18 Membranes in Power Generation
A Review of Current Uses and Emerging Applications

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18.1 INTRODUCTION

The production of electricity is one of the largest-scale industrial activities. Electricity can be generated from a variety of fuels, but the current mix heavily emphasizes coal and natural gas (NG). The process involves a number of steps, and separation technologies are needed to condition fuel, air, and water inputs, as well as control emissions and pollutants in waste streams.

Membranes can and do play an enabling role in a number of these steps. They are defined functionally by their selective permeability to fluid streams. For example, membranes can be used to filter particulates from gas or liquids, remove dissolved salts from water, and purify gas mixtures. As can be seen in other chapters of this handbook, membranes can be fabricated from a wide range of materials including polymers, ceramics, metals, or composites, with the specific composition greatly influencing the membrane performance and system economics.

This chapter reviews existing and emerging applications for membrane technology in stationary power generation. For example, filters are used to clean intake air for combustion and remove particulate emissions from coal-fired power plants [1], while membrane technologies are used for the purification of NG [2] and the conditioning of boiler feedwater for use in steam turbines [3]. The discussion is divided into three sections:

- The first section highlights the power generation industry trends with a system-level overview including the context for membrane utilization. A system-level understanding provides guidance on where membranes might play a role in the future and provides metrics for comparing the relative economics of different technologies.
- The second section reviews current uses of membranes in electricity generation, primarily in fossil fuel–fired power plants. For some functions, such as...
the filtration of combustion air in fossil fuel–fired power plants and the removal of particulate emissions in flue gases, membranes are the incumbent technology. In NG purification and water treatment applications, membrane-based technologies meet the performance requirements but compete with more cost-effective alternatives.

- The final section explores emerging applications in which membranes may play a role in the next few decades [4]. The discussion will focus on air separation membranes for advanced combustion cycles and membrane solutions for the capture of CO₂ emissions.

### 18.2 Overview of Power Generation Industry and Trends

Figure 18.1 shows the global power generation fleet in 2012 with about 179,000 electric power generating units spread over 80,000 plant sites accounting for a total generation capacity of about 5 TW [5]. Despite significant numbers of wind and solar power generating units in Europe and North America, global installed capacity is still dominated by large centralized facilities.

Figure 18.2 shows the current and projected electricity generation capacity by fuel type. Table 18.1 lists typical power plant parameters for facilities using different fuel types. Current power generation is dominated by thermal processes that use the action of heat generated by either renewable or nonrenewable fuels on a working fluid to drive a turbine. This includes fossil fuel combustion, nuclear fission, biomass combustion, geothermal extraction, or solar–thermal collection.

Fossil fuels account for almost three-quarters of global installed capacity and will continue to be important for at least the next few decades. Membranes can and do play an important enabling function in the operation of today’s fossil fuel–driven power plants, particularly coal- and NG-based units. In the future, the power generation industry will be...
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18.3 ROLES FOR MEMBRANES: TODAY

The two key performance requirements that determine whether a membrane technology is suitable for application in a power generation facility are performance capabilities and cost. Performance requirements of a membrane-based system are defined at the system level and often involve target purities for several components in filtered fluid streams. Other performance requirements include reliability and footprint targets.

Performance is a necessary, but not sufficient, criterion for the adoption of a technology. Economic competitiveness is often the key determinant in whether a technology is selected from multiple options capable of satisfying a given set of performance requirements. The technology costs are related primarily to the initial capital investment and the operating costs (OPEX) over the life of the plant. The reliability of a given technology can be particularly important, as technologies that require significant maintenance can adversely impact the overall operation of the plant.

Figures 18.3 and 18.4 show plant layouts for a pulverized coal (PC) power plant and a natural gas combined cycle (NGCC) power plant, respectively. Several subsystems where membranes are feasible are highlighted. However, actual development is dominated by economic considerations. These include fuel preparation, air filtration, water conditioning, and emission management. Membranes are economically favorable and finding widespread use in fuel preparation, air filtration, and emission management applications. They are candidates in specialized water conditioning applications. This section takes a closer look at these applications and discusses both the engineering rationale for membranes and some practical engineering issues related to their use.

Conceptually, a PC power plant operates using a thermodynamic Rankine cycle [11]. Coal is combusted with air in a boiler and the heat is used to generate steam. This steam is expanded through a turbine to generate electricity and is condensed and returned to the boiler. Cooling water is circulated through the condenser to remove waste heat. The flue gases from coal combustion are currently treated to remove particulates, mercury, dioxins, SOx, and NOx emissions. The waste slag is landfilled. The Rankine cycle subcritical PC power plant model described by the U.S. Department of Energy (DOE) is based on 550 MW power generation plant [11]. The plant utilizes bituminous coal at a rate of 198 MT/h, consuming 1.6 MM m³/h of air and rejecting 950 MW of heat using 1340 m³/h of water. The overall thermal efficiency of the plant is 36.8%. The U.S. Environmental Protection Agency (EPA) regulations govern the emission profile and limit particulate matter (PM) to 0.2 kg/MWh, SOx to 0.6 kg/kWh, and NOx to 0.5 kg/MWh [11].

NGCC power plants utilize a gas turbine (GT) in conjunction with a steam turbine. NG is combusted in air, and the resulting stream is expanded in a GT. The exhaust gas

### TABLE 18.1
Overview of Power Generation by Fuel Type

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>13</td>
<td>500–4000</td>
<td>20–30</td>
<td>0.70–0.90</td>
</tr>
<tr>
<td>Coal</td>
<td>40</td>
<td>300–2000</td>
<td>20–30</td>
<td>0.64</td>
</tr>
<tr>
<td>NG</td>
<td>21</td>
<td>500</td>
<td>50–60</td>
<td>0.11</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0.3</td>
<td>10–50</td>
<td>10–23</td>
<td>0.90</td>
</tr>
<tr>
<td>Solar thermal</td>
<td>&lt;0.1</td>
<td>1–40</td>
<td>20–30</td>
<td>0.33–0.75</td>
</tr>
<tr>
<td>Biomass</td>
<td>&lt;1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonthermal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydro</td>
<td>16</td>
<td>22,500</td>
<td>N/A</td>
<td>0.40</td>
</tr>
<tr>
<td>Wind</td>
<td>1.1</td>
<td>270–700</td>
<td></td>
<td>0.20–0.40</td>
</tr>
<tr>
<td>Solar (PV)</td>
<td>0.1</td>
<td></td>
<td></td>
<td>0.13–0.19</td>
</tr>
</tbody>
</table>


a Thermal efficiency is the electrical output (MWₑ) divided by the thermal output of the fuel (MWₑ).

b The capacity factor is the ratio of its actual output over a period of time to its potential output if it were possible for it to operate at full nameplate capacity.

