Seawater Desalination for Municipal Water Production

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Selected Paper prepared for presentation at the Southern Agricultural Economics Association Annual Meeting, Corpus Christi, TX, February 5-8, 2011

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Abstract

This paper examines the optimal allocation of several inputs in the context of seawater desalination by reverse osmosis (RO) as a source of municipal (or commercial or industrial) water. A cost-minimization model is developed, a production function is estimated, and sensitivity analyses are conducted using the optimization model to investigate the effect of environmental conditions and economic factors on the optimal input portfolio and the cost of operating a modeled seawater desalination facility. The objectives of this paper are to better understand the effect on the seawater desalination facility's costs and input portfolio from changes in water quality, membrane lifespan, daily operations schedule, and energy prices. Findings include that lower total facility costs are associated with warm-weather water quality parameters, longer membrane life, and mid-range daily operations schedule (14.265 hours/day). Under most conditions, an interruptible power supply regime reduces facility costs. Exceptions include when the interruptible power supply regime implies significant reductions in operating hours and the associated reduction in energy price is very small.

Introduction

Policy solutions to water scarcity are frequently divided into the two paradigms of supply enhancement and demand management. According to many, the era of supply enhancement is drawing to an end and the era of demand management is gaining momentum. Around densely populated cities like New York, Atlanta, or Los Angeles, most of the potential regional supply enhancement projects have already been constructed. For coastal cities, the alternative of seawater desalination remains, but seawater desalination is a relatively expensive water supply alternative. Nevertheless, interest in desalination has prompted feasibility and pilot studies in many, if not most, major coastal cities experiencing water scarcity. Using performance data from one such seawater desalination pilot study and a constructed model of a seawater desalination facility's behavior, this paper investigates the economic consequences imposed on a modeled seawater desalination facility from changes in environmental conditions, operations costs, and capital replacement costs.

Several production technologies exist for seawater desalination. Currently, the most commonly considered technology in the United States is reverse osmosis (RO), a process by which seawater is extracted from the ocean, pressurized, and passed through a set of RO membranes. The RO membranes separate the untreated seawater, also called the feed water, into two streams. One of the two streams is the fresh water, or permeate, that is eventually distributed to water consumers. The second stream is highly-saline brine, or concentrate, that is eventually returned to the ocean. The ratio of permeate to feed water is often referred to as the recovery rate. Typical recovery rates for seawater desalination by RO are between 40% and 60%. The majority of energy expenses at a seawater desalination facility are incurred to pressurize the feed water stream prior to the RO system. While the recovery rate is primarily dictated by the amount of pressure applied to the feed stream (the greater the pressure, the greater the recovery), other environmental conditions may influence the recovery rate and, in turn, may also affect the pressures, energy consumed, and energy costs associated with producing desalinated seawater.

Environmental conditions vary across space. Seawater closer to the north and south poles is, on average, cooler than seawater nearer to equatorial regions. In the United States, seawater from the Pacific coast is cooler than that from the same latitude of the Atlantic coast, due in part to the effects of the Gulf Stream. Moreover, these water conditions are not entirely static, considering the dynamic changes that may occur in the oceans as a consequence of global climate change. The model's response to environmental conditions sheds light on to the magnitude and the direction of cost changes as the potential locations of seawater desalination facilities are considered by state and local water managers.

In addition to conditions imposed on the facility by the natural environment, the human-made economic environment can imposes input prices on the facility. These prices, like environmental conditions, vary across space. Labor unions are more widespread across the northern US than in the south. This implies that labor costs, included in our model as a component of hourly operations costs, will vary across locales. In this paper, we show that higher hourly operations costs result in optimal input portfolios that are greater in capital and, naturally, lower in hours of daily operations. This implies that facility design and management scheme that is based on a default daily operation schedule of 16, 20, or 24 hours may be sub-optimal if the costs of hourly operations were ignored during the initial design and planning stages of the facility.

During their useful life, RO membrane performance declines due to exposure to fouling agents in the feed water. Eventually, these membranes become unusable and must be replace. The paper explores the economic consequences to the modeled desalination facility of varying lifespans of RO membranes. Energy costs are also investigated. In particular, the benefits of adopting an interruptible power supply scheme, under most realistic conditions, seems to be an economically prudent design-management decision. The paper proceeds with the following sections: literature review, discussion of data, economic methodology, results, and conclusion.

