KEY POINT: Total energy requirements for SWRO are dependent on feed water quality, permeate flux, recovery, membrane resistance, and energy efficiency of equipment.

SUMMARY OF ISSUES

Seawater desal is a very energy-intensive process. SWRO can require 6 times more energy than traditional treatment of surface water (Xu et al. 2009).

The RO process is predicated on the application of pressure to force water through a semi-permeable membrane against the natural osmotic gradient, resulting in a permeate stream very low in total dissolved solids (TDS) and a concentrate stream very high in TDS. Typically, pressures in the range of 1,000 psi must be continually applied to desalinate seawater using a single pass RO process, requiring the use of powerful and energy-intensive feed pumps.

Total energy consumption at RO facilities is much higher than the energy required to overcome the membrane’s osmotic pressure gradient. Total energy use is dependent on a number of plant and site-specific factors including (Veerapaneni et al. 2007):

- **Feed Water Quality.** Higher salinity and colder water requires more energy to desalinate than lower salinity, warmer water. Higher temperature feed water, such as cooling water from power plants, can significantly facilitate water permeability through membranes. Feedwater with lower salinity requires less osmotic pressure in the RO process. Both of these factors result in lower energy consumption.

- **Membrane permeability.** Higher membrane permeability (flux) requires less membrane surface area and fewer pressure vessels, which reduces capital costs. However, high flux membranes result in increased concentration polarization on the membrane surface. Polarization increases osmotic pressure requirements and results in excessive fouling, both of which increase energy demand (due to increased operating pressure requirements and chemical cleaning frequency).

- **Recovery.** Typically, 35 to 60 percent of the seawater fed into a membrane process is recovered as product water. The level of recovery has a significant impact on energy consumption. Increased recovery results in a corresponding increase in osmotic pressure, as well as an increase in concentration polarization. Although higher operating pressure is required for higher recovery, the amount of...
water that needs to be pressurized decreases with recovery. Optimal recovery rates vary based on feedwater quality and other site-specific conditions.

- In general, the energy consumption of SWRO alone varies between 8 to 12 kWh/kgal (2.1 to 3.2 kWh/m³). The energy consumption of the entire desal plant is typically greater than 16 kWh/kgal, including intake, pretreatment, and distribution (Veerapaneni et al. 2007).

- Although the high energy use associated with desal remains a significant issue, improvements in energy efficiency over the last 20 years (see STRATEGIES section below) have reduced the amount of thermal and pumping energy required for the various desal processes (NRC 2008).

- Renewable energy sources provide an opportunity to reduce the carbon footprint of desal plants. In some cases, independence from fossil fuels may also increase public support for a project (Xu et al. 2009).

- Currently wind energy holds the most potential as a renewable energy source and has been used for large desal plants in Australia (see case studies of Australian desal plants). More recently, the Beckton desal plant in London claimed the use of biodiesel to meet desal energy demand (BBCNews June 15, 2007).

- Recent increases in energy prices may make renewable energy more attractive for desal compared to conventional fossil fuels.

**STRATEGIES**

Energy use can be minimized through the use of commercially available equipment, including energy recovery devices, feed pumps, and centralized system design. Enhanced membrane technology and the use of renewable energy sources will also help to reduce overall (traditional) energy use and offset the carbon footprint associated with desal.

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1 Energy usage values should be taken cautiously because the "system" for which desal energy use is calculated and reported (i.e., basic RO process only, or including other ancillary equipment or processes) varies in the literature.
Energy recovery devices (ERDs)

A key reason behind improvements in the energy efficiency of seawater RO systems has been the development of highly efficient energy recovery devices that capture the energy resident in the concentrate stream of the RO process. Due to low net recoveries of the highly pressurized feedwater, 40 to 60 percent of the energy applied in the RO process can be lost if the concentrate is discharged without any attempt to recover that energy. In general, energy recovery devices can recover 75 to 98 percent of the input energy in the concentrate stream of a seawater RO plant (Stover and Cameron 2007). A number of energy recovery devices (EDRs) have been developed to recover energy from brine stream (Figure 1). These ERD systems can be divided into two general categories: centrifugal and pressure exchange devices.