Membranes are shaped by the need to meet significant increases in electricity demand while simultaneously addressing sustainability concerns such as CO₂ emissions and water availability [9]. There will be significant opportunities for the introduction of new technology to meet the dual challenges of efficiency and environment. According to International Energy Agency (IEA) projections, an additional 5890 GW of capacity will be added between 2012 to 2035, requiring a capital investment of $16.9 trillion (2010 USD) [10]. Factors that will shape the build-out in a given region include relative fuel prices, environmental regulations, and other market and policy drivers.
from the GT is used to generate steam using a heat recovery steam generator (HRSG) and then exhausted. Steam from the HRSG is then expanded in a steam turbine and condensed. The condensate is recirculated back to the HRSG. Makeup water and cooling water are used in a manner similar to the PC power plant. Combination of a thermodynamic Brayton cycle using the NG with and a Rankine cycle using the steam raised from the exhaust gas, a typical NGCC plant can achieve overall thermal efficiencies of up to about 60%.

The gas cycle produces about one-third of the total power output. The NGCC power plant modeled in the DOE base case generates 550 MW using GTs burning NG at a rate of 76 MT/h, consuming 2.6 MM m$^3$/h of air, and rejecting 560 MW of heat using 540 m$^3$/h of water. The overall thermal efficiency of the plant is 50.2%. Air quality requirements are similar to those governing coal plants [11].

The fuel preparation process for NGCC power plants involves conditioning of raw, wellhead NG to meet pipeline...
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18.3.1 Membranes for Fuel Preparation

18.3.1.1 Introduction

NG consumption in the United States in 2011 was approximately 24.4 trillion scf, with the maximum fraction of roughly 31% consumed for electric power generation [8]. Pipeline NG utilized for power generation is typically produced from gas or oil wells with methane (CH₄) as the main component (>80 vol.%). Wellhead NG also contains heavy hydrocarbons (C₃+), water vapor (H₂O), and impurities such as nitrogen (N₂), carbon dioxide (CO₂), and hydrogen sulfide (H₂S). The composition of raw NG varies greatly depending on the location and source; however, US pipeline NG composition is tightly controlled (Table 18.2). Therefore, it is necessary to condition the NG before distribution.

NG processing is the largest industrial gas separation application for membranes. Membrane market share in 2008 was 5%, with interest in this application growing rapidly [2]. Membranes for CO₂ and heavy hydrocarbon removal (C₃+) from NG continue to be the two largest membrane gas separation applications, while N₂ and H₂S removal from NG is in its early stages of commercialization [12]. Dehydration of NG using membranes is also attracting interest [13].

In all of these applications, polymeric membranes have been the focus of commercialization due to their relative ease of fabrication, lower cost, and scalability compared to other materials such as inorganic, metallic, supported, and liquid membranes [14]. Polymeric membranes comprise an ultrathin, nonporous separating layer in intimate contact with a highly porous support layer. Gas transport through these membranes typically obeys a solution-diffusion mechanism. The following section reviews system requirements, membrane performance targets, current membrane performance, and future development needs. Table 18.2 lists the gas component of interest, their typical pipeline specifications, first-generation membrane materials and their performance, competing technologies, and current challenges/development needs.

**TABLE 18.2**

**Overview of Membrane Technology for Natural Gas Purification Application**

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
<th>Typical Polymers and Selectivities w.r.t. Methane (CH₄)</th>
<th>Competing Technologies</th>
<th>Challenges for Membranes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>&lt;2 vol.%</td>
<td>Cellulose acetate, polyimide, perfluoropolymer = 10–30</td>
<td>Amine-based solvent absorption</td>
<td>Effect of impurities, plasticization</td>
</tr>
<tr>
<td>Water (H₂O)</td>
<td>&lt;120 ppm</td>
<td>Many &gt; 200</td>
<td>Glycol absorption</td>
<td>Pressure ratio limitations</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>&lt;4 vol.%</td>
<td>Perfluoropolymer = 2–3</td>
<td>Cryogenics</td>
<td>Low membrane selectivity</td>
</tr>
<tr>
<td>Heavy hydrocarbons (C₃+)</td>
<td>950–1050 Btu/scf, dew point, &lt;-20°C</td>
<td>Silicone rubber = 0.3</td>
<td>Refrigeration</td>
<td>Plasticization, low membrane selectivity</td>
</tr>
</tbody>
</table>

18.3.1.2 CO₂ Removal

CO₂ content in raw NG can be up to 20 vol.% with the desired pipeline spec being <2%. About 20% of the NG fields in the United States require acid gas removal [16]. The market for acid gas removal is expected to grow as lower-quality reserves with high CO₂ content are discovered and become economically viable. Membranes directly compete with absorption technology, which is commercially well proven in this application space. Membranes have proved to be advantageous compared to amine technology for high CO₂ concentrations (10%–20%), where relatively less maintenance and monitoring of operations are required (remote production sites), applications with space constraints (offshore gas processing), and low installation costs are required (small gas fields with 5–40 MM scfd production). Amine technology can however achieve almost complete removal of CO₂ from NG streams (<1%) with very low product (methane) loss of <2%–5%, which is the most critical factor in deciding the application of choice. Early membrane materials used in a single stage configuration were unable to meet this low hydrocarbon loss target, but with the advent of high CO₂ selectivity, robust membranes, and multistage process designs, the competitiveness of membranes has improved dramatically [17].

New materials with improved CO₂/CH₄ separation selectivity and membrane stability under realistic NG conditions have been developed; however, even after three decades of development, only three membrane material types have been commercialized: cellulose acetate–based Separex® (Honeywell’s UOP), Cynara® (Cameron) membranes, polyimide–based membranes from Medal® (Air Liquide) and Ube, and perfluoropolymer–based Z-top® membranes from Membrane Technology and Research, Inc. (MTR). The key reasons for the selection of the desired polymer for commercialization are the cost of material, ease of fabrication into commercially viable form, effect of impurities on membrane performance, and gas selectivity under realistic feed conditions.

High partial pressure CO₂, water vapor, and heavy hydrocarbon impurities in raw NG can absorb in the membrane causing plasticization [18]. Plasticization results in swelling of the polymer, increasing its chain mobility, and thus causing a sudden drop in membrane selectivity with increasing gas partial pressure [19]. Adequate membrane pretreatment, development of plasticization–resistant membranes, crosslinking strategies to stabilize membranes, and the use of polymeric materials less affected by plasticization are a few strategies proposed to reduce plasticization [20–23].