Literature Review

For many years, engineers have reduced the costs of water production by desalination. Reductions in the cost of desalination are demonstrated by Zhou and Tol (2005) for RO as well as for a variety of other desalination technologies. Wilf and Bartels (2005) cite several recent examples of seawater desalination facilities where the "water price" (i.e., the average cost of production per unit of water) has been decreased from about \$1.90/m^3 to about \$0.55/m^3 from 1988 to 2000. Wilf and Bartels cite eight items as the causes of these cost reductions; among the causes are: the use of optimized RO system recovery rates, the use of power plant cooling water as feed to the RO system, better performance from newer generation RO membranes, and variable speed drives. Variable speed drives allow high-pressure pumps in RO systems to operate at variable levels, allowing water production rates to vary with time as required by the system operator. The largest component of the total costs for seawater desalinated water are amortized payments on equipment (i.e., capital) at 48% of the total cost and electric power at 33% of total cost (Wilf and Bartels 2005).

Reducing energy consumption is a mainstay of efforts to reduce the costs of seawater desalination. Veerapaneni et al. (2007) describe new technologies for seawater desalination facilities in terms of the new technology's contribution to lower energy consumption at the RO system. For example, newer subsurface raw water intake structures, such as beach wells and filtration galleries, contribute to average cost reductions because those structures provide partially pre-filtered raw water, which do not foul the RO membranes as quickly as would be the case with traditional intake structures. Similarly, more recently developed pretreatment systems, including microfiltration and ultrafiltration systems, deliver higher quality water to the RO system than older generation pretreatment systems or no pretreatment system. Both improved raw water intake systems and pretreatment systems delivering higher quality water to the RO system contribute to lower RO system operating pressures and lower energy consumption of the RO system (Veerapaneni et al. 2007).

Modern RO membranes that allow greater water passage at lower system pressures can be used to reduce energy consumption by running an RO system at a lower operating pressure or can reduce capital cost of the RO system by using fewer membranes and running the fewer membranes at higher, or normal, pressures (Busch and Michols 2004). Capital savings from implementing RO membranes with greater water passage may come as downsized high-pressure pumps, downsized variable speed drives and reduced piping (Nemeth 1998).

Data

This paper uses experimental data from the Texas Seawater Desalination Demonstration Project (NRS Consulting Engineers 2008), a seawater desalination pilot project located on the Port of Brownsville Ship Channel near Brownsville, Texas (hereafter, Pilot). The Pilot was a jointly managed project involving the efforts of the local public water-service provider, the Brownsville Public Utilities Board (BPUB), the Port of Brownsville, the Texas Water Development Board, and NRS Consulting Engineers. The Pilot operated from February 2007 to July 2008, recording data on a raw water intake system, three prescreening systems, four pretreatment systems, and the RO system, using three different types of RO membrane. The operational data gathered from one of those sets of membranes that were in operation at the Pilot from January 2008 to July 2008 are used in this paper.

During the Pilot operations, the membranes were subject to several trial-periods called stages, following the protocols of the Texas Commission on Environmental Quality (TCEQ), which require the collection of a variety of water quality data and system performance data (NRS Consulting Engineers 2008). The data used in this paper include feed water temperature, feed water salinity, and system operating pressure, among others. These data are summarized in Table 1 for the entire RO membrane pilot run, and also separated into warm season and cool season summary statistics. Each TCEQ stage concluded with a cleaning of the membrane system, also called a membrane regeneration event or a clean-in-place (CIP) (NRS Consulting Engineers 2008). The operating time between each CIP is used as a proxy to estimate membrane fouling rates.

