**FAC 8415 Desalinization Plant**

| | |
|---|---|
| FY25 SUC: | $91.55 / KG |
| Source: | Inflated from previous FY using ENR labor and material cost indices to measure actual inflation |
| Original Source: | Multiple Commercial Sources |

# An Investigation of the Marginal Cost of Seawater Desalination in California


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## Abbreviations, Acronyms & Definitions

ADC: Affordable Desalination Coalition

Ann: Annual

Avg: Average or statistical mean

AF: An acre-foot of water or 325,851 gallons, which is enough water to flood one acre of land one foot deep and supply about four single-family households with enough water for one year AFY: Acre-feet per year kWh: Kilowatt-hour, or 1,000 watts of energy used for a duration of 1 hour

Marginal Cost: The cost of producing one more unit of a good, or in this report the cost of producing or saving and acre-foot of water. The marginal cost provides a mechanism to compare the cost of different water supply and conservation options on a realistic cost comparison basis.

MG: Million gallons

MGD: Million gallons per day, a 1 MGD facility is theoretically equivalent to 1,120 AFY at 100% capacity for 365 days a year

MMWD: Marin Municipal Water District

NPV: Net present value, a term used to account for the discounted future value of dollars

O&M: Operations and maintenance, this will exclude project design, capital costs and financing

PPM: Parts per million

## Executive Summary

There is much interest, but little clarity on the cost of desalinated seawater in California and how it compares to other urban water management options. To address this issue, this investigation collected general information along with costs and production records and cost projections for many prominent seawater desalination facilities and proposed projects in North America and California. Along with many others, this included Tampa Bay, Carlsbad, Santa Barbara, and Marin. These four projects are described and evaluated as case studies in this paper.

The marginal cost of water produced by any specific seawater desalination project will depend on many variables including:

Site characteristics
Size of the facility
Financing cost
Energy cost
Water quality conditions for intake seawater
Environmental mitigation and monitoring costs
Actual water production
Connection and pumping costs to existing infrastructure
Taxes (privately own facilities)
Profit (privately owned facilities)

***Seawater desalination for $800 to $1,000 per acre-foot?***

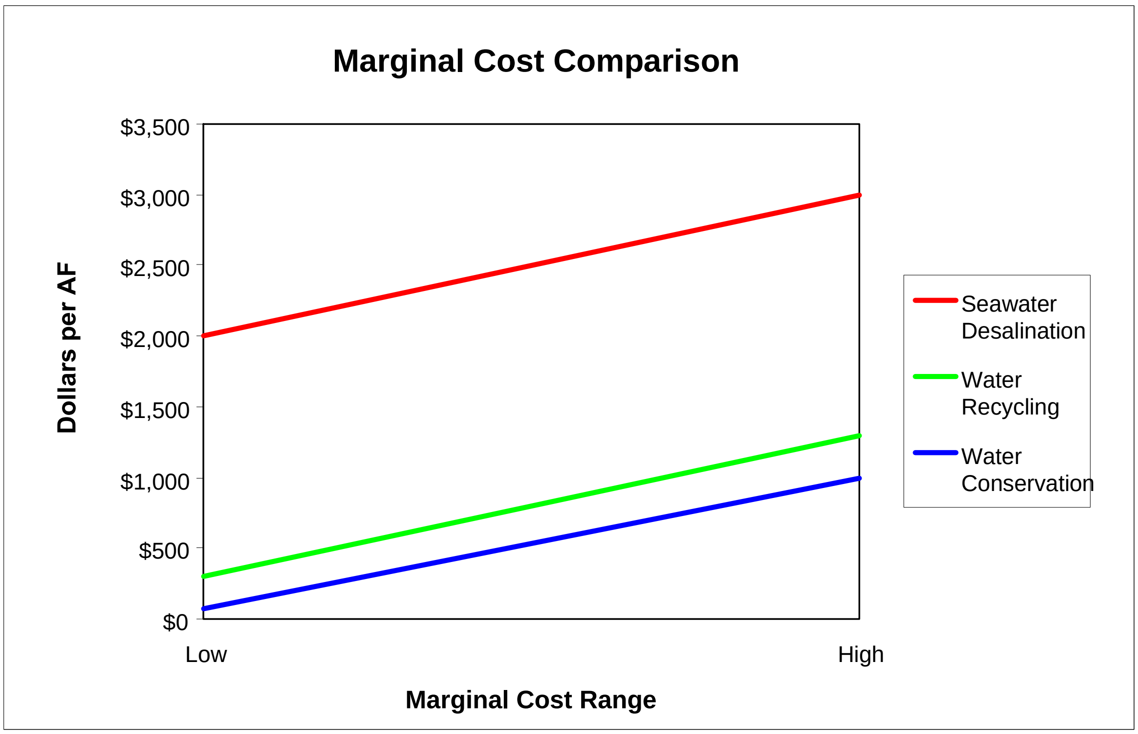
Some advocates of seawater desalination suggest marginal costs of $800 to $1,000 per acre-foot are now possible in California. However, despite a thorough investigation, **this study found no evidence of seawater desalination facilities in North America producing water in that cost range.** This study also found no credible evidence that new seawater desalination projects in California, given local conditions, could produce water in that cost range.