Membrane units are highly attractive for very small production wells (<5 million scfd) due to their low installation and operation costs. Simple, single-stage membrane design is used at this scale where the membrane unit separates CO₂ from the raw NG to achieve pipeline specification; however, 10%–15% methane is also lost in the permeate stream, which is often flared [2,24]. For small–scale systems (5–40 million scfd), two-stage membrane systems are used to reduce methane loss. In this gas flow range, amine and membrane systems compete with the final choice depending on site-specific factors. In a two-stage design, the permeate stream from the first membrane unit is compressed and passed through a second membrane unit to recover methane and minimize losses to <2%. The retentate from the second membrane unit, with significant amount of CO₂, is recycled to the feed of the first membrane unit [2]. Multiple stages can be added to achieve the desired NG composition for very high CO₂ content NG streams. For medium- to large-scale systems (more than 40 million scfd), membrane systems are considered less competitive compared to amine systems due to higher energy requirements and lower cost competitiveness. However, large NG sweetening projects using membrane technology have recently been announced [25,26].

The majority of a membrane system cost is associated with the large compressors required to pressurize the permeate stream and feed pretreatment operations required to remove heavy hydrocarbon and water vapor impurities; only about 10%–25% of the total system cost is associated with the membrane module [27]. Membranes for CO₂ removal applications are typically fabricated in either hollow fiber or spiral wound format. Hollow fiber approach has the advantage of greater membrane area per unit volume and greater operational flexibility and module fabrication cost [28].

With the size and growth of the NG market, it is expected that some novel polymeric membranes for CO₂ removal from NG will undergo pilot scale testing. In the near term, cellulose acetate–based membranes are expected to maintain their dominant position, with other membrane types increasing their market share due to their higher plasticization resistance properties [14].

18.3.1.3 C₅+, Hydrocarbon Removal

Raw NG is often saturated with C₅+, hydrocarbons such as propane, butane, and benzene, toluene, ethylbenzene, and xylene (BTEX) mixtures. These components need to be removed to reduce the NG dew point to meet pipeline specifications (−20°C). Heavy hydrocarbons if present in higher quantities, in associated gas (up to 10 vol.%), can be recovered and mixed with liquid oils and sold separately [29]. The current technology for C₅+, removal is refrigeration followed by condensation. The condensed liquids can be further separated by fractional distillation, to recover individual components. Current technology is expensive and hence there is an interest in exploring membrane technology [2,12].

Rubbery polymeric membranes fabricated on porous supports have been commercialized by MTR (VaporSep®) and GKSS [30]. Polydimethylsiloxane (PDMS) is the most recognized rubbery membrane for this application because it is cheap, is readily available, and has some of the highest permeabilities (C₅H₁₀ permeability ≈ 7500 Barrer) and reasonable selectivities (C₅H₁₀/CH₄ selectivity ≈ 4–6) [12,31,32]. Due to low membrane selectivities, a number of membrane stages and recycle streams are required to achieve significant heavy hydrocarbon recovery while minimizing methane loses. This makes processes based on PDMS inefficient for treating NG. A hybrid process design has been proposed.
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utilizing a single-membrane step to separate and concentrate the heavy hydrocarbons in the permeate stream [12]. The permeate stream is then compressed, followed by the condensation/removal of heavy hydrocarbons, with the high-pressure methane residue stream recirculated to the feed stream reducing the methane loss. Only a few novel membranes have shown highly selective, stable performance, and the currently available rubbery membranes are likely to remain dominant; however, the conventional refrigeration technology provides a stiff barrier for a broader membrane acceptance [14].

18.3.1.4 \( \text{N}_2 \) Removal

Around 14% of US NG has \( \text{N}_2 \) content higher than pipeline spec of <4% [2]. \( \text{N}_2 \) content in NG is reduced by dilution with low \( \text{N}_2 \) content NG or cryogenic distillation. However, cryogenic separations are capital intensive and practical for only large fields with 50–500 million scfd of gas production [12]. Membrane-based separations have a potential market for smaller-scale operations where cryogenic distillation is uneconomical.

For this separation, membranes can either be \( \text{N}_2 \) permeable or \( \text{CH}_4 \) permeable. Typically, glassy polymers are nitrogen permeable, while rubbery polymers are methane permeable [12,15]. For a 10% \( \text{N}_2 \) in \( \text{CH}_4 \) mixture, Baker has shown that a membrane requires a \( \text{CH}_4/\text{N}_2 \) selectivity of 6 (PDMS \( \text{CH}_4/\text{N}_2 \) selectivity ≈ 4) or a \( \text{N}_2/\text{CH}_4 \) selectivity of 17 (polyimide \( \text{N}_2/\text{CH}_4 \) selectivity ≈ 2) to achieve the same level of separation with a 4 vol.% \( \text{N}_2 \) in \( \text{CH}_4 \) product stream in a single-stage membrane [2]. A \( \text{CH}_4 \)-permeable rubbery membrane process remains most feasible, though requiring considerable recycling between multiple membrane units to improve methane recovery and recompression of the permeate methane for delivery to pipeline. The cost of recompression is not high enough to significantly impact the process economics at a small scale of operation and the process economics can be favorable, relative to both pressure swing adsorption (PSA) and cryogenic distillation [12]. The future for \( \text{N}_2 \) separation using membranes is with the development of more selective membranes (either \( \text{N}_2 \) or \( \text{CH}_4 \) permeable), finding use for the \( \text{N}_2 \)-rich gas stream, and improving methane recovery [14].

18.3.1.5 \( \text{H}_2\text{O} \) Removal

Water content of saturated NG is usually 1000 ppm. Concentrations less than about 100 ppm are needed to avoid hydrate formation and corrosion in downstream piping. The most widely used technology for water removal is glycol absorption [2]. Low cost, operational simplicity, and wide industry acceptance of glycol dehydration systems are stiff barriers to membrane acceptance. Even though membranes show very high \( \text{H}_2\text{O}/\text{CH}_4 \) selectivity >200, a significant amount of methane permeates the membrane due to pressure ratio limitations leading to methane loss with the permeating water. Just 1% loss making the process noncompetitive [13]. The partial pressure of water in the feed must be greater than that in the permeate stream; hence, the separation achieved is always smaller than the pressure ratio, regardless of membrane selectivity [2]. In order to improve the pressure ratio of the process, various schemes have been proposed: (1) operating at low permeate pressures by using a vacuum pump on the permeate side [2], (2) operating at atmospheric permeate pressure followed by recompression of the permeate gas and subsequent condensation of water vapor [15], and (3) using dry sweep gas on the permeate side to promote water permeation and reduce methane loss [33].

In the near future, it is unlikely that membranes will obtain a significant market share for water dehydration of NG because current commercial technologies are too well established and economical for membranes to compete. Since the membrane performance is limited by process design considerations, research and development (R&D) needs to focus on novel system designs, especially hybrid systems [14].

18.3.2 Air Filtration Applications

GTs are highly optimized machines that consume large quantities of air. An inlet air filtration system (AFS) is essential for the successful operation of a stationary GT for power generation. The filtration system protects the stationary GT from harmful debris in the ambient air, which can lead to issues such as FOD, erosion, fouling, and corrosion [34].