Methodology

Economic Model

Large municipal water suppliers are frequently organized as publicly-owned utility service providers. For example, BPUB is a public utility organization that provides the residents of the City of Brownsville with electrical and water services. Institutions like BPUB are typically subject to some sort of public oversight and/or public administration of service rates. This attribute of publically-owned water-services motivated the use of a cost-minimization framework, in lieu of a profit-maximization framework. Essentially, the decision being modeled in this paper is that of a single facility designer-manager, whose decisions are assumed to be independent of any retail or wholesale water price. The facility designer-manager is tasked with producing a set volume of water as inexpensively as possible, drawing from a set of potential inputs that include: energy, hours of operation, and capital for the RO system.

Table 1. RO Performance data and feed water quality data summary statistics for the Brownsville Seawater Desalination Demonstration Project.

Variable		unit	Obs	Mean	Std. Dev.	Min	Max
October 2007 to June 2008 (all seasons)							
recovery	r	rate	404	0.4922	0.0077	0.4755	0.5216
temperature	C	°C	405	22.409	3.482	14.111	30.278
salinity	s	mg/L	405	32,108	1,518	27,914	36,357
feed pressure	b	psi	405	822.83	28.52	743.00	918.00
May 2008 (warm season)							
recovery	R	rate	31	0.4874	0.0028	0.4847	0.4939
temperature	C	°C	32	28.196	1.291	26.167	30.278
salinity	S	tds	32	30,907	735	29,098	32,697
feed pressure	B	psi	32	797.38	23.21	744.00	851.00
January 2008 (cool season)							
recovery	R	rate	55	0.4870	0.0032	0.4801	0.4924
temperature	C	°C	55	17.203	1.679	14.111	21.389
salinity	s	tds	55	32,220	1,499	28,207	33,734
feed pressure	b	psi	55	827.36	18.20	767.00	850.00

The objective function is the annuity-equivalent (AE) of the total cost stream's net present value, following Rister et. al (2009). The total cost AE is annual cost of owning and operating a given set of inputs.

(1) $\min_{b,h,k} AE_{TotalCost}(b,h,k),$

Subject to:

(2) $q_f r(b,s,C)kh \geq \bar{q}$, and
(3) $r(b,s,C,FDF) = f(b,s,C,FDF),$

where the facility inputs include: k, the number of RO trains; b, the operating pressure of the system, and h, the hours of the facility is in operation each day. The first constraint (2) is a daily production requirement, ensuring the system's daily water production meets or exceeds $\bar{q}$. Daily water production is calculated from the daily water production rate of an individual RO train, equal to the rate of feed flow q_f multiplied by the portion of feed flow that is the recovered recovery rate, $r(e,s,F)$. The per-train daily water production rate is multiplied by the number of trains, k, and the hours, h, of the day the facility is in operation. Because this specification is such that production capacity is a linear product of the amount of RO system capital (i.e., the number of trains), constant economies of size with respect to capital, k, are assumed. This assumption is plausible, given RO technology has been shown to exhibit constant elasticities of size (Boyer et al. 2010). The second constraint is the production function, also called the recovery function, which is some function of operating pressure, b; feed water quality, salinity, s, and temperature, C; and the membrane's rate of fouling which is called the flux decline factor, FDF.

The objective function is composed of the summation of the AE costs of the following sub-components: capital, membrane replacement, energy, and hourly operations, as shown in equation (4):

(4) $AE_{TotalCost}(b, h, k) = AE_k(k) + AE_m + AE_e(b, k, h) + AE_h(h).$

Each input's AE is a function of the level of the input (i.e., the level of b, h, k) multiplied the per-unit price of a each input. Per-unit input prices are denoted with z, such that the per-unit input prices for capital, membranes, energy, and hours of operation are, respectively, z_k, z_m, z_b, and z_h. Since input prices are constant no matter the amount of each input used. An implicit assumption of this specification is that the modeled facility is a price-taker of all inputs and no economies of scale exist with respect to input purchases.

Additionally, this specification does not account for the effect of hours of operations on membrane life, i.e., $AE_m \neq f(h)$. Likely, membrane life depends to some degree on operational hours as well as feed water quality, such as turbidity, and operational parameters, such as pressure. For this paper, the study of the effect of membrane life on the costs of a seawater desalination facility are limited to sensitivity analyses, where a set of possible membrane lifespans are exogenously imposed.