Given the best presently available technology, this investigation found **realistic estimates of the marginal costs for seawater desalination in California will range from a minimum of about $2,000 to $3,000 or more per acre-foot of water produced.**

**This compares to typically much lower marginal costs of well under $1,000 per acre-foot for most urban water conservation measures.[1] Water recycling for urban areas typically costs between $300 and $1,300 per acre-foot.[2]** Both water conservation and recycling appear to be far from fully utilized in California's urban areas.[3]

For comparison, the relative marginal costs in California of seawater desalination, water recycling, and water conservation are shown in Figure 1 below.

**Figure 1**




While many agencies pursuing seawater desalination cite it as a drought proof supply, as evidenced by the demand reductions by urban consumers in California during a recent series of dry years, it appears many water managers may underestimate demand elasticity during shortages. Behavioral-based demand reductions during shortages can occur at very low cost to ratepayers and society.

Many areas in California are now seriously evaluating and pursuing a suite of promising new water conservation measures such as graywater use and local rainwater harvesting that may be less costly and environmentally beneficial compared to seawater desalination. Low-impact development and integrated watershed and floodplain management practices are also gaining favor that can increase groundwater recharge and locally available water supplies while improving environmental conditions.

A better understanding of the real costs of the various water management options is important to rational decision making and appropriately prioritizing limited funding for the best alternatives for individual water users and society. The realistic costs of seawater desalination need to be more transparent and understood by the public. Proponents of seawater desalination projects should clearly delineate the costs of the projects in the categories identified in this paper. Also the costs of emerging water management alternatives such as graywater use, and rainwater water capturing, low-impact development and integrated watershed and floodplain management practices should be better evaluated for identifying the most cost-effective options for improved water management in California.

## Background

California is faced with increasing competition for water supplies. Concern over the possible impacts of climate change further alarms many water managers. As a result, there is increasing interest in seawater desalination, its potential benefits, costs, energy use, and environmental impacts.

Some advocates of seawater desalination suggest the cost has decreased in recent years and is now similar to the cost of other urban water supply options.[4] Private water industry interests view the production and sale of desalinated seawater water as a potentially lucrative business opportunity. Some environmental advocates hope increased use of seawater desalination will reduce present or future water diversions and their impacts on California's rivers, streams, and groundwater basins. Others express concern over the cost, the potential privatization of water supplies, energy use and the environmental impacts, and potential health risks.[5] This investigation focuses exclusively on the cost issue and leaves the other important issues to other analyses.

Numerous new desalination projects are proposed in California and in various stages of development. These include proposed projects in Carlsbad, Huntington Beach, Santa Cruz, Marin County, and Cambria. In the early 1990s, a seawater desalination facility was constructed in Santa Barbara but immediately mothballed without being operated for water production.

The Carlsbad project, at 50 MGD design capacity, is the largest presently proposed project in California and the most progressed within the permitting process. It is proposed by a private corporation, Poseidon Resources, and is subject to less cost transparency than public projects. Since Poseidon Resources is seeking publicly subsidized funding and financing, and indicates a willingness to match the cost of existing water supply options, much interest is presently focused on the realistic cost of water produced by the proposed Carlsbad facility. This analysis evaluates the realistic cost of desalinated water for the proposed Carlsbad and other desalination facilities from which adequate cost records and projections could be obtained.

## What Will Large-Scale Seawater Desalination Realistically Cost in California?

With limited exceptions, water agencies and private interests involved in seawater desalination appear reluctant to release verifiable marginal costs analysis for their seawater desalination projects. This has troubled many observers since marginal costs analyses form the basis of integrated water resources planning and rational decision making for water management plans and infrastructure investments.