Air filtration is a mature technology. However, the continued advancement of GT technology has spurred advancements in the AFS, including the development of high-efficiency filters to improve compressor performance [35]. Modern-day filtration systems can comprise multiple filtration stages as shown in Figure 18.5. Each stage is selected based on the operating environment, GT technology, and quality of fuel. Membranes are typically used in the third stage of a multistage AFS and are described in greater detail. For detailed overview of AFSs, the reader is referred to other publications [35–37]. The configuration allows replacement of almost all filters while the GT is running without significant reduction of...

FIGURE 18.5 Multistage advanced air filtration system. (Adapted from Wilcox, M. et al., Int. J. Rotat. Machin., 2012, 2012.)
power over time. Other design factors to be considered are filter media type, media area, filter element dimensions, restriction/resistance to airflow (ΔP), particle removal (filtration) efficiency, dust holding capacity (DHC), and filter life [37].

AFSs typically have weather louvers that are effective in the removal of large objects or contaminants carried in the flow stream. Louvers are followed by screens to capture large pieces of paper, cardboard, bags, and other objects. The first stage of AFS uses inertial separators such as a demister vane or cyclone separators to remove entrained water droplets. Moisture coalescers are commonly installed downstream of the vane separator in environments with high concentration of liquid moisture in the air. The combination of vane/coalescer/vane is effective in the removal of particles >10 μm, water droplets, and wet salt [38].

The second stage of AFS consists of intermediate filters to remove dry impurities such as dust and dry salt in the 2–10 μm range that can cause erosion and FOD of GTs and lead to increased pressure loss and filter loading in the final high-efficiency filtration stage. Hydrophobic nonwoven filter media (e.g., spunbond, wet-laid media, and air-laid media) are typically used as intermediate filters to protect the final high-efficiency filter.

The third stage of AFS consists of high-efficiency filters for the removal of smaller particles (<2 μm), which lead to corrosion, fouling, and cooling passage plugging of GTs. Typically, microglass has been used as the conventional source for and preferred choice for these high-efficiency particulate air (HEPA) filtration media. The depth, tortuous pore structure, and high void volume of microglass media bring benefits of high efficiency, low pressure drop, and high dust loading capacities [39]. There is a trend to increase the filtration efficiency of this stage. Recently, expanded PTFE membrane and ultrahigh-molecular-weight polyethylene (UPE)-based materials have also been in use in the final stage. For low to medium dust load, static filters are used, while for high dust loads, self-cleaning pulse filters are preferred. Appropriate maintenance of the AFS is considered as important as the investment in a new system. Poor maintenance can result in leakage and degradation of the overall filtration efficiency [40].

Multistage AFS systems are highly efficient in the removal of solid and liquid impurities in air; however, vapors pose risks of accelerated GT corrosion. The development of filtration solutions for vapor removal remains an active area of research [41].

### 18.3.3 Water Intake Conditioning and Discharge Treatment

Water is a major input to electrical power generation. Globally, power generation trails only agriculture in water use for human activities [42]. Water is used for several purposes in thermal power plants including its use in cooling towers to remove waste heat, and its use as the working fluid in steam turbines and flue gas desulfurizers for the removal of wastewater residues. For each of these uses, the water quality must be carefully controlled to minimize scaling, fouling, or corrosion. Most power plants have a water treatment subsystem to treat intake water to meet system requirements. In addition, any discharge water must be treated to satisfy environmental regulations.

Figure 18.6 shows the power plant subsystem water flow paths for a typical steam turbine with two separate water circulation loops. In the working fluid loop, steam is generated in the boiler and then expanded through a steam turbine to generate electricity. Condensed water is returned to the boiler to be recirculated through the cycle. A small fraction of the condensate is purged as blowdown to prevent the buildup of solids. Makeup boiler feedwater is added to maintain sufficient fluid levels.

Table 18.3 shows a breakdown of the water requirements for the DOE base case NGCC and PC-fired power plants discussed in the previous section. Cooling tower use dominates the water demand with only a small fraction of water used for steam turbine makeup.

### TABLE 18.3

Specific Water Use for NG- and Coal-Fired Power Plants

<table>
<thead>
<tr>
<th></th>
<th>Water Demand (m³/min) [gpm]</th>
<th>Specific Water Demand (m³/MWh) [kgal/MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling tower</td>
<td>8.9 [2400]</td>
<td>1.0 [260]</td>
</tr>
<tr>
<td>Condenser makeup</td>
<td>0.1 [30]</td>
<td>0.01 [3]</td>
</tr>
<tr>
<td>Coal (subcritical)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling tower</td>
<td>20.5 [5500]</td>
<td>2.2 [600]</td>
</tr>
<tr>
<td>Condenser makeup</td>
<td>0.3 [80]</td>
<td>0.03 [9]</td>
</tr>
<tr>
<td>FGD makeup</td>
<td>3.9 [1050]</td>
<td>0.4 [10]</td>
</tr>
</tbody>
</table>

Membranes are a candidate technology for each of these applications. However, they are only used regularly in the treatment of boiler feedwater for steam turbine makeup application. The selection criterion is related more to the economics rather than performance. Each of these applications is examined in more detail to understand where membranes can be utilized and what developments are required for broader adoption.

### 18.3.3.1 Cooling Tower Water Treatment

Cooling loops can be designed as once-through and open recirculation. Once-through configurations use a single pass of water through the condenser heat exchanger (HX) before discharge. Discharge water is typically only a few degrees warmer than the intake water. This mode is favored when a large amount of water is available. Open-recirculating designs circulate water through a cooling tower with evaporation of only a fraction of water. Makeup water is added to the cooling loop to replace evaporation losses. This approach requires considerably less water, due to the large latent heat of vaporization of water. Since the evaporation of water increases the concentration of dissolved solids, a purge stream is also needed in this application.

In practice, open-recirculating systems are the most common mode of cooling. However, trade-offs exist between water usage and water treatment costs. The primary driver for cooling water treatment is the prevention of corrosion, scale formation, and fouling through the combined interactions of dissolved minerals, dissolved oxygen, and biological activity with the cooling tower materials [3,43]. These effects can be managed through blowdown, along with the use of chemical additives and/or filtration [44]. Figure 18.7 shows a simplified water balance for the cooling loop. Makeup water (M) is added to replace the evaporation losses (E), while blowdown (B) is removed to manage the build-up of minerals in the water. The total amount of water circulating in the tower is fixed (viz., \( M = E + B \)).

