the cost of CO_2 avoided is about $65/ton, given the assumption of $10/ton for the total CO_2 T&S cost.

Vacuum pumping is applied to generate driving force for membrane gas separation. The permeate-side pressure in the cross-flow module is about 0.2 bar. Deployment of membrane-based CCS decreases the net plant efficiency by approximately 6 percentage points on an absolute basis, compared with the reference plant without CO_2 capture. Increases in the CO_2 permeance do not significantly improve the net plant efficiency but lower the capture cost. Figure 3 shows the cost of CO_2 capture by membrane-based NOAK technology as a function of CO_2 permeance and installed membrane module price. The cost of CO_2 capture decreases nonlinearly with increased CO_2 permeance for a range of membrane prices. The cost share by component in percentage varies with membrane CO_2 permeance and price. However, for a given membrane price, increases in CO_2 permeance beyond 3,500 GPU would not bring a significant cost benefit for advanced capture systems because vacuum pumps, CPU, and their parasitic loads dominate the overall capture cost. To decrease the cost of CO_2 capture, it is necessary to lower the manufacturing price of high-performance membranes. At the membrane price of $50/$m^2$ assumed widely in the literature, the breakeven CO_2 permeance at which the plant LCOE of both membrane and amine technologies is the same is about 2,250 GPU, whereas the breakeven value is about 4,000 GPU when compared with the cost target of $30/ton CO_2. For either of the benchmarks, the breakeven CO_2 permeance varies significantly with membrane price.

In addition to the membrane price, the capture cost estimates are also affected by variability or uncertainty in other major factors, which include capacity factor and fixed charge factor, as well as membrane

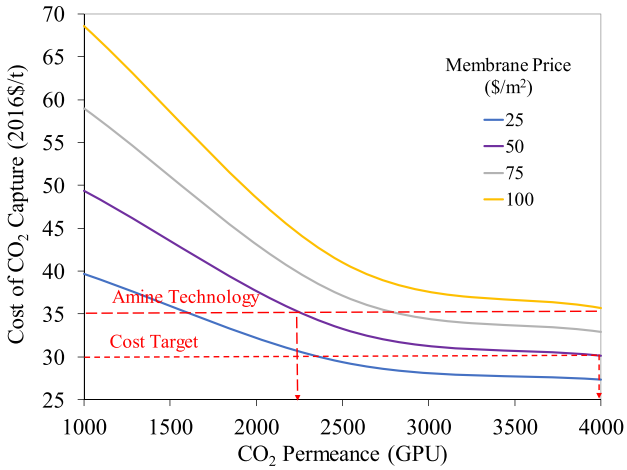

Figure 3. Variability in Cost of CO_2 Capture by Membrane Permeance and Price of NOAK Membrane Technology

selectivity, equipment efficiency and cost, and process and project contingencies. To characterize the effects of variability and uncertainty in these parameters and provide the information on likelihood of specific outcomes, a probabilistic analysis was conducted using the IECM (Rubin and Zhai, 2012). Probabilistic distribution functions (PDFs) were first assigned to uncertain parameters and were then sampled randomly for 500 times to yield a cumulative distribution function of the cost of CO_2 capture. Depending on the availability of information, the assigned PDF for each uncertain parameter was based on the synthesis from the literature, as well as the author's judgment in the cases wherein information was not available. Table 2 summarizes the PDF assumptions. Please note that making a different choice of PDFs and/or including

Parameter	Nominal Value	Probabilistic Distribution	Reference(s)
Power Plant			
Capacity factor (%)	85	Uniform (75, 85)	Zhai and Rubin, 2013
Fixed charge factor (fraction)	0.1128	Uniform (0.1000, 0.1207)	National Energy Technology Laboratory, 2012; Zhai and Rubin, 2013
Capture System			
CO_2/N_2 selectivity (ratio)	40	Uniform (30,50)	Zhai and Rubin, 2013; Merkel et al., 2010
Vacuum pump efficiency (%)	85	Uniform (70,85)	Mat and Lipscomb, 2017; Zhai and Rubin, 2013
Vacuum pump cost ($/kW)	1340	Uniform (500,1,340)	Shao et al, 2013; Zhai and Rubin, 2013
Membrane module price ($/m^2)	50	Triangle (25, 50,100)	Giordano et al., 2017; He et al., 2015; Scholes et al., 2013; Zhai and Rubin, 2013; National Energy Technology Laboratory, 2012; Ramasubramanian et al., 2012; Merkel et al., 2010
Process contingency (%)	10	Triangle (5, 10, 20)	National Energy Technology Laboratory, 2012; Electric Power Research Institute, 1993
Project contingency (%)	10	Triangle (5, 10, 20)	National Energy Technology Laboratory, 2012; Electric Power Research Institute, 1993

