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

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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 CO2 capture. To be competitive with amine-based nth-of-a-kind (NOAK) technology or meet a more ambitious cost target for 90% CO2 capture, advanced membranes should have a higher CO2 permeance than 2,250 GPU and a higher CO2/N2 selectivity than 30 if their installed prices are higher than $50/m². 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 (CO2) 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 CO2 (U.S. Department of Energy, 2013).

Membrane-based capture systems have engineering and economic advantages over absorption-based CO2 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 CO2 permeability and permeance, good CO2 versus nitrogen (N2) 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 CO2 capture (Khallipour 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 CO2 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 CO2 permeability and CO2 versus nitrogen (N2) selectivity...
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 CO₂ permeability ranging from 100 to 1,000 Barrer and a good CO₂/N₂ 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 CO₂ permeability and CO₂/N₂ 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 CO₂ 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 Hag, 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 CO₂ removal efficiency and high CO₂ purity. To decrease the parasitic load for CO₂ 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 CO₂ and then increase the CO₂ partial pressure in flue gas. However, Franz et al. (2013) further note that the recycled excess CO₂ 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 CO₂ 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/m²–$80/m² 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.
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 CO₂ 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 CO₂ 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 CO₂ 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-CO₂ 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 CO₂ in flue gas; combustion air is used as a sweep gas in a countercurrent or sweep module to recycle the permeated CO₂, and the permeate gas from the first stage is delivered to a cryogenic CO₂ 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 CO₂ permeance and CO₂/N₂ selectivity are at least 1,000 GPU and 30, respectively, and when the CO₂/N₂ selectivity is higher than 50, increasing the CO₂ permeance appears more important than the CO₂/N₂ selectivity in enhancing the economic viability of advanced capture processes with CO₂ recycling (Zhai and Rubin, 2013; Merkel et al., 2010). So the CO₂ permeance was varied from 1,000 to 4,000 GPU in the IECM simulations, whereas the CO₂/N₂ selectivity was fixed at 40. The major techno-economic performance of the CPU was based on that reported by the National Energy Technology Laboratory.

Figure 2. Membrane-Cryogenic Purification for Post-combustion CO₂ Capture
| 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$_2$O                                  | 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)
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% CO2 capture decreases the net plant efficiency by approximately 11 percentage points on an absolute basis, compared with the reference PC plant without CO2 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 CO2 transport and storage (T&S) costs, whereas the LCOE of a plant with an NOAK system capturing CO2 at the cost of $30/ton is estimated to be $82.6/MWh; the cost of CO2 capture by amine technology is about $35/ton, whereas the cost of CO2 avoided is about $65/ton, given the assumption of $10/ton for the total CO2 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 CO2 capture. Increases in the CO2 permeance do not significantly improve the net plant efficiency but lower the capture cost. Figure 3 shows the cost of CO2 capture by membrane-based NOAK technology as a function of CO2 permeance and installed membrane module price. The cost of CO2 capture decreases nonlinearly with increased CO2 permeance for a range of membrane prices. The cost share by component in percentage varies with membrane CO2 permeance and price. However, for a given membrane price, increases in CO2 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 CO2 capture, it is necessary to lower the manufacturing price of high-performance membranes. At the membrane price of $50/m² assumed widely in the literature, the breakeven CO2 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 CO2. For either of the benchmarks, the breakeven CO2 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

| Section | Parameter | Value |
|---------|-----------|-------|
| Overall cost for CO2 capture | Power plant LCOE (2016, constant $/MWh) | |
| | Case I: 2,500 GPU for CO2 permeance | 85.3 | 131.2 |
| | Case II: 4,000 GPU for CO2 permeance | 82.6 | 117.3 |
| Cost of CO2 capture (2016, constant $/ton) | Case I: 2,500 GPU for CO2 permeance | 33.2 | 87.1 |
| | Case II: 4,000 GPU for CO2 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.

*Referring to the assumption by NETL for advanced membranes based on the test experience (National Energy Technology Laboratory, 2012), N2, Ar, and O2 have identical permeance. The permeabilities of Ar and O2 may be higher than the N2 permeability, depending on specific materials. However, their fractions in flue gas are much less than the N2 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.

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).

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).

The CO2 transport and storage costs are not included.

For the reference plant without CO2 capture, the plant LCOE is $57.0/MWh, which is the IECM modeling result.