At the simplest level, the economics of cooling tower water treatment operations involve optimizing the blowdown rates against the maintenance costs. In the limit of high blowdown rates, the low recirculation minimizes scale formation. However, the high water flow rates result in higher costs for raw water and chemicals due to the low residence time in the system. Conversely, low blowdown rates result in a higher tendency for scaling and fouling thus offsetting the reduced water usage by higher maintenance costs. Today, membranes are generally not economically competitive as the primary approach for cooling tower water treatment applications is dominated by chemical additives.

Membranes have however attracted interest as part of hybrid treatment systems. Figure 18.8 shows a side stream filtration configuration where a portion of the water is filtered to help reduce the blowdown volumes while removing suspended solids. Suspended solids often act as a nutrient source for microbiological organisms; thus, reducing its content leads to reduced biological growth rates and biologically induced corrosion. Practically, the successful operation of a side stream filtration system is based on a number of factors including the relative flow of the side stream, the level of filtration, and integration of the side stream filter with other cooling tower management operations, such as chemical dosages. A recent study of several side stream filtration systems concluded that side stream filtration can be a viable option in some situations, but that further development is required to identify optimal operating parameters [46].

### 18.3.3.2 Steam Cycle Makeup Water

Makeup water requirements for the steam cycle are considerably smaller than those for the cooling tower. However, the water quality requirements are significantly more stringent, due to the more aggressive conditions encountered in the boiler. The most significant impurities are dissolved minerals and oils that can cause scaling in the boiler. The permissible amount of dissolved solids, silica and suspended solids, and the alkalinity/hardness depend on the operating conditions of the boiler. Higher-quality steam boilers have lower tolerance for impurities.

In most large thermal power plants, the sources of water are rivers or underground aquifers. Since these sources are relatively clean, only minor treatment is needed to remove suspended material and dissolved salts. In modern power plants, ion exchange (IX) is the most widely used technology for this purpose. IX systems remove dissolved ions through adsorption, with periodic regeneration to remove the ions, resulting in the production of saline brine [4]. These systems generally require low investment costs and are favored for relatively low salinity feedwater with less onerous restrictions on chemical waste disposal.

Reverse osmosis (RO) and electrodialysis (ED) membrane systems are also used with the state-of-the-art moving...
towards hybrid systems. Several designs have progressed to the pilot and commercial stage. RO systems use a semipermeable membrane to selectively remove dissolved ions. RO systems have comparatively higher investment costs; however, they are favored for brackish or seawater use as a boiler feed. Several pilot systems have been operated in the Middle East, including Jordan’s Rehab (200 m$^3$/day with 7 m$^3$/day used for boilers) and Al-Hussein (100 m$^3$/day with feeds containing 2200 ppm TDS) power plants and Iraq’s Hartha (100 m$^3$/day with river water with 3000 ppm TDS) power plant [47–49]. A recent pilot study comparing RO and IX for boiler feedwater treatment reported that RO systems would require about 50% more feedwater (lower water recovery) but were found to be economically favorable for feedwater with higher TDS [50].

ED systems comprise alternating stacks of anion- and cation-exchange membranes between two electrodes. An electrolyte solution between the membranes and ions is removed under the influence of the transverse electric field [45,51]. The process is suitable for industrial brackish water desalination of feed streams with salinity up to about 5000 mg/L TDS for plants with capacity in the range from about 100 to 20,000 m$^3$/day.

Hybrid systems have attracted interest in recent years due to their potential for reducing costs, decreasing environmental impact from discharge streams, and expanding the envelope of source waters that can be treated [52]. For example, electrodeionization (EDI) is a hybrid process involving ED and IX. In an EDI system, the space between the IX membranes is packed with IX resins. The addition of the resin improves the conductivity across the cell and allows the production of highly deionized water. EDI systems have attracted interest for boiler feedwater treatment applications [53]. Hybrid systems using combinations of RO and IX have also been piloted and commercialized [54].

The economics of boiler feedwater treatment are strongly dependent on local conditions, including the water quality and site-specific factors such as discharge regulations and financial assumptions. Tools have been developed by various governments and nonprofit and commercial entities to help with the economic analysis [49,50,55–57].

18.3.3.3 Flue Gas Desulfurization

Wastewater Treatment

Emission control systems in a power plant also require water. Flue gas desulfurization (FGD) systems in coal-fired power plants remove SO$_2$ from the exhaust flue gas by reacting it with lime or limestone in a wet scrubber system generating wastewater that must be treated before discharge. FGD wastewater treatment involves removal of the gypsum precipitate, adjustment of the pH, and the removal of any toxic dissolved metals. This is typically accomplished using a combination of gravity-driven processes, chemical flocculants, absorption, and biological processes. Membrane approaches are currently not economically competitive for this application [58].

18.3.3.4 Conclusion and Outlook

At present, membranes play an important, but limited, role in the treatment of water in thermal power plants. For the boiler feedwater application, there has been some interest in membranes for desalination of brackish feedwater. However, there are alternate, lower-cost options for the cooling tower water treatment and FGD wastewater treatment applications.

One development that may alter the technology landscape for cooling water and boiler feedwater treatment is the increased competition for water from municipal, agricultural, and industrial users. Combined with pressures on supply, more power plant operators are considering the use of lower-quality impaired water resources [59]. Examples of impaired water include brackish aquifers, produced water from hydrocarbon recovery operations, municipal waste, and...
Particulate matter (PM) is found in flue gas from PC power plants and in raw syngas from coal gasification. PM causes air pollution, and it is regulated by the U.S. EPA. PM<sub>2.5</sub> is a fine particle standard (<2.5 µm particles) with the 24 h emissions regulated at 35 µg/m<sup>3</sup>; PM<sub>10</sub> is a coarse particle standard (<10 µm particles) with the 24 h emissions regulated at 150 µg/m<sup>3</sup> [62].

A number of different techniques are available for the removal of particulates from gas emissions, including baghouses (also known as fabric filters), electrostatic precipitators (ESPs), and scrubbers. Figure 18.3 in the previous section shows the location of the baghouses with respect to other equipment in the overall power production system. Baghouses are highly effective (99.9%) in removing PM over a wide range of particle sizes as shown in Figure 18.9. Baghouse has lower installation costs compared to ESPs; however, operational expenses are higher due to higher pressure drops. There are a number of factors on which the choice of PM removal system depend on, including the CAPEX, pressure drop, energy use (or OPEX), reliability, and maintenance.

A baghouse typically consists of two separate single-stage, in-line, multicompartment units, with the bags supported by steel cages [11]. The PM collects on the outside of the bags. The gas molecules can pass through the filter, whereas the particulates are trapped on the surface of the filter. Large particles are separated by impaction or sieving, medium particles by direct interception, and small particles by diffusion [1]. In an alternate setup, reverse air bags are used. The PM collects on the inside of the bags in that case.