Production function estimation results and selection

The production function is modeled with three different specifications. The specification that we denote as the one-required-input (or ori) production function is partially inspired by Wilf and Bartels (2005), who describe the effectiveness of the energy input as a function of feed water salinity, temperature, membrane fouling and membrane compaction. The last two parameters are usually bundled together into a "flux decline factor" (FDF), which captures reductions in membrane permeability with time (Wilf and Bartels 2005). These statement implies the following form:

(5) $r_{ori} = \Gamma e,$

where e is the RO system feed pressure and Γ is the effect of pressure on recovery and is a function of salinity, temperature, and the FDF. This specification is named the one-required-input because, assuming the coefficient on energy is positive, the energy input is the only input which must be greater than zero to ensure that some measure of production will occur. The one-required-input specification for RO system recovery is the following:

(6) $r_{ori} = (\alpha_{\mathrm{e}} + \alpha_s \mathrm{s} + \alpha_C \mathrm{C} + \alpha_{FDF} \ln t_1)e + u.$

The purpose of the production function is to be able to estimate the effect of water quality variables (i.e., salinity and temperature) on the energy input (pressure) while controlling for the FDF. Since the FDF is not directly measured, a proxy is used: t_1, which refers to the amount of system runtime since the last membrane-regenerating event, or clean-in-place (CIP).

Other production functions are also investigated, including the Cobb-Douglas (7) and the Linear (8):

(7) $r_{cd} = \alpha_0 e^{\alpha_e} s^{\alpha_s} C^{\alpha_C} {t_1}^{\alpha_{FDF}} u$

(8) $r_l = \alpha_0 + \alpha_e e + \alpha_s s + \alpha_C C + \alpha_{FDF} t_1 + u.$

Coefficient values and p-values for the estimated production functions are reported in Table 2. The production functions' response to changes in each of the variables (except for FDF) are presented in Figure 1. Many of the estimated coefficients are significant and exhibit reasonable characteristics. For example, in all three specifications, the coefficients on energy and temperature are positive, and the coefficients on salinity and flux-decline are negative. While the R^2 values for all three specifications are reasonable, the one-required-input specification outperforms the others in explanatory power.

Table 2. Estimation results for the production function (or recovery function) for three specifications in the context of seawater desalination by reverse osmosis.

Variable		Coefficient	RO Estimate	RO p-value	Cobb-Douglas Estimate	Cobb-Douglas p-value	Linear Estimate	Linear p-value
Constant		α_0			6.1169E-02	0.000	6.1169E-02	0.000
Energy	b	α_e	7.7580E-04	0.000	3.2718E-01	0.000	3.2718E-01	0.000
Salinity	s	α_s	-7.4300E-09	0.000	-2.4140E-02	0.224	-2.4140E-02	0.001
Temperature	C	α_C	2.9300E-06	0.000	4.8510E-02	0.000	4.8510E-02	0.000
Time	t_1	α_{FDF}	-7.2400E-09	0.000	-1.8166E-03	0.003	-1.8166E-03	0.000
		R^2	0.9997		0.4531		0.5235	
		F-stat			82.64		109.58	