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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

![Figure 3. Variability in Cost of CO$_2$ Capture by Membrane Permeance and Price of NOAK Membrane Technology](image)

Table 2. Probabilistic Distribution Assumptions for Uncertain Parameters

| 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 |
additional uncertainties beyond those shown in Table 2 may affect the probabilistic distributions of CO₂ capture cost.

Capacity factor and fixed charge factor are common to both plants with and without CO₂ 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 CO₂ capture by NOAK membrane technology for two levels of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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
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/m² 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 of installed capacity, which is equivalent to 20 power plants of 500 MW size.

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/m² 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 CO2 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 CO2 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 CO2 permeance than 2,250 GPU and a CO2/N2 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 lower CO2 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 CO2 capture. For illustrative purposes, Table 3 summarizes the properties of those membranes with a high CO2 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 CO2 capture. Polaris, a high-performance polymeric membrane (up to 2,000 GPU for CO2), may be the only one that has reached the pilot scale of 20 ton of CO2 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 CO2 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 CO2 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...
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 CO2 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-Wawde et al., 2018). Thus economic incentives are particularly important to early deployment of FOAK capture systems. Reuse of the captured CO2, such as CO2-enhanced oil recovery and CO2 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 CO2 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

| Class | Membrane | Pressure (atm) | Temperature(°C) | CO2 Permeability (Barrer) | CO2/N2 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 | 0.3 | 30 | 606 | 44 | Liu et al., 2016 |
| TR    | TR-2 | 0.3 | 30 | 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 CO2 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-vinylxyethoxy)ethyl methacrylate; PBT, polybenzothiazole; BE, butyl ether; POEM, poly(oxymethylene methacrylate); PB, polybenzothiazole; DME, dimethyl ether; AO, amidoxime.
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.

REFERENCES
Abanades, J.C., Rubin, E.S., Mazzotti, M., and Herzog, H.J. (2017). On the climate change mitigation potential of CO2 conversion to fuels. Energy Environ. Sci. 10, 2491–2499.

Baker, R.W., Merkel, T., and Freeman, B.C. (2018). Large pilot testing of the MTR membrane post-combustion CO2 capture process. National Energy Technology Laboratory project Kickoff Meeting, https://www.netl.doe.gov/File%20Library/Research/Coal/carbon%20capture/post-combustion/MTR-Kickoff-Presentation-Public-FF0031587-FOA1788.pdf.

Baker, R.W., Freeman, B., Kniep, J., Wei, X., and Merkel, T. (2017). CO2 capture from natural gas power plants using selective exhaust gas recycle membrane designs. Int. J. Greenh. Gas Con. 66, 35–47.

Binns, M., Lee, S., Yeo, Y.K., Lee, J.H., Moon, J.H., Yeo, J.G., and Kim, J.K. (2016). Strategies for the simulation of multi-component hollow fibre multi-stage membrane gas separation systems. J. Membr. Sci. 497, 488–471.

Brunetti, A., Drioli, E., Lee, Y.M., and Barbieri, G. (2014). Engineering evaluation of CO2 separation by membrane gas separation systems. J. Membr. Sci. 454, 305–315.

Brunetti, A., Scura, F., Barbieri, G., and Drioli, E. (2010). Membrane technologies for CO2 separation. J. Membr. Sci. 359, 115–125.

Diego, M.E., Bellas, J.M., and Pourkashanian, M. (2018). Techno-economic analysis of a hybrid CO2 capture system for natural gas combined cycles with selective exhaust gas recirculation. Appl. Energy 215, 778–791.

Dong, G., Li, H., and Chen, V. (2013). Challenges and opportunities for mixed-matrix membranes for gas separation. J. Mater. Chem. A 1, 4610–4630.

Du, N., Park, H.B., Dal-Cin, M.M., and Guiver, M.D. (2012). Advances in high permeability polymeric membrane materials for CO2 separations. Energy Environ. Sci. 5, 7306–7322.

Electric Power Research Institute. (1993). Technical Assessment Guide Vol. 1: Electricity Supply, Rev. 7, Report TR-102276-VIR7 (Electric Power Research Institute).

Figueras, J.D., Fout, T., Plasynski, S., Mlvried, H., and Srivastava, R.D. (2008). Advances in CO2 capture technology—the US department of energy’s carbon sequestration program. Int. J. Greenh. Gas Con. 2, 9–20.