This project was undertaken to better identify realistic marginal costs of seawater desalination in California and the actual or realistic costs of various categories of costs. These categories are listed below and include facility design, capital, operating, maintenance, energy use, permitting and environmental mitigation and monitoring costs. Ideally, the sub categories of the costs listed below should have been tallied and compared. However, despite considerable effort, it was not possible to obtain detailed and credible enough cost figures for most of the various categories in order to provide a reliable comparison. However, data useful in identifying likely overall marginal costs were obtained and will be used in this analysis.

**Cost Categories for Seawater Desalination Projects:**

**Capital Costs**
Land/site acquisition and right-of-way for pipelines
Building construction
Electrical connections
Miscellaneous piping and plumbing
Intake pipes, screens
Prefiltering components
Pumps
Membranes and cartridges Discharge
pipes, diffusers
Facility controls and monitoring equipment
Treated water connection to water distribution system including pipes, pumps, tanks
Construction contingency
Contractor costs – overhead, profit, bonding, insurance, etc
Mitigation, including capital for sensitive area acquisition for protection/environmental mitigation
Taxes (privately owned facilities)

**Operations and Maintenance Costs (O&M)**
Electricity
Treatment chemicals
Membrane replacement
Pump maintenance/replacement
Plant operator labor
Plant maintenance labor

Solids disposal
Environmental monitoring and mitigation costs
Carbon offsets
Profit (for privately owned facilities)
Taxes (for privately owned facilities)

**Miscellaneous Design and Approval Costs**
Design fees
Permitting fees
EIR and public process costs

**Financing Costs**
Financing term and interest rate

In addition to the above noted costs categories, other factors would impact marginal costs, including actual production from the facility compared to design production, and uphill delivery of desalinated water to existing infrastructure for the service area. Since seawater desalination draws its source water at or below sea level, the distribution and delivery of the product water to its targeted service area will require uphill pumping. Service areas with high elevations will require more pumping, and incur the associated higher energy cost for delivering the water to end users.

## The Affordable Desalination Collaboration

The Affordable Desalination Collaboration (ADC) is a group of desalination industry advocates and many California water agencies interested in seawater desalination. The organization is chaired and managed by industry advocates and leaders in promoting desalination. Their mission "is to demonstrate affordable, reliable and environmentally responsible reverse osmosis desalination technologies and to provide a platform by which cutting edge technologies can be tested and measured for their ability to reduce the overall cost of the SWRO treatment process." [6]

### *ADC indicates the cost seawater desalination ranges from around $800 to $1,000 per acre-foot of fresh water produced*

The Affordable Desalination Collaboration's website has a test results page with links to numerous spreadsheets with analyses that indicate the cost seawater desalination ranges from around $800 to $1,000 per acre-foot of fresh water produced.[7] According to ADC's CEO and Managing Director, the engineering assumptions, such as optimum membrane feed pressures for the different membranes tested, were based on a pilot project with tests conducted in Port Hueneme, California in 2005 and 2006.[8] The remainder of the **cost figures in the ADC projections were not based on an actual operating facility but instead were estimates and projections**.[9] Given the membership and participants of this group,[10] it is very likely that these figures serve as a primary source of widely circulated suggestions that the cost of seawater desalination is now similar to the cost of other water supply sources. Many interested observers find the prospect of seawater desalination in California at a marginal cost near or below $1,000 per acre-foot highly appealing.

### *Problems with ADC costs projections*

However, a review of ADC's website costs analysis for their theoretical 50 MGD facility found many fundamental flaws with the cost projections and associated assumptions. [11] These include:

***Energy Costs is underestimated***

An energy cost of $0.08/kWh was used for the ADC analysis. This compares with an energy cost of $0.116/kWh determined in two recent independent analyses for the proposed Carlsbad project[12] and $0.12 for the Marin project.[13] Energy is one of the largest components of O&M costs. This represents an underestimate of about 32% for this major cost.

***Energy requirement is underestimated***

The range for the specific energy use assumption in the ADC analyses, which represent the overall energy efficiency of the desalination process, appear unrealistically low. It ranges from a low of 10 kWh/1000 gallons to a high of 14 kWh/1000 gallons of water produced. The ADC tests were a series of short-run tests with new membranes, generally less than a full day run for each test, and the membranes were tested for less than a full year of run time.[14] This does not replicate operating a facility at 100% of design capacity 95% of the time for 365 days per year, which is the assumption of ADC's marginal costs calculations. It also does not reflect performance decline from membrane scaling and clogging during an assumed 6-year membrane life.