Figure 1. Development of ERDs

Centrifugal ERDs include Francis turbines (also known as reverse running pump), Pelton turbines, and hydraulic turbochargers. These devices transfer concentrate pressure to mechanical power and then back to feed pressure. Centrifugal ERDs are in the form of a turbine, driven by the brine stream and attached to a shaft common to a pump or an electric motor. As shown in Figure 1, the first ERDs deployed in municipal SWRO plants were Francis turbines. In the 1990s, Francis turbines were taken over by Pelton turbines, which operate at higher efficiency are more simple to implement, and are more reliable. The net efficiency with which the Pelton turbines transfer energy can reach as high as 80 percent (Stover and Cameron 2007). Hydraulic turbochargers provide similar performance to Pelton turbine ERD systems.
The 13.2 mgd (50,000 m³/d) SWRO plant in Fukuoka, Japan, which initially had no ERD system, was retrofitted with a Pelton turbine. The Pelton turbine reduced SWRO energy consumption from 19.76 to 15.3 kWh/kgal (5.10 to 3.96 kWh/m³). The turbine now operates at about 81 percent efficiency, resulting a net transfer efficiency of 65.4 percent (Stover and Cameron 2007).

**Pressure exchange devices** transfer the concentrate pressure directly to the feed stream (i.e., pressure exchanger). These positive displacement technologies, such as the Energy Recovery Inc. Pressure Exchanger and Desalco Work Exchange, were developed to avoid efficiency losses associated with energy transformation inherent in centrifugal devices. These devices place the concentrate and feedwater in direct contact in pressure-equalizing or “isobaric” chambers resulting in net transfer efficiencies approaching 98 percent (Stover and Cameron 2007).

Most SWRO plants built after 2002 utilize pressure exchange ERDs. For example, the Ashkelon desal plant uses double work exchanger energy recovery (DWEER) to recover energy from concentrate (Stover and Cameron 2007). The Perth I desal plant uses Isobaric pressure exchange (PX) ERDs from Energy Recovery Inc. Some SWRO plants in Spain and the Caribbean that formerly use Pelton turbines have been retrofitted with isobaric devices (Stover and Cameron 2007).

Table 1, on the following page, provides a comparison of the Peloton turbine and a pressure exchanger device, including advantages and disadvantages associated with each approach.
Table 1. Comparison of ERDs between Pelton turbine and pressure exchanger

<table>
<thead>
<tr>
<th>Description</th>
<th>Pelton turbine</th>
<th>Pressure exchanger (PX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Transfers hydraulic pressure of RO concentrate to drive high-pressure pump. No booster pump required</td>
<td>Places concentrate and feedwater in direct contact in pressure-equalizing (“isobaric”) chambers. Pressurized feedwater from the ERDs combines with the discharge of the high-pressure pump to feed the membranes. Booster pump is required to circulate high-pressure water through the membranes and the ERDs.</td>
</tr>
<tr>
<td>Net energy transfer efficiency</td>
<td>80%</td>
<td>98%</td>
</tr>
<tr>
<td>Concentrate disposal</td>
<td>Pelton pump must discharge at atmospheric pressure, and a concentrate disposal pump may be required.</td>
<td>Isobaric ERDs discharge at pressures greater than atmospheric pressure, so a brine disposal pump is not typically required</td>
</tr>
<tr>
<td>Performance</td>
<td>Design is often optimized for a particular operating window. Flow changes can significantly reduce device efficiency.</td>
<td>Isobaric ERDs decouple the ERD and high-pressure pump. Performance varies little with water recovery, flow rate or pressure.</td>
</tr>
<tr>
<td>Ease of operation</td>
<td>Both are easy to operate, are flow-driven, and self-adjusting to changes in flow rates. Operators are generally more familiar with Pelton turbines</td>
<td>Both have a strong track record for reliability. Close to 100% uptime expected.</td>
</tr>
<tr>
<td>Reliability</td>
<td>Both have a strong track record for reliability. Close to 100% uptime expected.</td>
<td>Both have a strong track record for reliability. Close to 100% uptime expected.</td>
</tr>
<tr>
<td>Impact on feed water</td>
<td>No impact on feedwater quality or flow rate because brine and feedwater are kept separate.</td>
<td>Because feedwater and brine streams are mixed, feedwater concentration and flow rate increase prior to RO.</td>
</tr>
<tr>
<td>Fail-safe operation and redundancy</td>
<td>Failure of a turbine requires immediate shutdown of the RO train or significant operating cost increase.</td>
<td>For mid and large SWRO trains, PX devices can be arrayed in parallel. One rotor out of service has minimal impact on membrane performance. Plant can continue running until service is performed.</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Require periodic changes of seals and bearings.</td>
<td>Require no periodic maintenance and no service of seals or bearings</td>
</tr>
<tr>
<td>Device life</td>
<td>Turbines typically made with stainless steel alloys which offer resilience against debris damage. Like other stainless steel equipment in plant, the metal may corrode, wear and fatigue.</td>
<td>Pressure transfer occurs in a ceramic rotor enclosed in ceramic components. Ceramic is more brittle than most metals, but three times harder than stainless steel, and it never corrodes in seawater.</td>
</tr>
</tbody>
</table>

Source: Information extracted from Stover and Cameron 2007
As presented in Table 1, centrifugal ERDs are limited in capacity and have a maximum net transfer efficiency of approximately 80%. Furthermore, these devices are usually optimized for narrow ranges of flows and pressures; their efficiency declines with seasonal or operational changes.