Expanded polytetrafluoroethylene (ePTFE) membrane-based bags are dominant as bag filter material and provide higher efficiency and the advantage of lower pressure drop by preventing dust migration into the media, as compared to nonmembrane bags. ePTFE is stable up to 260°C, enabling utility for numerous applications. However, there are certain challenges to the adoption of ePTFE-based membrane filtration, which have limited their adoption. ePTFE membranes act as surface filters due to minimal thickness, while most high-efficiency air filters require high dust handling capacity (DHC). ePTFE membranes are very thin by their nature (10–25 mm) causing manufacturing process variations and structural challenges [39]. Three key cleaning methods are utilized and are classified as shaker filtration, which uses physical agitation for cleaning; reverse gas fabric filtration (RGFF), which uses air pressure for cleaning; and pulse-jet fabric filtration (PJFF),

which uses air pulses for cleaning (Figure 18.10). PJFF has gained wider acceptance due to its smaller footprint with typical pressure drops of up to 8.5 in. Wg. RGFF provides the advantage of longer bag life of up to 6 years with typical pressure drops in the 4–11 in. Wg range [64].

A key research area is the study of the effect of selective catalytic reduction (SCR), selective noncatalytic reduction (SNCR), dry particulate adsorbent injection, and SO2 removal systems on the removal efficiency, pressure drop, and lifetime of the baghouses. The use of fabric filters in PC boilers is increasing every year due to the stringent particulate emission standards. Pennsylvania Power and Light was the first utility to install a baghouse in 1973, and up until 2005, more than 129 RGFFs were installed on ~28 GW of power plant capacities [64] (Figure 18.10).


18.4 ROLES FOR MEMBRANES: TOMORROW

The future of the power generation industry will be shaped by several factors including growing demand for electricity from an expanding global population, increasing standards of living, and increasing constraints imposed by environmental impact and fuel availability. In recent decades, concerns about greenhouse gas emissions and the long-term availability of fossil fuels have prompted investment in generation from renewable sources such as wind and solar power. CO2 capture technologies have also attracted attention. Several membrane-enabled concepts are at the advanced R&D and pilot stages and may find roles in future energy systems. This section reviews recent developments in the areas of air separation and CO2 capture.

One other area of note is the use of electrochemical membranes for power production and energy storage.
Electrochemical membranes are at the heart of some promising technologies for grid-scale energy management, such as high-energy solid electrolyte batteries, and more efficient and distributed generation through solid oxide fuel cells [65,66]. However, a detailed discussion of these topics is out of the scope of this chapter, and the interested readers are referred to other reviews on the subject [67].

The new technologies reviewed here involve significant changes to a simple thermal power plant. As such, detailed quantitative comparisons against existing baseline power plants are not within the scope of this review. The discussion will, however, explore how the system-level requirements translate into membrane-specific performance targets. Areas where sufficient performance exists will be highlighted, as well as areas where additional development is needed to satisfy performance requirements and improve process economics. Membrane technologies have shown feasibility for all the application areas; however, demonstration of the membrane technologies at a relatively large scale and cost competitiveness with first-generation commercial technologies are the biggest hurdles for acceptance.

### 18.4.1 Emission Management: CO₂ Separation Membranes

Climate change can have a significant impact on energy usage over the next decades with significant R&D investment globally to develop technologies for CO₂ capture and sequestration (CCS) or utilization for enhanced oil recovery (EOR). It is estimated that the capture systems represent over 75% of the total cost of CCS, and hence it is essential to both reduce the technical risks and reduce the costs [68]. Globally, coal-based power is the largest source of electricity generation and is forecast to remain so until around 2035. Unfortunately, coal-based power plants have one of the highest CO₂ emissions per unit energy produced (~0.32–0.35 tons/MWh) accounting for approximately 40% of global CO₂ emissions [69]. Three approaches to CO₂ capture have been proposed—postcombustion, precombustion, and oxy-fuel technologies [68,70].

The postcombustion technology involves CO₂ capture from power PC plant flue gas (CO₂/N₂ separations), and the precombustion technology involves CO₂ capture from integrated gasification combined cycle (IGCC) power plant syngas (H₂/CO₂ separations). The first-generation technology proposed for both these applications involves absorption (Rectisol® or Selexol™) [11]. The U.S. DOE predicts that the conventional absorption system used to capture 90% CO₂ will result in a capture cost of $40–100/ton CO₂, with around 80% increase in LCOE for postcombustion and around 30% for precombustion technology, respectively [11]. DOE has provided a target of <$10 tons for captured CO₂ with <5% increase in LCOE for postcombustion and <10% increase in LCOE for precombustion carbon capture technology for commercial deployment by 2035 [27,71]. Membrane-based separation systems are being actively considered for CO₂ capture, and the following sections provide system-level targets for membrane development and summarize the current membrane materials and technology developments.

#### 18.4.1.1 Membranes for Precombustion CO₂ Capture

The precombustion technology utilizes IGCC producing raw syngas from coal gasification in the presence of oxygen and steam followed by the removal of tar, particulates from raw syngas, and then water gas shift reactors to further convert CO and water to CO₂ and H₂ [68]. Proposed CO₂ removal membrane technology can be used to purify this syngas stream at 30–50 bar, 250°C–350°C, with a typical composition of 42 vol.% H₂, 31 vol.% CO₂, 24% H₂O, 0.9 vol.% CO, and small amounts of N₂, H₂S, and CH₄ [11]. The syngas is then burned with air and the produced hot exhaust gas is utilized to generate electricity.

High-temperature H₂-selective and ambient temperature CO₂-selective membranes have been proposed for this application [27]. H₂-selective membranes have the advantage of being operated at elevated temperature by integrating with or using immediately downstream of the low-temperature shift reactor, with the potential to improve the thermal efficiency of the process [69,72]. Permeation of water vapor along with the H₂ in the permeate stream leaves a dry high-pressure CO₂-enriched residue. N₂ from the air separation unit (ASU) is typically mixed with H₂ at the combustion turbine as a diluent to control flame temperature. Advantageously, the high-pressure N₂ can be used as a sweep to reduce energy requirements for recompression of permeated H₂ and improve the separation driving force [73,74]. It is desired to improve the H₂ recovery of the desired membrane process while also achieving >90% CO₂ capture. However, the benefits of improved efficiency associated with high H₂ recovery (>90%) are offset by the increased capital expense due to the large membrane areas needed to achieve the high membrane stage cut [69]. Because the CAPEX of the membrane is proportional to the area and the specific cost for the membrane, this trade-off can be partly mitigated by improving the membrane permeance, leading to a lower total area required to achieve a given H₂ recovery rate, or by reducing the specific cost of the membrane [69]. The fuel slip due to residual components of fuel value such as unpermeated H₂ along with unshifted CO, CH₄, and other components, can be recovered by using a catalytic oxidizer to combust the fuel slip producing steam to generate electricity using steam turbine or by overall heat integration (Figure 18.11). Alternatively, cryogenic condensation of CO₂-enriched residue to recover the uncondensed fuel slip components has also been considered [27].