By comparison, the O&M records from the Tampa Bay facility, which operates with warmer temperature and lower salinity feed water than seawater facilities in California can expect, indicate that in 2007, with new membranes, the energy requirement was 9kWh/1000 gallons produced. The energy requirement increased to 15.9kWh/1000 gallons in 2009 with membranes that were less than three years old.[15] The Santa Barbara facility, located near the site of the ADC tests, projects an energy requirement of 17.1kWh/1000 gallons produced with a refurbished and modernized facility.[16] The proposed Marin facility projects an energy requirement of 15kWh/1000 gallons to 16kWh/1000 gallons per water produced during drought periods with a new state-of-the-art facility using feed water with generally lower salinity and warmer temperatures than typical California seawater.[17] Table 1 provides an energy use comparison.

**Table 1**
**Energy Requirement Comparison**

| Facility | ADC | Tampa Bay | Santa Barbara | Marin |
|---|---|---|---|---|
| Water Temp (°F) | 53.6 to 64.4 | 86 | 56 - 65 | 62.7 (avg) |
| Salinity (ppm) | 31,668 | 29,000 | 34,000 | 21,700 (avg) |
| kWh/1000 gal | 10 to 14 | 15.9 | 17.1 | 15 to 16 |

***Capital costs are underestimated***

The capital costs in the ADC projections per MGD of capacity are much lower than other completed or proposed projects. Table 2 below provides a comparison of capital cost per MGD of design capacity for various facilities discussed in this paper. The ADC high estimate is 17% lower than the actual capital cost of the Tampa Bay facility. As noted, the Tampa Bay location has advantages for feed water quality compared to California facilities. These advantages, subsequently discussed in this paper, would increase capital costs for a comparable facility in California. The capital cost for the proposed Carlsbad facility in California is presently 41% higher than the ADC high estimate.

**Table 2**
**Capital Cost per MGD Design Capacity (2009 Dollars)**

| Project | ADC (Low Estimate)[18] | ADC (High Estimate)[19] | Tampa Bay[20] | Santa Barbara[21] | Carlsbad | Marin[22] | Marin[23] |
|---|---|---|---|---|---|---|---|
| **Design Capacity** | 50 MGD | 50 MGD | 25 MGD | 6.7 MGD | 50 MGD | 10 MGD | 5 MGD |
| **Capital Cost (Millions)** | $239.3 | $313.8 | $190.3 | $59.6 | $534 | $131.4 | $88.6 |
| **$ (Millions)/MGD** | $4.8 | $6.3 | $7.6 | $8.9 | $10.7 | $13.1 | $17.7 |

***Intake water salinity lower than average seawater***

Average intake water salinity of 31,688 parts per million (ppm) was reported for the ADC tests and cost projections.[24] This compares to 33,520 ppm for the proposed Carlsbad site[25] south of Port Hueneme and 34,000 ppm for the Santa Barbara site[26] just north of Port Hueneme. Given present membrane technology, the higher source water salinity for the Carlsbad and other California coastal sites will result in either higher product water salinity or the selection of membranes with lower water permeability, which correlates with lower salt permeability.[27] Membranes with lower water permeability require higher feed water pressure, which will result in higher energy use. [28]

***Unrealistic water production assumptions***

The ADC cost projections are based on unrealistic water production assumptions of operating at 100% of design capacity 95% of the time for 356 days per year. This is a production level that the best comparative example in North America, the Tampa Bay facility discussed below, has not come close to achieving on an annual basis. As noted above, the ADC tests were a series of short-run tests with new membranes, generally less than a day long run for each test, and the membranes were tested for less than a full year of run time.[29] This does not reflect operating a facility at 100% of design capacity for 95% of the time, 365 days per year. It also does not reflect performance decline from membrane scaling and clogging during an assumed 6-year membrane life. Even with the best known chemical and physical maintenance techniques, reverse osmosis membranes are known to experience a performance decline as they age and suffer increased clogging and scaling. Declining performance as membranes age will lower water production or require increased design capacity, either of which would increase marginal costs over the life of the project.