While the pressure exchangers offer higher efficiency, the equipment costs are also comparatively higher than in the indirect device group. The advantage of one approach over another depends on several factors such as feed water salinity, RO system design and operation, unit energy costs, project capacity, projected lifetime, performance, and ease of operation and maintenance. For example, if energy is a critical issue to overall operating costs, the higher-efficiency pressure-work exchangers often will be the device of choice. However, if the project costs are dominated by the capital expenditures, today’s pressure-work exchangers have a disadvantage due to their higher equipment costs and current component size limitations (that is, multiple units may be needed at large scales).

**High Pressure Pumps**

Significant energy efficiency can be achieved by optimizing the specific speed of the high pressure pumps (Veerapaneni et al. 2007). For large desal plants, feed water flow can be increased by centralized RO feed pumps that feed either larger skids or several smaller skids. A large high-pressure pump has a significant advantage in pumping efficiency and cuts total cost of equipment and maintenance expenses (Liberman and Liberman 2000).

**Centralized System Design**

High pressure pumps and energy recovery systems can be designed as a “pressure center” (rather than operating independently) for potentially greater system efficiency and flexibility. A centralized system design is utilized at the Ashkelon SWRO Desalination Plant. Four high-pressure pumps are used to supply seawater to the RO trains in each half of the plant through a common line (one of the four pumps is installed as stand-by). Forty DWEER units in the energy recovery center receive pressurized concentrate from all of the RO trains and transfer the energy to the RO feed water. The pressurized feed water is then pumped to the RO trains through a common feed line. This approach allows optimization of each system independently. Pump efficiency is a function of capacity and in the Ashkelon plant, maximum pump efficiency can reach 88.5% (Liberman, Figon and David Hefer 2005).
Enhanced membrane efficiency

To fully utilize the capacity of high-permeability RO membranes, and to accommodate the use of even more permeable RO membranes in the future, it is imperative to reduce fouling and concentration polarization effects and to develop new module configurations and system designs to avoid or overcome thermodynamic restriction.

Currently, the most direct and effective way to protect against membrane fouling is with effective pretreatment to remove suspended/colloidal matter and dissolved organic matter. As an alternative to fouling-resistant membranes, fouled membranes that could be cleaned easily with low-cost oxidants (e.g., chlorine) would be desirable. However, RO membranes cannot tolerate oxidants such as free chlorine, and they require chlorine removal from the feedwater before being processed by the RO modules.

In recent years improvements in membrane technology have significantly reduced fouling. Membranes have shifted from the original cellulose acetate membranes to thin-film composite (TFC) membranes. In the past few years, several variations of TFC membranes have been commercialized in an attempt to reduce fouling. Many of these developments have resulted from the addition of polymer to smooth the surface or surface modifications such as addition of different functional groups to change the surface charge. While these improvements reduce fouling, truly fouling-resistant membranes are yet to be realized. Thus, opportunities exist to modify existing or create new membrane formulations or alter surface characteristics to reduce fouling.

Improvements in module design have also improved efficiency. For example, the Long Beach Water Department in California (LBWD) has developed a two-pass nanofiltration (NF/NF) process for seawater desal (LBWD 2009). The NF/NF process is arranged in two pass configuration with Pass 1 NF vessel permeate used as feed for Pass 2 NF vessel. The LBWD estimated that the NF/NF process could save 20-30 percent energy as compared to SWRO. An 0.3 mgd (1,136 m$^3$/d) demonstration-scale testing is being conducted to compare the two pass NF/NF process with conventional SWRO.