Table 2. Probabilistic Distribution Assumptions for Uncertain Parameters

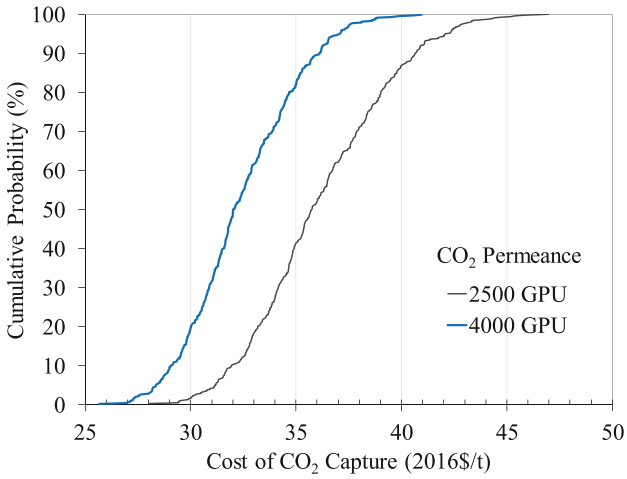

Figure 4. Cumulative Distributions of Cost of CO_2 Capture by Membrane-Based NOAK Technology

additional uncertainties beyond those shown in Table 2 may affect the probabilistic distributions of CO_2 capture cost.

Capacity factor and fixed charge factor are common to both plants with and without CO_2 capture. So, the identical set and sequence of 500 random samples was assigned to the two common parameters, whereas independent parameters for the NOAK capture system were sampled randomly (Rubin and Zhai, 2012). Figure 4 shows the resulting cumulative distributions of the cost of CO_2 capture by NOAK membrane technology for two levels of CO_2 permeance: 2,500 and 4,000 GPU. For the given PDFs, the capture cost has an average of $36.2/ton and a 95% confidence interval of $30.3 to 42.9/ton for the 2,500-GPU case and an average of $32.4/ton and a 95% confidence interval of $27.6 to 37.6/ton for the 4,000-GPU case. The probability that the capture cost is less than $35/ton is about 41% for the 2,500-GPU case and about 82% for the 4,000-GPU case. In contrast, the probability that the capture cost is less than $30/ton is not more than 20% for the 4,000-GPU case. This asymmetry results from the nonsymmetric distributions of major parameters relative to the nominal values, including capacity factor, equipment cost, membrane price, and contingencies.

Technological Learning from FOAK to NOAK Capture Systems

Costs of a new energy or environmental technology often decline as it is improved, deployed, and commercialized. A hybrid approach that combines top-down learning curves with the techno-economic analysis discussed above is adopted to estimate the scale of cumulative installed capacity required to achieve long-term cost targets for advanced membrane technology. To perform this mission, the capital and operating and maintenance (O&M) costs of the FOAK plant have to first be determined. The major parameters and assumptions that distinguish between NOAK and FOAK membrane technologies are also given in Table 1. Referring to the results from the systems analysis, the capture systems use two hypothetical high-performance membranes: 2,500 and 4,000 GPU for the CO_2 permeance. The major cost results based on the IECM simulations are also reported in Table 1 for both FOAK and NOAK technologies. For the given assumptions, the cost of CO_2 capture by FOAK technology is about 150% higher than that of NOAK technology on average. Numerous capture plants, therefore, have to be installed to reach the NOAK level.