Frankfurt School-UNEP Centre/BNEF. (2014). Global Trends in Renewable Energy Investment (UN Environment’s Economy Division, Frankfurt School-UNEP Collaborating Centre for Climate & Sustainable Energy Finance, and Bloomberg New Energy Finance). http://www.fs-unep-centre.org.

Franz, J., Schiebahn, S., Zhao, L., Rienesche, E., Scherer, V., and Stolten, D. (2013). Investigating the influence of sweep gas on CO2/N2 membranes for post-combustion capture. Int. J. Greenh. Gas Con. 13, 180–190.

Giordano, L., Roizard, D., Bounaceur, R., and Favre, E. (2017). Evaluating the effects of CO2 capture benchmarks on efficiency and costs of membrane systems for post-combustion capture: a parametric simulation study. Int. J. Greenh. Gas Con. 63, 449–461.

Hasan, M.F., Baliban, R.C., Elia, J.A., and Floudas, C.A. (2012). Modeling, simulation, and optimization of postcombustion CO2 capture for variable feed concentration and flow rate. 1. Chemical absorption and membrane processes. Ind. Eng. Chem. Res. 51, 5642–5664.

He, X., Fu, C., and Hagg, M.B. (2015). Membrane system design and process feasibility analysis for CO2 capture from flue gas with a fixed-site-carrier membrane. Chem. Eng. J. 268, 1–9.
Hu, B., and Zhai, H. (2017). The cost of carbon capture and storage for coal-fired power plants in China. Int. J. Greenh. Gas Con. 65, 23–31.

Hussain, A., and Hagg, M.B. (2010). A feasibility study of CO2 capture from flue gas by a facilitated transport membrane. J. Membr. Sci. 359, 140–148.

IECM. (2018). Integrated Environmental Control Model (IECM) Version 11.2 (Carnegie Mellon University). https://www.cmu.edu/epp/iecm/index.html.

Intergovernmental Panel on Climate Change (IPCC). (2014). Summary for Policymakers. In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, and P. Eickemeier, et al., eds. (Cambridge University Press), pp. 10–20.

Johnson, J. (2018). Tax incentives expected to drive growth of CO2 capture. Chem. Eng. News 96, 16.

Kanehashi, S., Chen, G.Q., Ciddor, L., Chaffee, A., and Kentsis, S. (2019). The impact of water vapor on CO2 separation performance of mixed matrix membranes, J. Membr. Sci. 492, 471–477.

Karimi, F., and Khalilpour, R. (2019). Evolution of carbon capture and storage research: Trends of international collaborations and knowledge maps. Int. J. Greenh. Gas Con. 37, 362–376.

Khalilpour, R., Mumford, K., Zhai, H., Abbas, A., Stevens, G., and Rubin, E.S. (2015). Membrane-based carbon capture from flue gas: a review. J. Clean. Prod. 103, 286–300.

Lassequette, E., Carta, M., Brandani, S., and Ferrari, M.C. (2016). Effect of humidity and flue gas impurities on CO2 permeation of a polymer of intrinsic microporosity for post-combustion capture. Int. J. Greenh. Gas Con. 50, 93–99.

Lee, K.P., Arnot, T.C., and Mattia, D. (2011). A review of reverse osmosis membrane materials for desalination—development to date and future potential. J. Membr. Sci. 370, 1–22.

Lim-Wawde, K., Zhai, H., Kauffman, R.J., and Rubin, E.S. (2018). Assessing carbon pollution—electrical power generation pathways: Electric power generation pathways. Energy Policy 118, 3006–3014.

Luo, J., Hou, X., Park, H.B., and Lin, H. (2016). High-performance polymers for membrane CO2/N2 separation. Chem. Eur. J. 22, 15980–15990.

Luis, P., Van Gerven, T., and Van der Bruggen, B. (2012). Recent developments in membrane-based technologies for CO2 capture. Prog. Energ. Combust. Sci. 38, 419–448.

Mantripragada, H.C., Zhai, H., and Rubin, E.S. (2019). Boundary Dam or Petra Nova—Which is a better model for CCS energy supply? Int. J. Greenh. Gas Con. 82, 59–68.

Mat, N.C., and Lipscomb, G.G. (2017). Membrane process optimization for carbon capture. Int. J. Greenh. Gas Con. 62, 1–12.

Merkel, T.C., Wei, X., He, Z., White, L.S., Wijmans, J.G., and Baker, R.W. (2012). Selective exhaust gas recycle with membranes for CO2 capture from natural gas combined cycle power plants. Ind. Eng. Chem. Res. 52, 1150–1159.