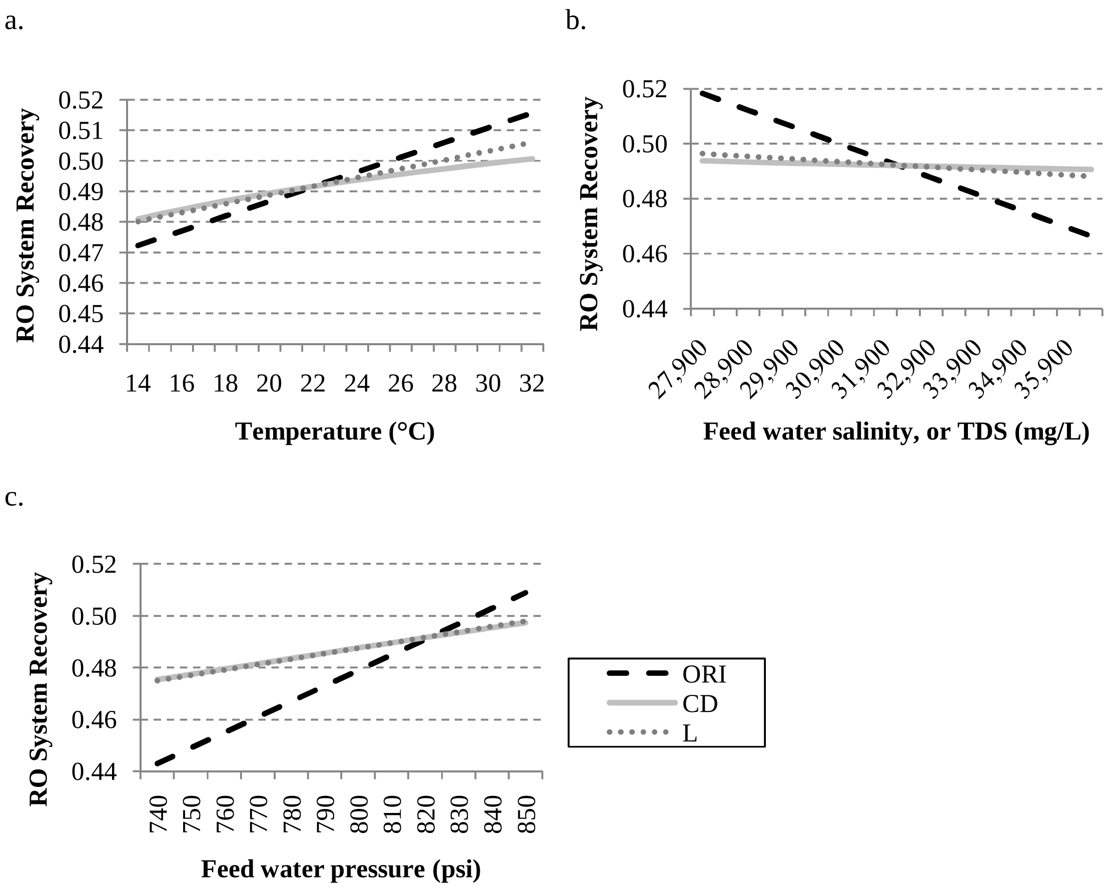

Figure 1. The responses of each of three production functions, denoted ORI, CD, and L for one-required-input, Cobb-Douglas, and linear, to changes in feed water temperature (panel a), feed water salinity (panel b), and feed water pressure (panel c), with all other factors held constant. Note: except as indicated on the x-axis of each panel, all other variables are held constant at the following values: temperature: 22.4 °C; salinity: 32,108 mg/L; pressure: 823 psi, t_1: 591.6 hours.

Results

This section on results proceeds in four sub-sections: environmental conditions, membrane replacement, hourly operations, and energy costs. Each of these sub-sections essentially explores the model's sensitivity to exogenously imposed changes to the following baseline parameters: feed water quality, membrane lifespan, hourly operation restrictions and hourly operational costs, and energy costs. In all of the following results, the daily production requirement is imposed and held constant as is the replacement time variable, t_1, our proxy for the flux decline factor.

Environmental Conditions

This section on environmental conditions is motivated by two objectives: first, to evaluate the effect of different functional form specifications of the recovery function, to ensure responses of the cost-minimization model are not an arbitrary consequence of functional form selection; and secondly, to estimate the cost response to environmental conditions. The environmental conditions are categorized as "warm season" and "cool season", with water quality parameters for these "seasons" taken from averages of the Pilot data for May 2008 and January 2008, respectively. The annuity equivalents for each input are calculated using each of the three previous production functions and imposing the "warm season" and "cool season" feed water quality parameters. These results are presented in Figure 2.