Learning from FOAK to NOAK levels in technology deployment for carbon capture could proceed at a similar pattern as other environmental control technologies (Rubin et al., 2007; Riahi et al., 2004). A coal-fired power plant with CO_2 capture is decomposed into several subsystems: base plant (e.g., steam cycle and cooling system), conventional air pollution control systems (e.g., electrostatic precipitator, selective catalytic reduction, flue gas desulfurization), and membrane-based carbon capture process. Their learning rates and initial installed capacities mainly refer to those estimated by Rubin et al. (2015, 2007) for future plants with post-combustion CO_2 capture: the initial installed capacity is 120 GW for base plant, 230 GW for air pollution control systems, and 0.5 GW for membrane-based capture process. The initial capacity for membrane-based CCS is similar to that of a full-sized power plant, which is larger than two amine-based

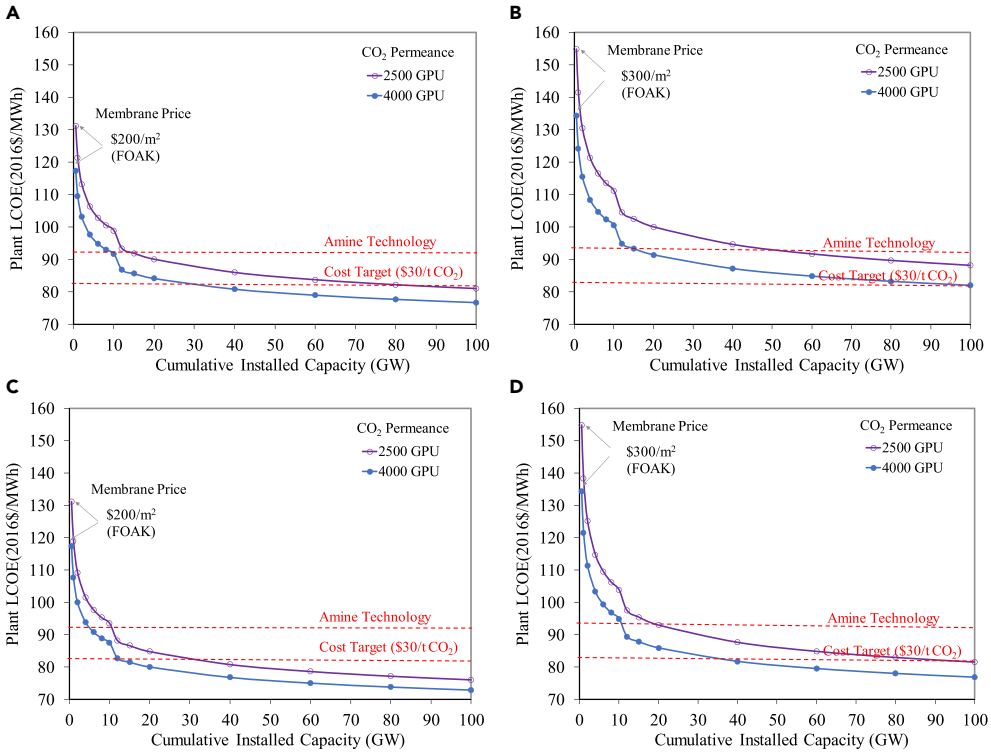

Figure 5. Evolution of Plant Levelized Cost of Electricity with Cumulative Installed Capacity of Membrane-Based Capture Systems

(A) Membrane cost: $200/m^2, learning rates: 11% in capital and 22% in O&M.

(B) Membrane cost: $300/m^2, learning rates: 11% in capital and 22% in O&M.

(C) Membrane cost: $200/m^2, learning rates: 13.8% in capital and 27.5% in O&M.

(D) Membrane cost: $300/m^2, learning rates: 13.8% in capital and 27.5% in O&M.

post-combustion capture demonstration projects in the world: Boundary Dam (110 MW) and Petra Nova (240 MW) (Mantripragada et al., 2019); the learning rates measured as the reduction in cost for each doubling of cumulative installed capacity are 11% and 22% for the capital and total O&M costs of membrane-based process, respectively, unless otherwise noted; the capital cost learning rates are 5% for base plant and 11% for air pollution control systems, whereas there is no learning in their future O&M costs because they are much mature. In addition, financing is assumed to decrease from a high-risk level to a low-risk level after 10 GW of installed capacity, which is equivalent to 20 power plants of 500 MW size.