Renewable Energy

The relatively extensive carbon footprint of desal compared to conventional water supply options may make desal unfavorable. Independence of fossil fuel energy sources, through the use of renewable energy sources unassociated with greenhouse gas emissions could be highly favorable for desal in the public’s view. As a result, renewable energy has been declared to power the majority of the large-scale desal plants in Australia and UK. The development of renewable energy has become a more important component of desal investment.
Several alternative energy sources hold promise for desal in remote offgrid areas (García-Rodríguez 2003; Tzen, Theofilloyianakos and Kologios 2008; NRC 2008). These include photovoltaic (Richards and Schäfer 2003) and heat-driven processes, such as direct solar evaporation (Trieb and Müller-Steinhagen 2008; Trieb et al. 2009), closed geothermal (Bourounia, Deronzierb and Tadrista 1999), ocean thermal energy conversion, and salinity-gradient solar ponds (Lu, Walton and Swift 2001).

Although generally valued by the public, the costs associated with renewable energy to support desal can be significant (and can actually increase overall desal costs). Exploitation of renewable energy and development of desal plants typically requires intensive capital investments. There are also limitations related to the temporal and spatial dependency of renewable resources (including associated high land requirements) (Mathioulakis, Belessiotis and Delyannis 2007). The design of combined plants must take into account a number of local parameters, including geographical conditions, topography of the site, capacity, type of energy available at low cost, availability of infrastructure (including electricity grid), plant size, and feed water quality.

The Kwinana SWRO plant in Perth is the largest facility of its kind in the world to be powered by renewable energy credits (Stover and Crisp 2008). Electricity for the desal plant, which has an overall 24 MW requirement and a production demand of 15.5 to 23.3 kWh/kgal (4.0 to 6.0 kWh/m³), from the 83 MW Emu Downs Wind Farm (operated since 2006). Similarly, the Kurnell SWRO desal plant in Sydney entered a renewable energy supply agreement in which the plant would be powered by wind energy from the new 132 MW Capitol Wind Farm (SydneyWater 2008).

In California, Poseidon Resources Corporation committed the Carlsbad desal facility to be the first major California infrastructure project to go carbon neutral (Poseidon 2007). Onsite carbon footprint reduction measures for the Carlsbad desal plant will be achieved by applying high efficiency energy recovery devices, green construction of the desal plant, use of on-site solar power generation, CO₂ sequestration for post-treatment applications, energy reductions in supplemental water reclamation treatment, and sequestration of coastal wetlands. Overall, the associated annual emissions savings from onsite mitigation efforts is approximately 13,190 to 13,431 metric tons of CO₂ per year (Poseidon 2008). For more information see the case study of the Carlsbad desal facility.

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BENEFITS & COSTS

Benefits

- The reduction in SWRO energy use in the past 20 years has had a significant and direct effect on operating costs.
- Renewable energy sources provide an opportunity to reduce the carbon footprint of desal plants.
- In some cases, independence from fossil fuels may also increase public support for a project.

Costs

- The high energy requirement of desal still remains a significant issue. One of the major hurdles to desal implementation is high energy intensity and associated costs.
- The energy consumption of seawater desal can account for 44 percent of the total annualized SWRO cost (Miller 2003), and 50 percent of annual operating costs (Veerapaneni et al. 2007). Reducing energy consumption holds the greatest economic potential to reduce the total desal cost (NAS 2008).
- Desal processes can result in substantial greenhouse gas emissions, increasing public concerns (and decreasing public support) over implications for climate change.
- With recent cost decreases in renewable energy, and cost increases in conventional energy sources, the use of renewable energy sources for desal will likely increase.

KEY UNCERTAINTIES

Practical Limits to Energy Efficiency of RO

In the 2008 report, Desalination: A National Perspective, the National Research Council (NRC), Committee on Advancing Desalination Technology concludes that the practical upper limit of energy savings that can be realized through advances in RO membranes is approximately 15 percent (NRC 2008). This estimate was made by assuming a system operating at 40 percent recovery with a 95 percent energy recovery device and a new advanced seawater RO membrane...
with twice the permeability of today’s best available membranes while not sacrificing salt rejection characteristics—a huge advancement above today’s best available technology.

This simple analysis implies that the RO process is approaching a state of diminishing returns as it relates to energy usage. Improvements in module design that enable operation at higher fluxes appears to have the greatest potential for reducing the overall operating costs of desal because the capital costs and energy costs per cubic meter of permeate produced would simultaneously be reduced. Alternatively, a breakthrough in an alternate technology to RO may allow even greater energy savings.

NRC (2008) also identified the following energy-research needs:

- Configurations and applications for desal to utilize low-grade or waste heat
- Impact of future energy prices on existing desal technology over time, including evaluation of the costs and benefits of capital investments in renewable energy sources.
- Approaches for integrating renewable energy with desal

ADDITIONAL RESOURCES


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