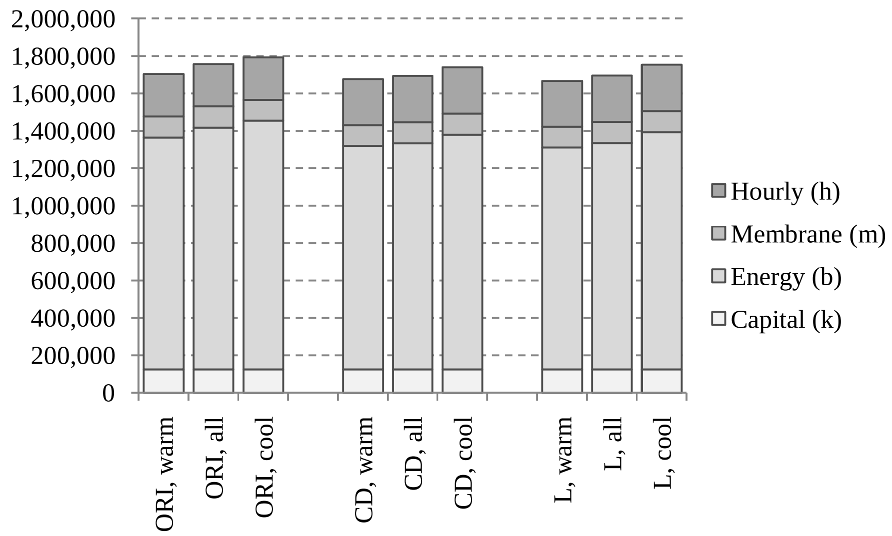

Figure 2. Annuity equivalents of input costs for modeled seawater desalination facility, using three production functions, where ORI, CD, L denote one-required-input, Cobb-Douglas, and linear, respectively; and using three sets of seasonal-based feed water quality parameters, i.e., the warm season, all seasons, and the cool season.

Optimal cost values and input levels are fairly similar across all recovery function specifications (Figure 2). Additionally, the seasonal costs move in the same direction, i.e., for all specifications, costs are more expensive in the "cool season" and less expensive in the "warm season". Greater membrane permeability has been shown to be associated with higher feed water temperatures (Goosen et al. 2002). This results in lower energy costs during the warm season, since that is when the membranes are most permeable. Since all three specifications appear to be reliable, later sections will employ only the production function specification that we denoted desalination, or *d*. The facility's cost response to seasonal changes implies that, in general, warmer climates may have a cost advantage with respect to operating seawater desalination facilities. Also, in any given climate, during the summer months when water demand is typically the greatest, seawater desalination facilities may be producing water at the lowest per-unit cost, holding all other factors constant throughout the year.

Membrane Replacement

Lu et al. (2006) and See et al. (1999) characterize membrane degradation as one of two types: reduction in the water permeability of the membrane and increase in salt transportation through the membrane. Either significant reductions in water permeability or significant increases in salt transportation can indicate that a set of membranes is coming to the end of its useful life and must be replaced. Many RO membrane manufacturers project a 4-6 year life-cycle. In the Pilot report, a 5-year useful life is assumed (NRS Consulting Engineers 2008) in the financial and economic sections. Sturdivant et al. (2009) assume 6 years for their analysis. The objective of this section is to determine the effect on total costs if the useful-life of membranes is underestimated or overestimated.

The impact on facility costs of imposed levels of membrane lifespan on the costs of a seawater desalination facility are explored in Table 3. If membrane replacement time is assumed to be 6 years, but actually turns out to be 4 years, the estimated change in costs for a facility is a positive increase in the annuity equivalent cost by 44,642 (i.e., 2.5%) in US$2010. This issue is a concern for managers of desalination facilities because many of these facilities are operated under the assumption that a variety of capital components (e.g., membranes, pumps, piping, etc) will fail due to mechanical breakdown and/or wear-and-tear and need to be replaced. The budgets of these facilities typically includes a capital replacement fund, or a “sinking fund”, to replace such components. The size of this fund and the recurring payments “sunk” into this fund are based on the expected useful life of those components, the number of components in the facility, and the expected costs of the components. If the case is that the lifespan of RO membranes is being overestimated, then facility managers need to anticipate higher membrane replacement costs will be incurred in the nearer future.

Table 3. Calculated changes in annuity equivalent costs of a modeled seawater desalination facility using reverse osmosis as the membrane replacement time (i.e., membrane lifespan) is exogenously imposed.