Figure 5A shows the learning curves for the initial membrane capital cost of $200/m^2 assumed in the base case. The required scale of cumulative installed capacity for the evolution from an FOAK level to any cost target can be derived from each curve. The membrane module price for any given LCOE along each curve can also be back-calculated through trial-and-error modeling in the IECM. Making membrane technology competitive with amine-based NOAK technology requires about 14 GW of capacity installed for the 2,500-GPU case and about 10 GW for the 4,000-GPU case. To reach the target of $30/ton requires about 30 GW capacity for the 4,000-GPU case. After such amounts of installed capacity, the membrane price is projected to decrease from the initial price of $200/m^2 to $106/m^2, $156/m^2, and $50/m^2, respectively. The deployment of improved materials remarkably reduces the time or capacity required to achieve a cost target.

The hybrid analysis gives important implications for the evolutionary trend of future costs of advanced membrane technology with increased learning experience for a given scenario. Technological learning, however, is often under uncertainty. Rubin et al. (2015) recommend a systematic use of parametric analyses to examine the effects of uncertainties in the assumed rates of technological change. Figures 5B–5D further demonstrate the sensitivity of learning curves to the assumptions of initial membrane capital cost and learning rates. Figure 5B shows that if the initial membrane capital cost increases from $200/m^2 to

$300/m^2 for the 2,500-GPU case, the required capacity for membrane technology has to rise from 14 to 51 GW to make it competitive with amine-based NOAK technology. Figure 5B also indicates that even for the higher permeance, the cost target of $30/ton would not be reached without learning up to 100 GW if the initial FOAK membrane price starts from $300/m^2. In contrast, fast learning reduces the scale of required experience. As shown in Figure 5C, the cumulative installed capacity required for achieving the cost target of $30/ton falls from 30 to 12 GW for the 4,000-GPU case if the capital and O&M learning rates of membrane technology, respectively, increase by 25%–13.8% and 27.5%. So, membrane properties, initial membrane capital cost, and learning rates are the important factors that influence the scale of installed capacity or the time required toward commercial-scale implementation.

DISCUSSION

Breakthroughs in both membrane materials and process engineering for CO_2 capture are crucial to create an economically viable solution for decarbonization of the electric power sector. Membrane property targets identified for advanced membrane technology inform selection, design, and synthesis of new-generation materials for post-combustion CO_2 capture. The deterministic and probabilistic results indicate that to be competitive with amine-based NOAK technology or meet a more ambitious cost target, advanced membranes should have a higher CO_2 permeance than 2,250 GPU and a CO_2/N_2 selectivity of at least 30 if their installed prices are not less than $50/m^2. Challenges and opportunities coexist for membrane technology in meeting the targets. Current commercial gas separation membranes for industrial applications have much low CO_2 permeance on the order of 100 GPU (National Energy Technology Laboratory, 2013). Depending on how thinly the selective layer could be manufactured, some classes of advanced polymeric membranes like PIM, PEO, and TR "step out" from the pool shown in Figure 1 with a good possibility for cost-effective CO_2 capture. For illustrative purposes, Table 3 summarizes the properties of those membranes with a high CO_2 permeability above 250 Barrer. However, they basically stay at an early stage of research and development, such as material synthesis and laboratory-scale experiment. Few membranes have undergone extensive pilot trials for post-combustion CO_2 capture. Polaris, a high-performance polymeric membrane (up to 2,000 GPU for CO_2), may be the only one that has reached the pilot scale of 20 ton of CO_2 captured per day (TPD) (about 1 MWe) with an aimed extension to 200 TPD (Baker et al., 2018; White et al., 2017, 2015).

In addition to the improvements in material properties, countercurrent air sweep, hybrid process configuration, and exhaust gas recycling are effective options to enhance the viability of membrane-based capture systems. However, the effects of excess recycled CO_2 on air combustion and overall plant efficiency need to be under careful investigation. In addition, the presence of humidity and minor air pollutants in flue gas likely affect the gas transport properties. In general, the competitive sorption of water, sulfur oxides, and nitrogen oxides decreases both the CO_2 permeability and selectivity for glassy polymers when compared with the pure gas case, whereas the gas permeability increases strongly with water vapor activity for rubbery polymers due to the membrane swelling by water (Lasseuguette et al., 2016; Kanehashi et al., 2015). Large-scale pilot and demonstration projects are needed to rigorously examine the performance of advanced membranes under harsh conditions. Expected outcomes from such projects can be incorporated into the systems research to guide the selection of separation materials and to improve the design of reliable and efficient separation processes for applications to both power and non-power sectors (Roussanaly and Anantharaman, 2017). Sustained investments in research, development, and demonstration on advanced materials and novel processes, therefore, should be made from the government and private sectors to enhance technology growth.