***O&M costs underestimated***

The ADC analyses have unrealistic overall O&M costs ranging from a low of $496 per acrefoot to a high of $616 per acre-foot. A 2009 report by Carollo Engineers determined the

O&M costs for a rehabilitated and modernized Santa Barbara facility would be $1470 per acre-foot.[30] This is more than double the ADC high cost projection. Costs based on a pilot project by Kennedy/Jenks Consultants for a proposed new, state-of-the–art 10 MGD facility in Marin projected O&M marginal costs of $1,107 per acre-foot for a facility being operated at 100% capacity.[31] The Marin facility is proposed to be sited along San Rafael Bay in the San Francisco Bay. As a result of bay water mixing with runoff from inland California, in most years the Marin facility would be operating with significantly lower feed water salinities and frequently warmer feed water temperatures than typical California seawater. This should result in lower O&M costs for the Marin facility compared to projects using typical California seawater, yet the O&M cost projections are nearly double the highest ADC projected cost.

***Inaccurate discount rate for net present value calculations***

The net present value calculations in the ADC spreadsheets do not accurately account for the discount rate as the difference between the rate of inflation and the interest rate for financing. Rather than subtracting the assumed inflation rate of 3% from the financing rate of 5% for a 2% discount rate, which is standard economics practice, the ADC calculations use a 5% discount rate. Using the proper discount rate actually lowers the long-term capital costs, but this issue is more than offset by underestimated initial capital cost assumptions and other underestimated cost assumptions.

***Costs estimates do not include many necessary costs***

The marginal costs do not include any land cost for citing a facility, costs for an intake water structure, brine discharge structure, or necessary improvements to deliver the desalinated water to a local distribution system for end users.[32] The marginal costs assumes that a facility will be co-located with a power generating plant and share the generating plant's cooling intake water facility, which will not always be possible.[33] In addition, the ADC assumptions do not account for high capacity electrical power lines that will often be necessary to provide adequate power supply to desalination facilities. Cost also do not include expenses for administrative, laboratory, legal, reporting or management.[34]

***Costs figures do not include environmental mitigation and monitoring***

The ADC marginal costs figures do not account for environmental permitting costs, or substantial environmental mitigation and monitoring costs that can be expected for new facilities as a condition of environmental permits.

A more thorough analysis of all the ADC assumptions and calculations may reveal additional problems with the projections, but this is sufficient to illustrate that these figures are not a reliable indication of realistic seawater desalination costs in California. ADC's CEO/Managing Director appears aware that these projections are based on many "best case" assumptions, some of which may no longer be valid.[35] However, the figures remain on ADC's website at the time of this writing as valid projections for seawater desalination cost. The figures appear to provide a reference point as valid cost estimates for desalinated seawater for many interested parties, including agencies considering or planning seawater desalination facilities. Therefore, it is important to note the limitations of the ADC cost projections.

## Case Studies

To better assess the realistic costs of seawater desalination in California, this investigation collected actual and projected cost and water production data on a broad range of constructed and proposed desalination projects in California and North America. Despite considerable effort, in many cases, very limited data were available. However, sufficient data were collected to provide the following four case studies and to develop a realistic marginal cost estimate range for seawater desalination in California.

### Marin Project

The Marin Municipal Water District (MMWD) in the San Francisco Bay Area recently approved an EIR and issued a Notice of Determination to build a 5 MGD desalination facility expandable to 15 MGD. MMWD is now moving forward with detailed design work and permitting for the facility.

The Marin facility is proposed to be located on land already owned by MMWD along San Rafael Bay in the northern part of San Francisco Bay. The San Francisco Bay experiences water temperatures and salinities that range from typical seawater near the Golden Gate to less saline, and often warmer estuarine conditions further upstream in the estuary. The water quality conditions in San Rafael Bay vary widely based on tide cycles, wind conditions, season and runoff conditions for the very large watershed that includes most of California's Central Valley and the Sierra Nevada mountains. As a result of bay water mixing with freshwater from inland California, in most years the facility would operate with feed water with significantly lower salinity compared to California seawater. There would also be periods when water temperatures would be warmer than California seawater.

MMWD conducted a desalination pilot project to better understand conditions for the proposed site and optimum facility design parameters. A water quality sampling program at the proposed site was conducted between March 2005 and April 2006.[36] This was during a period of very wet winters with serious flooding in California. As a result, freshwater outflow through San Francisco Bay was heavier than occurs in many years, and particularly during drought years. Salinity readings recorded during the pilot study ranged from a high of 29,000 ppm to a low of 2,500 ppm, with an average of 21,700 ppm.[37] The area is documented to have salinities of up to 32,000 ppm.[38] Water temperatures recorded during the pilot study ranged from a high of 69.8 degrees F to a low of 50 degrees F with and average of 62.7 degrees F. [39] The maximum temperature documented is 71.1 degrees F. [40]

Pilot program data were used to develop capital and operating costs projections for a 5 MGD and 10 MGD facility that could be expanded to 15 MGD. MMWD did not release an actual marginal cost analysis for the 5 MWD or 10 MGD facility. Furthermore, MMWD did not publicly release any capital or O&M cost projections for a 15 MGD facility, despite board approval of the facility in 2009.