Membrane Replacement Time	Membrane Cost AE	Total AE	Change in Total AE from $T_R = 5$	% Change in Total AE from $T_R = 5$
T_R	AE_m	AE_{total}	US$2010	%
1	374,425	2,144,298	350,495	19.54
2	229,060	1,954,297	160,494	8.95
3	182,772	1,880,645	86,842	4.84
4	140,572	1,838,445	44,642	2.49
5	129,394	1,810,698	16,895	0.94
6	112,499	1,793,803	0	0.00
7	99,269	1,780,573	-13,230	-0.74

All AE values in US$2010.

Operational Hours

In the model, the operational costs component of the objective function can change as a consequence of two factors: the number of hours in a day that the facility operates and the per-hour cost of hourly operations. Hourly operations costs include labor costs and any other facility-wide costs incurred on the hour, such as heating or air conditioning of workspaces. Optimization and cost results associated with a range of imposed daily operation hours are displayed in Table 4.

Table 4. Calculated changes in annuity equivalent costs of a modeled seawater desalination facility using reverse osmosis as daily operating hours are exogenously imposed.

Daily Operating Hours	Hourly Operations Cost	Total Cost	Change in Total AE from h*[a]	% Change in Total AE from h*[a]	Optimal levels of inputs/recovery		
					capital	energy	recovery
h	AE_h	AE_{total}	US$2010	%	k	b	r
4	63,568	2,222,437	464,314	26	29	857	0.513
8	127,135	1,867,711	109,589	6	15	829	0.496
12	190,703	1,781,888	23,766	1	10	829	0.496
14.265	226,693	1,758,123	0	0	8	871	0.522
16	254,270	1,814,798	56,676	3	8	794	0.475
20	317,838	1,789,511	31,388	2	6	829	0.496
24	381,405	1,823,200	65,078	4	5	829	0.496

All AE values in US$2010.

[a] In optimum portfolio of baseline scenario, h* = 14.265.

The most interesting result displayed in Table 4 is that the optimal number of operational hours is substantially less than a full 24-hour day. The unrestricted optimal level of daily operational hours is 14.265. As facility operational hours are reduced, input substitutions are made into capital (to increase hourly production capacity), resulting in an increase in the overall cost of the facility. As facility operational hours are imposed to be higher than the optimal, substitution away from capital occurs. The facility operates over a greater part of the day, uses less capital, and thereby achieves the daily production requirement at a greater cost. Therefore, important implications exist for facility designers who do not consider the costs of hourly operations. If hourly operations are ignored, a facility designer may generate a sub-optimal design that includes the lowest, technically-feasible amount of capital and assumes 20 or 24-hour daily operation schedule for the facility. According to our model, this design could be more expensive than a facility designed with a little more capital and operated for fewer hours of the day.

While no specific context of per-hour operations cost (e.g., high-priced, unionized labor) is considered in this paper, the results displayed in Table 5 indicate that a facility's total cost and the input mix are affected by imposing different values for the per-hour price of operations. The per-hour operating cost is represented by z_h in the first column in Table 5. As z_h changes, these results show qualitatively similar findings to those suggested in Table 4. In particular, designing for a 24-hour daily operation schedule are not optimal, even under the assumption that per-hour operations cost are on the order of $15/hour (i.e., relatively, inexpensive hourly operations). Furthermore, as hourly operations become more and more expensive, substitutions are made into capital that will allow a facility to generate the same level of output while operating over fewer hours of the day. This implies that for areas like the northeastern United States, where relatively high labor costs as well as winter-time heating costs might suggest relatively high per-hour operations costs, an optimal facility design-management strategy has higher levels of capital by which the facility can generate more water per hour in fewer hours of the day.

Energy Costs

Given the results of the previous section (i.e., that the costs and quantities of hourly operations have implications for the optimal levels of capital), the consideration of an interruptible power supply scheme may be important as well. From the Pilot report, interruptible supply is an electrical power contract which grants the facility a

Table 5. Calculated changes in annuity equivalent costs of a modeled seawater desalination facility using reverse osmosis as the per-unit cost of daily operating hours are exogenously imposed.