Reverse osmosis (RO) is the worldwide leading desalination technology today. Improvements in RO membranes over 30 years have significantly lowered the membrane cost per unit volume of water produced by more than 10 times since 1978 (Lee et al., 2011). Similar cost reductions are likely for gas separation membranes. The successful evolution of advanced membrane technology from FOAK to NOAK levels requires a large scale of capacity to be installed, depending on material properties, initial membrane capital cost, and learning rates, as well as capture cost target. A larger scale of learning experience is likely needed for conventional membrane-based capture systems to meet a given cost target, compared with advanced hybrid capture systems. Fast learning for advanced capture systems using high-performance membranes can significantly save the required scale of experience. Figures 5B and 5D also indicate that faster learning rates than 13.8% in the capital cost and 27.5% in the O&M cost are needed for carbon capture systems with larger initial capital costs than $300/m^2 if technological

Class	Membrane	Pressure (atm)	Temperature(°C)	CO_2 Permeability (Barrer)	CO_2/N_2 Selectivity	Reference
PIM	PIM-300-2 d	3.5	35	4,000	41.7	Wang et al., 2016
PIM	PIM-300-1 d	3.5	35	3,083	30.7	Wang et al., 2016
PIM	TZPIM-2	3.4	25	3,076	31	Du et al., 2012
PIM	MTZ100-PIM	0.68	25	2,057	41.6	Wang et al., 2016
PIM	AO-PIM-1	2.0	35	1,153	35	Wang et al., 2016
PEO	PEO–PBT + PEG–DBE	0.3	30	750	40	Du et al., 2012
TR	TRO-4	1.0	35	629	32	Du et al., 2012
PEO	Pebax+PEG-DME			606	44	Liu et al., 2016
TR	TR-2			597	30	Liu et al., 2016
PEO	PEGDA/PEGMEA(99)	4.0	35	570	41	Du et al., 2012
PEO	Pebax1074/PEG1500 (50/50)	5.0	60	527.7	34.6	Wang et al., 2016
PEO	PEGDA/PEGMEA (91)	4.0	35	520	41	Du et al., 2012
PEO	Pebax1657/PDMS-*g*-POEM (50/50)	1.0	35	475.1	41.7	Wang et al., 2016
PIM	Cardo-PIM-1	0.2-0.3	30	430	33	Du et al., 2012
PEO	TEGMVE/VEEM (14/1)	1.0	25	410	46	Wang et al., 2016
PEO	PEO–PBT + PEG–BE	0.3	30	400	50	Du et al., 2012
PEO	PEGDA/PEGMEA (70)	4.0	35	320	47	Du et al., 2012
PEO	DB30/MM9(70)	1.0	35	308	47	Du et al., 2012
PEO	TEGMVE/VEEM (4/1)	1.0	25	280	50	Wang et al., 2016
PEO	DM14/MM9(70)	1.0	35	260	48	Du et al., 2012
PEO	PEGDA/PEGMEA (50)	4.0	35	250	41	Du et al., 2012

Table 3. High-Performance Polymeric Membranes for Post-combustion CO_2 Capture

PEGDA, poly (ethylene glycol) diacrylate; PEGMEA, poly(ethylene glycol) methyl ether acrylate; TEGMVE, (2-(2-(2-methoxyethoxy)ethoxy)ethyl vinyl ether; VEEM, 2-(2-vinyloxyethoxy)ethyl methacrylate; PBT, polybenzothiazole; BE, butyl ether; POEM, poly(oxyethylene methacrylate); PBT, polybenzothiazole; DME, dimethyl ether; AO, amidoxime.

learning is just up to 40 GW of capacity instead of 100 GW. Otherwise, an ambitious cost target (e.g., $30/ton) could not be achieved. Learning by doing is to lower the cost of membrane technology and, in turn, the cost of low-carbon electricity generation.