A recent independent analysis based on MMWD's publicly released cost figures determined the marginal costs of the 5 MGD facility to be $3,600 per acre-foot of product water and the 10 MGD facility to be $2,903 per acre-foot.[41] These marginal costs figures were in nominal dollars to provide a better comparison to water conservation program costs publicly released by MMWD.

These marginal costs did not include a 15% construction contingency fee identified in MMWD reports.

For this analysis, the marginal costs are updated to include the 15% construction contingency fee and the financing costs are discounted back to net present value terms in 2009 dollars. The result is a marginal cost of $3,009 per acre-foot for the 5 MGD facility and $2,430 for the 10 MGD facility. Table 3 below provides costs for various categories that are the basis of these marginal costs figures.

**Table 3**
**Marginal Cost for Marin's Proposed Desalination Facility**

| Facility Capacity | Capital Cost (Millions) | Annual Cap Cost (Millions) | Ann Op Cost at 100% (Millions) | Projected Avg Annual Op Cost[42] (Millions) | Total Avg Ann Cost (Millions) | Avg Ann Production[43] (AF) | Marginal Cost per AF |
|---|---|---|---|---|---|---|---|
| 5 MGD | $111.2 | $5.0 | $6.5 | $4.1 | $9.1 | 3,024 | $3,009 |
| 10 MGD | $173.4 | $7.4 | $12.4 | $6.8 | $14.7 | 6,048 | $2,430 |

The capital cost figures include the costs of connection to MMWD's water distribution system. The capital cost figures reflect shared use of an existing pier with the nearby Marin Rod and Gun Club for part of the feed water intake structure to reduce the cost of this facility. The rejected brine would be discharged with wastewater from the nearby Central Marin Sanitation Agency, reducing the cost of a discharge structure.

Unlike the ADC energy costs projection of $0.08/kWh noted above, MMWD assumes a $0.12/kWh average energy cost in their O&M projections.[44]
It should also be noted that these marginal cost figures are based on water production with the management scheme indicated in MMWD's EIR for the facility.[45] Under the proposed management scheme, the facility would be operated at 50% of capacity during wet years, and 100% of capacity during drought years to reduce costs, energy use, and environmental impacts. This analysis assumed 23 wet years of production for every 2 years of drought production. The operating costs were reduced to reflect the reduced production in most years. Operating the facility at 100% capacity in all years would result in a marginal cost several hundred dollars lower, since the capital costs would be spread over higher water production and the facility would produce more water during conditions of more favorable intake water quality on San Francisco Bay during wet years. However, it would also result in higher overall costs to ratepayers for water produced unnecessarily in wet years when adequate supply already exists for the service area.

**Tampa Bay Project**
The largest facility now functioning in North America is the 25 MGD Tampa Bay project, which began operation in 2003. The project has a troubled history. Shortly after beginning operations, serious problems developed which required closing the facility and undergoing a major rehabilitation to correct design and construction flaws. Rehabilitation was completed and water production resumed in 2007. Since the Tampa Bay project is an actual operating facility, it provides information useful for assessing the cost of seawater desalination. Using Tampa Bay as a

base case, operating conditions can be adjusted to reflect local conditions in California to provide a more accurate projection of realistic costs for seawater desalination facilities in California.

A recent independent analysis determined the marginal costs of water actually produced at the Tampa facility since 2003 is $1,826 per acre-foot.[46] The results of the analysis are summarized in the following tables. Tampa Bay Case 1 in Table 4 below was based on a total capital cost of $158 million financed 30 years at 5.2%, and an average of 7-year O&M costs and water production from all seven operating years from 2003 through 2009.

**Table 4**
**Tampa Bay Case 1**

| Total Capital Cost | Ann Cap Cost | Avg Ann O&M | Avg AF/Yr Produced | Marginal Cost/AF |
|---|---|---|---|---|
| $158 Million | $7,250,167 | $9,620,560 | 9,240 | **$1,826** |

Tampa Bay Case 2 in Table 5 below was based on a total capital cost of $158 million financed 30 years at 5.2%, and an average of 2-year O&M costs since completion of rehabilitation and water production for 2008 and 2009.