Hourly Operating Cost	Hourly Operations Cost	Total Cost	Change in Total AE from baseline[a]	% Change in Total AE from baseline[a]	Optimal inputs/recovery levels			
					capital	energy	hours	recovery
Z_h	AE_h	AE_{total}	US$2010	%	k	b	h	r
15	151,129	1,536,642	-135,321	-8	6	871	19.02	0.522
30	226,693	1,671,962	0	0	8	871	14.27	0.522
35	264,476	1,709,745	37,782	2	8	871	14.27	0.522
40	268,674	1,743,821	71,858	4	9	871	12.68	0.522
45	272,032	1,777,057	105,095	6	10	871	11.41	0.522
60	329,736	1,864,639	192,677	12	11	871	10.37	0.522
100	431,797	2,056,335	384,372	23	14	871	8.15	0.522

All AE values in US$2010.

[a] In baseline scenario, $Z_h = 30$.

discounted per-unit price of electricity with the condition that the facility may have its electricity supply reduced or stopped altogether during periods of peak electrical demand (NRS Consulting Engineers 2008). Our model indicates that a tradeoff between limited hours of operation, reduced energy costs, and capital expenditures is not only possible but likely to be beneficial under most reasonable scenarios.

The results in Table 6 suggest that access to interruptible power supply may be a very effective cost-reducing mechanism for seawater desalination facilities. First, consider the case when interruptible power supply is not effective, in the second row of results in Table 6. The energy price reduction afforded by interruptible power supply is relatively small, $0.01; and the restriction on operating hours is relatively large, $h \leq 8$. Under these conditions, the total cost of a facility will increase. The increase in costs is mostly due to the substitution into capital. A facility restricted to less than or equal to 8 hours of operation per day must purchase additional RO trains for the facility to generate sufficient gallons per hour to meet the daily production requirement. But these conditions do not seem particularly realistic.

Table 6. Calculated changes in annuity equivalent costs of a modeled seawater desalination facility using reverse osmosis as the per-unit energy cost are varied and hours of operation are restricted.

Electricity Price	Max Daily Operating Time	Energy Cost	Hourly Operations Cost	Total Cost	Change in Total AE from baseline[a]	% Change in Total AE from baseline[a]	Optimal inputs/recovery levels			
							capital	energy	recovery	hours
z_b ($/kwh)	h <=	AE_e	AE_h	AE_{total}	US$2010	%	k	b	r	h
0.15	24	1,292,404	226,693	1,758,123	0	0	8	871	0.522	14.27
0.14	8	1,206,244	120,903	1,775,319	17,196	1	15	871	0.522	7.61
0.14	12	1,206,244	181,355	1,686,380	-71,743	-4	10	871	0.522	11.41
0.14	14	1,206,244	201,505	1,676,652	-81,470	-5	9	871	0.522	12.68

All AE values in US$2010.

[a] In baseline scenario, h <= 24 and $z_b = 0.15$

Interruptible energy prices are likely to incur a greater than $0.01/kwh reduction in price and are unlikely to restrict operational hours from a maximum of 24 hours to a maximum of 8 hours. Note, even with a $0.01 reduction in the price of energy, with operations restricted to 12 hours, interruptible power supply will reduce a facility's total costs. This outcome makes sense in the context of the optimization results presented in Table 4, i.e., with no restrictions on daily operating hours the optimal level of h is 14.265 hrs. Therefore, in this model, any interruptible power scheme that reduces the price of energy without reducing daily operation hours below 14.265 will unequivocally reduce the facility's total costs.

Conclusion

This paper investigates the significance of several input attributes to the costs of operating a seawater desalination facility. We show that our model is relatively robust to the selection of several functional form specifications for the production function. In the model, a seawater desalination facility is more expensive to operate under "cool weather" conditions and less expensive under "warm weather" conditions. This suggests that, other considerations held constant, warmer climes may have a slight cost advantage when considering seawater desalination and that high water demand seasons correspond with the relatively cheaper "warm season" production costs.

The sensitivity of the model to costs of hourly operations and restrictions of hourly operations is noteworthy because our results suggest that in areas with relatively high per-hour operations cost, the optimal input portfolio for a facility includes relatively greater amounts of capital. The investigation of interruptible power supply concluded that under most realistic conditions, interruptible power supply is an economically beneficial power scheme for the modeled seawater desalination facility.

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