Given the high cost of FOAK capture systems shown in Figure 5, carbon regulations and policies are important to the establishment of market demands for CCS. However, moderate constraints on CO_2 emissions from the electric power sector may not boost large-scale penetration of CCS under pressure of low natural gas prices and substantial cost reductions in renewables (Lim-Wavde et al., 2018). Thus economic incentives are particularly important to early deployment of FOAK capture systems. Reuse of the captured CO_2, such as CO_2-enhanced oil recovery and CO_2 conversion to fuels, can bring an income stream to incentivize carbon capture technology development in the near term (Zhai et al., 2015), although its climate change mitigation potential may be of concern from the life cycle perspective (Abanades et al., 2017). Tax credits for carbon sequestration are also expected to drive growth of CO_2 capture (Johnson, 2018). In addition, to accelerate the pace of technological innovation and evolution, international collaborations, especially among those countries with heavy dependence on fossil fuels, also need to be reinforced to share the knowledge and data from CCS projects and to create interactive networks that integrate or

make better use of individual strengths in technology, manufacturing, cost, and resource (Hu and Zhai, 2017; Karimi and Khalilpour, 2015).

Limitations of the Study

Pending the availability of data on such factors as initial installed capacity of FOAK membrane technology, initial membrane capital cost, and learning rates, improved learning models are needed to make more robust projections on advanced membrane technology.

METHODS

All methods can be found in the accompanying Transparent Methods supplemental file.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.isci.2019.03.006.

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AUTHOR CONTRIBUTIONS

H.Z. conceived the study, performed the analysis, and wrote the manuscript.

DECLARATION OF INTERESTS

The author declares no competing interests.

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ISCI, Volume *13*

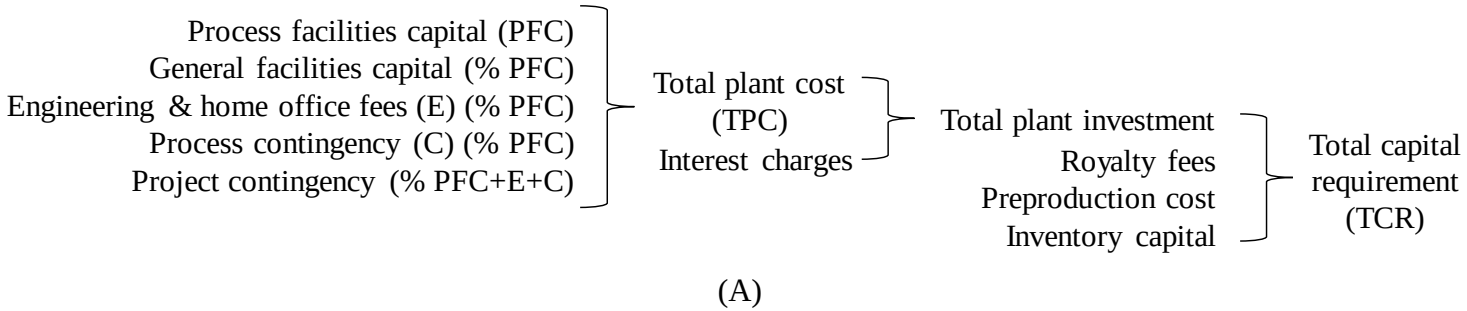
Supplemental Information

Advanced Membranes and Learning Scale Required for Cost-Effective Post-combustion Carbon Capture