**Table 5**
**Tampa Bay Case 2**

| Total Capital Cost | Ann Cap Cost | Avg Ann O&M | Avg AF/Yr Produced | Marginal Cost/AF |
|---|---|---|---|---|
| $158 Million | $7,250,167 | $16,953,837 | 20,173 | **$1,200** |

Table 6 below shows that if the Tampa Bay facility was constructed with 2009 dollars and experienced for the 30-year life of the project the same operating costs and production the facility actually experienced during its first sever years, the marginal costs of water produced will be $1,961.

**Table 6**
**Tampa Bay w/2009 Cap Cost and Case 1 assumptions**

| Total Capital Cost | Ann Cap Cost | Avg Ann O&M | Avg AF/Yr Produced | Marginal Cost/AF |
|---|---|---|---|---|
| $190.3 Million | $8,495,447 | $9,620,560 | 9,240 | **$1,961** |

Table 7 below shows that if the Tampa Bay facility was constructed with 2009 dollars and experienced the same operating costs and production levels for the 30-year life of the project as the facility actually experienced in the two years since completion of the major rehabilitation, the marginal costs of water produced would be $1,262.

**Table 7**
**Tampa Bay with 2009 Cap Cost and Case 2 Assumptions**

| Total Capital Cost | Ann Cap Cost | Avg Ann O&M | Avg AF/Yr Produced | Marginal Cost/AF |
|---|---|---|---|---|
| $190.3 Million | $8,495,447 | $16,953,837 | 20,173 | **$1,262** |

The marginal costs figure of $1,262 per acre-foot is based on the actual costs and performance of an actual, full-scale facility and is only about 30% higher than the high marginal cost estimate by ADC. However, **it is important to note numerous costs differences between this facility and California facilities.** The Tampa Bay energy cost thus far is lower then expected energy costs in California, feed water is much warmer than in California, the feed water salinity is lower, and the geography of the service area is much flatter so less energy will be required to pump the water produced uphill to end users. It is also important to note that the two years of operations would not reflect potentially declining membrane performance as they age and reach the end of their operating life, which is generally assumed to be six years. These important factors that add significantly to the cost of a project in California will subsequently be discussed in more detail in this paper.

Table 8 below is based on operating records provided by Tampa Bay Water and show water production and energy use since the Tampa facility was initially completed in 2003.

***Energy at $0.04/kWh?***

Original cost projections for the Tampa Bay project assumed a very low electrical cost of $0.04/kWh.[47] However, as indicated in Table 8, **recent records obtained from Tampa Bay Water document actual energy cost of $0.069/kWh in 2004 rising to $0.096/kWh in 2009.**[48] Also note that the kWh's of energy consumption per 1,000 gallons of water produced rapidly increases after the installation of new membranes. This occurred after completion of the facility in 2003 and was exacerbated by inadequate pretreatment systems. However it occurs again, but to a lesser extent, after upgrading the pretreatment systems and replacement of the membranes in 2006. This appears indicative of a decline in membrane performance that can be expected as the membranes age, even with the best pretreatment, chemical, and physical flushing maintenance processes in place. It demonstrates that projections of desalination energy consumption and production levels based on short-term trials, as in the ADC projections previously discussed, are not realistic for long-term operation performance.

**Table 8**
**Tampa Bay Desalination Energy Use Analysis[49]**

| Fiscal Year | Energy Use kWh/MG | Total Energy use kWh | Water Production (MG) | Energy Cost | Avg Energy Cost per MG Produced | Avg Energy Cost $/kWh | Energy Consumption kWh/1000 gal |
|---|---|---|---|---|---|---|---|
| 2003 | | NA | 2,680.53 | $1,398,349.08 | $521.67 | NA | NA |
| 2004 | 23,010 | 39,792,325 | 1,729.34 | $2,772,641.73 | $1,603.29 | $0.069678 | 23.01 |
| 2005 | 34,680 | 9,156,107 | 264.02 | $826,440.86 | $3,130.22 | $0.090261 | 34.68 |
| 2006 | NA | 1,234,519 | 0.00 | $99,110.21 | NA | $0.080282 | NA |
| 2007 | 8,995 | 29,279,472 | 3,255.04 | $2,623,705.29 | $806.04 | $0.089609 | 9.00 |
| 2008 | 13,407 | 98,695,350 | 7,361.40 | $8,282,058.69 | $1,125.07 | $0.083915 | 13.41 |
| 2009 | 15,923 | 92,122,660 | 5,785.61 | $8,843,750.00 | $1,528.58 | $0.096000 | 15.92 |