Merkel, T.C., Lin, H., Wei, X., and Baker, R. (2010). Power plant post-combustion carbon dioxide capture: an opportunity for membranes. J. Membr. Sci. 359, 126–139.

National Energy Technology Laboratory (2013). DOE/NETL advanced carbon dioxide capture r&D program: technology update, https://www.netl.doe.gov/fflibrary/Research/Cool/ carbon%20Capture/handbook/CO2-Capture- Tech-Update-2013.pdf.

National Energy Technology Laboratory (2012). Current and Future Technologies for Power Generation with Post-Combustion Carbon Capture, Final Report DOE/NETL-2012/1557.

Rafiq, S., Deng, L., and Hagg, M.B. (2016). Role of facilitated transport membranes and composite membranes for efficient CO2 capture—a review. Chembioeng Rev. 3, 68–85.

Ramasubramanian, K., Verweij, H., and Ho, W.W. (2012). Membrane processes for carbon capture from coal-fired power plant flue gas: a modeling and cost study. J. Membr. Sci. 421, 299–310.

Rah, K., Rubin, E.S., Taylor, M.R., Schrattenholzer, L., and Hounshell, D. (2004). Technological learning for carbon capture and sequestration technologies. Energy Econ. 26, 559–564.

Robeson, L.M. (2008). The upper bound revisited. J. Membr. Sci. 320, 390–400.

Roussanaly, S., and Anantharaman, R. (2017). Cost-optimal CO2 capture ratio for membrane-based capture from different CO2 sources. Chem. Eng. J. 327, 618–628.

Roussanaly, S., Anantharaman, R., Lindqvist, K., Zhai, H., and Rubin, E. (2016). Membrane properties required for post-combustion CO2 capture at coal-fired power plants. J. Membr. Sci. 511, 250–264.

Rubin, E.S., Azvedo, I.M., Jaramillo, P., and Yeh, S. (2013). A review of learning rates for electricity supply technologies. Energy Policy 86, 198–218.

Rubin, E.S., Mantripragada, H., Marks, A., Versteeg, P., and Kitchin, J. (2012). The outlook for improved carbon capture technology. Prog. Energ. Combust. Sci. 38, 630–671.

Rubin, E.S., and Zhai, H. (2012). The cost of carbon capture and storage for natural gas combined cycle power plants. Environ. Sci. Technol. 46, 3076–3084.

Rubin, E.S., Yeh, S., Antes, M., Berkenpas, M., and Davison, J. (2007). Use of experience curves to estimate the future cost of power plants with CO2 capture. Int. J. Greenh. Gas Con. 1, 188–197.

Schouls, C.A., Ho, M.T., Wiley, D.E., Stevens, G.W., and Kentish, S.E. (2013). Cost competitive membrane—cryogenic post-combustion carbon capture. Int. J. Greenh. Gas Con. 17, 341–348.

Shao, P., Dal-Cin, M.M., Guiver, M.D., and Kumar, A. (2013). Simulation of membrane-based CO2 capture in a coal-fired power plant. J. Membr. Sci. 427, 451–459.

Shelley, S. (2009). Capturing CO2: membrane systems move forward. Chem. Eng. News 104, 42–47.

Tong, Z., and Ho, W.W. (2017). Facilitated transport membranes for CO2 separation and capture. Sep. Purif. Technol. 52, 156–167.

Turi, D.M., Ho, M., Ferrari, M.C., Chiesa, P., Wiley, D.E., and Romano, M.C. (2017). CO2 capture from natural gas combined cycles by CO2 selective membranes. Int. J. Greenh. Gas Con. 61, 168–183.

U.S. Department of Energy. (2013). Carbon Capture Technology Program Plan (U.S. Department of Energy’s Office of Fossil Energy).

Vinoba, M., Bhagyalalakshmi, M., Alqaheem, Y., Alomari, A.A., Perez, A., and Rana, M.S. (2017). Recent progress of fillers in mixed matrix membranes for CO2 separation: a review. Sep. Purif. Technol. 88, 431–450.

Wang, S., Li, X., Wu, H., Tian, Z., Xin, Q., He, G., Peng, D., Chen, S., Lin, Y., Jiang, Z., and Guiver, M.D. (2016). Advances in high permeability polymer-based membrane materials for CO2 separations. Energy Environ. Sci. 9, 1863–1890.