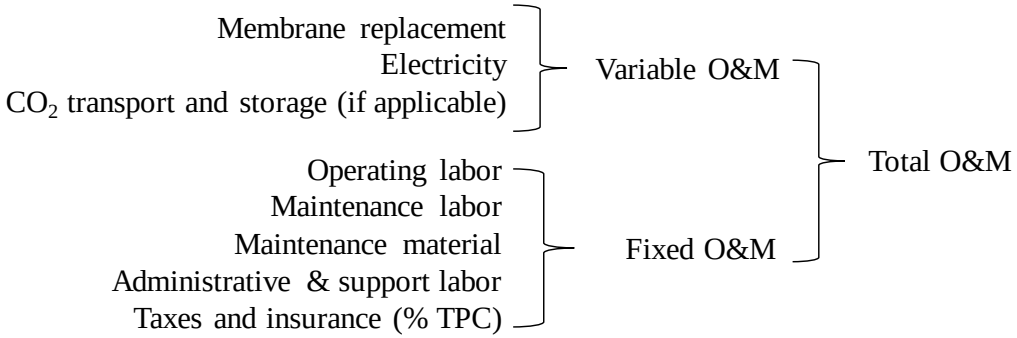
Haibo Zhai

TRANSPARENT METHODS

To explore high-performance membrane materials for cost-effective CO_2 capture, this study employs the Integrated Environmental Control Model (IECM), a power plant modeling tool developed by Carnegie Mellon University (IECM, 2018). The IECM provides systematic estimates of the performance, emissions, costs, and uncertainties of fossil fuel-fired power plants with and without CCS. In the IECM, performance models of amine- and membrane-based CO_2 capture systems are established based on basic mass and energy balances rooted in thermodynamics and are further coupled with engineering-economic models that estimate the capital cost, annual operating and maintenance (O&M) costs, and total annual levelized cost of electricity (LCOE) of an overall power plant and environmental control systems (Zhai and Rubin, 2017, 2013; Berkenpas et al., 2009; Rao et al., 2002). For illustrative purposes, Figure S1 presents the capital and O&M cost estimation methods for membrane-based capture systems in the IECM (Zhai and Rubin, 2013). More details of the membrane models including the multi-component gas separation simulation and the costing method are available elsewhere (Zhai and Rubin 2017, 2013).



(A)



(B)

Figure S1. Cost estimation methods for membrane-based capture systems, related to Table 1 (A) capital cost (B) O&M costs (Zhai and Rubin, 2013)

The latest IECM v11.2 is used to evaluate the engineering-economics of membrane-based capture systems employing high-performance materials at various levels of maturity, including both FOAK and NOAK technologies. A comparative analysis is further performed to determine the membrane properties necessary to make membrane technology competitive with amine-based CO_2 capture or achieve a cost target for CO_2 capture. The cost of CO_2 capture is used as a major metric for evaluation (Rubin, 2012):

$$\text{Cost of } CO_2 \text{ capture } (\$/\text{tonne}) = \frac{\text{LCOE}_{cc} - \text{LCOE}_{\text{Ref}}}{(tCO_2/\text{MWh})_{cc}} \quad \text{(S1)}$$

where LCOE_{cc} is the LCOE of the plant with CO_2 capture ($/MWh), excluding the CO_2 T&S costs; LCOE_{Ref} is the LCOE of the reference plant without CO_2 capture ($/MWh); and $(tCO_2/\text{MWh})_{cc}$ is the amount of CO_2 captured per unit of MWh (tonne/MWh).

In addition to the bottom-up techno-economic analysis, the top-down approach based on learning curves can also be used to estimate the future cost of power plants with CO_2 capture and the time-related scale of deployment. To estimate the cost of advanced membrane technology and determine the scale of installed capacity required for technological evolution from FOAK to a cost target, this study adopts a hybrid approach proposed by Rubin *et al.* (2016), which combines the techno-economic analysis with learning curves. The widely-used one-factor learning model is applied to project the evolutionary LCOE of a power plant with CO_2 capture as a function of the cumulative installed capacity of membrane-based capture systems. The one-factor learning model has the form (Rubin et al., 2015):

$$Y = a \cdot x^b \quad \text{(S2)}$$

Where Y is the unit cost of the technology, x is the cumulative experience, *a* is the cost of the first unit, and *b* is a parametric constant. The quantity (2^b) is defined as the progress ratio, while

($1-2^b$) is defined as the learning rate and is reported as the percentage or fraction reduction in cost for each doubling of cumulative installed capacity. Eq. (S2) is also often transformed to a log-linear equation with *b* as the line slope. The component-based learning rates refer to the estimates by Rubin *et al.* for power plants with post-combustion CO_2 capture (Rubin et al., 2015, 2007), which are reported as the percentage reduction in cost for each doubling of cumulative installed capacity. The capital and O&M costs of the first capture plant are based upon the IECM estimates. Once the learning curve of plant LCOE is established by summing the individual component costs at each capacity level, the required scale of installed capacity can be derived from it in conjunction with LCOE estimates from IECM modeling for plants with FOAK and NOAK capture systems.

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