For 90% CO₂ capture rate with 70%–90% H₂ recovery, an H₂/CO₂ selectivity between 20–60 and H₂ permeance of ~1000 GPU have been estimated for a single-stage membrane process [69]. Metal membranes are the leading candidates for high-purity H₂ production (H₂/CO₂ selectivity >1000), and due to their high-temperature stability, they are also considered for integration with the low-temperature water gas shift reactor [75,76]. Stability under the presence of sulfur and H₂ embrittlement remain active areas of research. Ceramic and
zeolite membranes have also received considerable attention and show high H$_2$/CO$_2$ selectivity $\sim$10 to 100; however, long-term stability under steam remains an area of research [76–78]. Polymeric membranes are advantageous from a manufacturability and scale-up economics viewpoint; however, lower H$_2$ permeance, H$_2$/CO$_2$ selectivity, and thermal stability require further investigation [79]. Advanced module designs, use of multiple membrane stages, and recycle of streams have been proposed to achieve the desired H$_2$ recovery [80–82]. Once candidate materials capable of achieving the necessary H$_2$/CO$_2$ selectivity have been achieved, optimization efforts should be focused on improving H$_2$/N$_2$ selectivity to prevent N$_2$ back diffusion into the retentate stream, improving the H$_2$ permeance to reduce membrane area and improving membrane stability under high-pressure syngas conditions and manufacturability at the scales needed for power plant applications [27,69].

18.4.1.2 Membranes for Postcombustion CO$_2$ Capture

The postcombustion technology utilizes a PC power plant where coal is burned in air in a boiler to make high-pressure steam utilized for power generation. The flue gas is then processed to remove particulates and SO$_x$ and then emitted to the atmosphere [11]. The proposed CO$_2$ capture membrane technology can be used to purify the flue gas stream after the FGD unit, which is at $\sim$1.05 bar, 50°C with a typical composition of 12 vol.% CO$_2$, 11 vol.% H$_2$O, 73 vol.% N$_2$, and 4.4 vol.% O$_2$ with <100 ppm of SO$_2$ and NO$_x$ [83]. The schematic diagram of a PC power plant is shown in Figure 18.3 with the location of desired flue gas capture technology. The low driving force due to low CO$_2$ feed concentration and ambient feed pressure pose challenges for membrane utilization [84]. Various techniques have been proposed to increase the CO$_2$ concentration in the feed gas including the use of O$_2$-enriched air (30–60 vol.% O$_2$) for coal combustion [85] and the use of combustion air as a sweep for CO$_2$ permeate [71]. Additionally, to improve the pressure ratio across the membrane, some feed compression ($\sim$2–3 bar) and partial permeate vacuum ($\sim$0.2 bar) have been proposed [71].

It has been estimated that to achieve $>$90% CO$_2$ capture with about $>$80% CO$_2$ recovery, membrane selectivity between 100 and 200 would be required for a single-stage membrane [71]. Liquid membranes have been proposed and extremely high selectivities (up to 4500) have been reported [86,87]. However, the effective permeance of the membranes under real operating conditions is difficult to estimate and stability over long time scale is a key issue. Polymeric membranes have shown the most promise in terms of scale-up and economics. However, for the CO$_2$/N$_2$ mixture, both experimental studies and theoretical computations come to the conclusion that a maximal selectivity of 70–80 can be achieved by physical separation membranes [88,89]. Hence, it can be concluded that a single-stage membrane will be unable to achieve the desired separation. Multiple membrane stages and recycle of streams have been proposed to achieve the desired CO$_2$ recovery [71,84,90]. Similar to precombustion membrane systems, economic trade-off between the benefits of improved efficiency associated with high CO$_2$ recovery is offset by the increased capital expense due to the large membrane areas needed to achieve the high CO$_2$ recovery. Polymeric materials with a selectivity of 50 and a permeance of 1000 GPU have been developed by MTR (Polaris™) and demonstrated at 1 MW pilot scale using a novel system design [71]. The development of high-permeance membranes ($\sim$4000 GPU or more) and reduction of membrane skid costs below $50/m^2$ need to be demonstrated to improve the membrane scenario [71]. Better understanding of the influence of flue gas minor components such as water vapor, SO$_2$, NO$_x$, and fly ash particles on membrane performance needs to be carefully studied [88].

18.4.2 Energy Efficiency: Air Separation Membranes

Air separation units (ASUs) separate nitrogen and oxygen from air for industrial and power generation applications. In power generation, oxygen can be used in a number of advanced cycles with potentially higher thermal efficiencies or fuel flexibility. Examples include gasification or oxygen-enriched...
conversion of coal to syngas for power production or chemical production. A number of different technologies can be used for air separation. Of these, cryogenic distillation, membrane separation, and pressure swing absorption (PSA) are the most commonly used (Table 18.4). In oxy-fuel technology, high-purity (95%) oxygen is utilized instead of air for coal combustion producing a high-purity CO₂ effluent, which after removal of water vapor can be used for sequestration or EOR applications. In some applications, oxygen-enriched air is utilized. Energy-efficient O₂/N₂ separations are the key enabling separation technologies for oxy-fuel approach with ion transport membranes (ITMs) being actively considered as a potential alternative to cryogenics [91].

Oxygen production using cryogenic separation is currently the most cost-effective technology when large volumes of production of separation gases are required. The world’s first air separation plant was started in 1902, and today more than 2800 plants are operated in more than 80 countries [93]. Membrane systems are usually used for the production of oxygen-enriched air and are used for smaller applications with ~20 TPD production capacities where CO₂ and water impurities can be tolerated by the overall system [92].

Air separation membranes are typically dense ceramic (typically perovskite) membranes, which selectively permeate oxygen in ionic form. Over the past two decades, Air Products (ITMs) and Praxair (oxygen transport membranes [OTMs]) have worked towards the commercial scale-up of these membranes for applications in power generation, gasification, and gas to liquid conversion [94]. Air Products has focused on a planar configuration, whereas Praxair on tubular membranes.

The proposed benefits of such technologies are related to lower oxygen production costs, lower usage of water compared to a typical cryogenic unit, smaller footprint, and fuel flexibility [94]. Typical inputs and outputs are shown in Figure 18.12. Depending on the exact chemical composition, ITMs operate in the range from 600°C to 900°C.