White, L.S., Amo, K.D., Wu, T., and Merkel, T.C. (2017). Extended field trials of Polaris sweep modules for carbon capture. J. Membr. Sci. 542, 217–225.

White, L.S., Wei, X., Pande, S., Wu, T., and Merkel, T.C. (2015). Extended flue gas trials with a membrane-based pilot plant at a one-ton-per-day carbon capture rate. J. Membr. Sci. 496, 48–57.

Zhai, H., Ou, Y., and Rubin, E.S. (2015). Opportunities for decarbonizing existing US coal-fired power plants via CO2 capture, utilization and storage. Environ. Sci. Technol. 49, 7571–7579.

Zhai, H., and Rubin, E.S. (2013). Techno-economic assessment of polymer membrane systems for postcombustion carbon capture at coal-fired power plants. Environ. Sci. Technol. 47, 3006–3014.

Zhai, H., Riensche, E., Blum, L., and Stolten, D. (2010). Multi-stage gas separation membrane processes used in post-combustion capture: Energetic and economic analyses. J. Membr. Sci. 359, 160–172.
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 CO₂ 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 CO₂ 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).
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 CO₂ capture or achieve a cost target for CO₂ capture. The cost of CO₂ capture is used as a major metric for evaluation (Rubin, 2012):

\[
\text{Cost of CO}_2\text{ capture ($/tonne) } = \frac{\text{LCOE}_{cc} - \text{LCOE}_{Ref}}{(t\text{CO}_2/M\text{Wh})_{cc}}
\]  

(S1)

where \(\text{LCOE}_{cc}\) is the LCOE of the plant with CO₂ capture ($/M\text{Wh}$), excluding the CO₂ T&S costs; \(\text{LCOE}_{Ref}\) is the LCOE of the reference plant without CO₂ capture ($/M\text{Wh}$); and \((t\text{CO}_2/M\text{Wh})_{cc}\) is the amount of CO₂ captured per unit of M\text{Wh} (tonne/M\text{Wh}).

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 CO₂ 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 CO₂ 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):

\[
Y = a \cdot x^b
\]

(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.

REFERENCES

- Berkenpas, M. P., Kietzke, K., Mantripragada, H., McCoy, S. T., Rubin, E. S., Versteeg, P. L., and Zhai, H. (2009). IECM Technical Documentation Updates Final Report, Carnegie Mellon University, Pittsburgh, PA. Available at [https://www.cmu.edu/epp/iecm/iecm_docpubs.html](https://www.cmu.edu/epp/iecm/iecm_docpubs.html).
- Integrated Environmental Control Model (IECM) Version 11.2 (2018). Carnegie Mellon University, Pittsburgh, PA. Available at [https://www.cmu.edu/epp/iecm/index.html](https://www.cmu.edu/epp/iecm/index.html).
- Rao, A.B., and Rubin, E.S. (2002). A technical, economic, and environmental assessment of amine-based CO\(_2\) capture technology for power plant greenhouse gas control, Environ. Sci. Technol. 36(20), 4467–4475.
- Rubin, E.S., Mantripragada, H., and Zhai, H. (2016). An Assessment of the NETL Cost Estimation Methodology. Prepared for the U.S. Department of Energy’s National Energy Technology Laboratory, Pittsburgh, PA.
- Rubin, E.S., Azevedo, I.M., Jaramillo, P., Yeh, S. (2015). A review of learning rates for electricity supply technologies, Energy Policy 86, 198–218.
- Rubin, E.S. (2012). Understanding the pitfalls of CCS cost estimates, Int. J. Greenh. Gas Con. 10, 181–190.
- Rubin, E.S., Yeh, S., Antes, M., Berkenpas, M., Davison, J. (2007). Use of experience curves to estimate the future cost of power plants with CO\(_2\) capture, Int. J. Greenh. Gas Con. 1(2), 188–197.
- Zhai, H., and Rubin, E.S. (2017). IECM Technical Documentation: A Two-Stage Membrane System with Air Sweep for Postcombustion Carbon Capture and Storage, Carnegie Mellon University, Pittsburgh, PA. Available at [https://www.cmu.edu/epp/iecm/iecm_docpubs.html](https://www.cmu.edu/epp/iecm/iecm_docpubs.html).
- Zhai, H., and Rubin, E.S. (2013). Techno-economic assessment of polymer membrane systems for postcombustion carbon capture at coal-fired power plants, Environ. Sci. Technol. 47(6), 3006–3014.