The main membrane parameters are the flux that dictates the membrane area required for a particular amount of oxygen production and selectivity that dictates the purity of oxygen produced. Both the ITMs and OTMs are highly selective and operate at high temperatures. The principle for separation is an electrochemically driven process. The O₂ is adsorbed at the surface, reacts to form O₂⁻ ions, and is transported through the ceramic membrane due to difference in chemical potential. The ions recombine into O₂ on the other side. N₂ is not allowed to pass through. The membrane also allows electrons to pass through and hence no external source of electricity is required. The end result is a hot O₂ stream and a hot pressurized N₂ (O₂ depleted) stream. Several major challenges have been overcome in the quest to commercialize these technologies. The manufacturability issues still exist, which include the following:

- **Defects**: Pinhole defects and cracks allow the passage of N₂. These pinhole defects cause the efficiency of the membrane to separate O₂ to fall significantly. The processing must be optimized to avoid the formation of these defects.
- **Coefficient of thermal expansion (CTE)-related problems**: Since the system is operated at elevated temperatures, residual stresses from CTE mismatch between the ceramic membrane and other materials of construction for the modules must be minimized to prevent cracking.
- **Other thermomechanical stress-related challenges**: The planar vs. tubular configurations lead to difference stress profiles that impact life.
- **Cost at scale**: Ceramic processing typically involves high temperatures, which requires expensive furnaces. Automation, lay-up, screen printing, tape casting, and laser machining have all been considered.

### 18.5 Outlook

Future investment in electricity production will need to balance the need for increased power generation against environmental constrictions such as the availability of water
and current and future emission standards. There will be significant opportunities for the introduction of a new technology to meet these dual challenges of efficiency and environment.

Fossil fuels will continue to play a significant role in power generation for the next few decades. Membrane technologies already play important roles in the conditioning of NG, air filtration, water treatment, and emission management. There is an active R&D in the areas of process intensification, air and water cleanup, and hybrid systems, and the prospects for the expanded use of membranes in each of these existing functions have already been discussed in each section. The most promising opportunities include the removal of CO₂ from NG and the conditioning of impaired water resources for cooling tower and boiler makeup and baghouse filters with improved efficiency.

For the longer term, several membrane-enabled concepts, including air separation membranes and CCS systems, are at advanced R&D and pilot stages. These tests will need to successfully demonstrate the performance, life, scalability, and economic competitiveness of these new approaches to ensure a role in next-generation power plants. To penetrate into these spaces, membrane systems will need to leverage their historical advantages in modularity and performance. This will be particularly true for membranes to become competitive in large-scale installations, where alternate technologies have traditionally enjoyed a cost advantage. In this regard, hybrid systems that combine existing membranes with an alternate separation technology can sometimes achieve performance and economics superior to each component option.

In order for membranes to expand further into existing application spaces, and compete in emerging ones, they must be both technically feasible and economically competitive. R&D can improve the performance and economics of membrane systems in several ways. This includes the development of novel membrane materials, improved manufacturing processes, and new system configurations. Each of these areas is ripe for progress.

Novel membrane materials with improved selectivities, permeabilities, or stability could alter the performance envelope for membrane systems, provided the right targets are met. Care must be taken to focus R&D efforts on the critical limitations for particular options. For example, improvements in selectivity for applications where the membrane performance is flux limited will have limited impact.

Manufacturing processes are a second area for innovation. Scale-up of new membrane materials from the lab to pilot scale is a nontrivial task. Robust coating processes, flexible packaging, and more effective quality control tools could all improve the manufacturing yields and costs associated with membrane systems. This could have an immediate impact in areas where membranes are a technically viable solution, but are not currently economically competitive with alternate separation technologies.

Finally, the design of new system configurations can offer improved performance and economics. One area ripe for innovation is the development of hybrid systems. In gas separation applications, the use of a membrane to achieve a low stage cut, followed by a second unit operation to achieve high purity, could offer benefits in energy requirement, system footprint, and cost over the stand-alone components.

A significant R&D effort is already being invested in achieving the breakthroughs needed for many of the applications in power generation described in this chapter. However, the greatest gains are expected from an integrated approach that combines all three areas. For example, integration between system design and material development can open up new performance envelopes. Similarly, module configurations can be designed with manufacturability in mind. Closer integration between lab and pilot scale systems during R&D can more closely link materials and manufacturing. Collaboration is already occurring in the membrane community between these areas, and further connections between researchers active in each of these areas can accelerate innovation in not just membranes in power generation but in other industries as well.

**ABBREVIATIONS**

- **µm** Micrometer (micron = 10⁻⁶ m)
- **AFS** Air filtration system
- **ASU** Air separation unit
- **BTEX** Benzene, toluene, ethylbenzene, and xylene
- **CAPEX** Capital costs
- **CC** Combined cycle
- **CCS** Carbon capture and sequestration
- **COE** Cost of electricity
- **CTE** Coefficient of thermal expansion
- **DOE** U.S. Department of Energy
- **ED** Electrodialysis
- **EDI** Electrodeionization
- **EIA** Energy Information Administration
- **e-PTFE** Expanded polytetrafluoroethylene
- **ESP** Electrostatic precipitator
- **FGD** Flue gas desulfurization
- **FOD** Foreign object damage
- **GPU** Gas permeation unit
- **GT** Gas turbine
- **GW** Gigawatt (1000 MW)
- **HEPA** High-efficiency particulate air
- **HX** Heat exchanger
- **ITM** Ion transport membrane
- **kW** Kilowatt (1000 watt)
- **kWh** Kilowatt-hour
- **LCOE** Levelized cost of electricity
- **M** 1000
- **m³/h** Meter cube/hour (= 35.3147 scfh)
- **mg/L** Milligram/liter
- **MM** Million
- **MT/h** 1000 ton/hour
- **MW** Megawatt (1000 kW)
- **MWₑ** Megawatt electric
- **MWh** Megawatt-hour
- **MWₜₜ** Megawatt thermal
Membranes in Power Generation

NG  Natural gas
NGCC  Natural gas combined cycle
O&M  Operation and maintenance
OPEX  Operating costs
OTM  Oxygen transport membrane
PC  Pulverized coal
PDMS  Polydimethylsiloxane
PJFF  Pulse-jet fabric filtration
ppm  Parts per million
PSA  Pressure swing absorption
PTFE  Polytetrafluoroethylene
PV  Photovoltaic
R&D  Research and development
RGFF  Reverse gas fabric filtration
RO  Reverse osmosis
scf  Standard cubic feet
scfd  Standard cubic feet per day
SCR  Selective catalytic reduction
SNCR  Selective noncatalytic reduction
TDS  Total dissolved solids
TPD  Ton per day
TW  Terawatt (1000 GW)
UPE  Ultrahigh-molecular-weight polyethylene
USD  US dollar
Wg  Water gage also water column or Wc
1 in. Wg (1 in. WC, 1 in. H₂O) = 25.4 mm H₂O = 0.036 psi
1 psi = 27.68 in. Wg (39.2°F)
1 bar = 14.5038 psi
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