***Use of preheated feed water from power plant discharge***

The Tampa facility is co-located with a power generation project and uses the power plant's cooling water discharge as warm feed water for the desalination facility. This reduced the capital cost of the facility and provides heated feed water that reduces operating costs. Records obtained from Tampa Bay Water indicate an average feed water temperature of 86 degrees F. Seawater water temperatures in Southern California average around 55 to 60 degrees F.[50] Cooler feed water temperatures have a substantial impact on energy use for seawater desalination. According to membrane manufacturers, the general rule is a 3% increase in energy use for each 1.8 degree F drop in feed water temperatures.[51] New regulations for once-through cooling water in California will have the effect of prohibiting the shared use of warmed water discharged from the cooling systems of power plants after 2017.[52]

***Feed water salinity is lower than average seawater***

The Tampa facility is located where it experiences lower feed water salinity due to mixing with land-based freshwater inflows. The Tampa Bay facility has feed water with an average salinity of 29,000 ppm.[53] This compares to typical seawater salinity of 32,000 ppm to 35,000 ppm. Intake water salinity at the proposed Carlsbad site in California averages 33,520 ppm.[54] Given present membrane technology, the higher source water salinity for most California sites will result in either higher product water salinity or the selection of membranes with lower water permeability, which correlates with lower salt permeability.[55] Membranes with lower water permeability require higher feed water pressure, which will result in higher energy use.[56] Membranes used in higher feed water salinities may also experience a more rapid performance decline compared to membranes used in areas with lower salinities.

**Since the Tampa facility operates with lower salinity and warmer seawater intake temperatures than experienced on California, the costs should be expected to be significantly higher in California.**

**Santa Barbara Project**

In 1992, a 6.7 MGD facility was completed in Santa Barbara at a capital cost of $34 million[57] ($59.6 million in 2009 dollars). The facility was mothballed four months after completion and since that time has not been operated for water supply production. After several original partners withdrew from further participation in the project, some of the components were removed and sold. The remaining facility has been maintained by the City of Santa Barbara in a mothballed state for a cost of about $100,000 per year.[58] A recent detailed engineering analysis of the facility by Carollo Engineers determined it could be rehabilitated with more up-to-date technology and reactivated for $20.2 million. The result would be a facility with a 2.8 MGD capacity.[59]

The 2009 Carollo report for Santa Barbara determined the O&M cost of a rehabilitated facility, excluding past and rehabilitation capital cost, would be $1,470 per acre-foot of water produced.[60] Energy costs were based on September 2008 pricing for the city of $0.086/kWh.[61] This may not be realistic for future energy costs as evidenced by the actual 2009 energy cost for the Tampa Bay project of $0.096/kWh[62] and projected energy costs for the proposed project in Marin of $0.12/kWh and Carlsbad of $0.116/kWh.

It is important to note that even with the potentially low energy cost assumption, the O&M cost alone for a rehabilitated and modernized facility in Santa Barbara is projected to be $1,470 per acre-foot of water produced. As is evidenced by past capital costs for the Santa Barbara facility and the figures for the Marin facility in Table 3, the capital cost will result in a total marginal cost well above $2,000 per acre-foot of water produced if the facility is brought back into operation.

**Carlsbad Proposed Project**

Poseidon Resources is a private corporation working to develop a 50 MGD seawater desalination facility in Carlsbad, California. Poseidon projects a $534 million capital cost for the proposed 50 MGD facility.[63] O&M costs and a marginal cost analysis were not publicly released. There has been considerable interest in the realistic marginal cost of water for this proposed facility. But since the proposed project is privately managed, there is no requirement for cost transparency.

A recent independent study examined costs figures from the Tampa Bay facility and adjusted the costs for local conditions at the proposed Carlsbad site.[64] In order to reflect a reasonable range of uncertainty with assumptions and cost variables, four cases of marginal costs with a range of assumptions were developed for the proposed Carlsbad project. Average energy cost for the Carlsbad facility was assumed to be $0.116/kWh,[65] which is consistent with two independent analyses[66] and differs from Poseidon Resources' estimate of $0.075/kWh figure.[67] All four cases are expressed in net present value terms in 2009 dollars. The four cases along with a summary of the assumptions in each case are listed below. Interested readers are referred to the report "Marginal Cost Analysis for the Proposed Carlsbad Project" for a full description of the analytical techniques and assumptions in the four Carlsbad cases.[68]

As shown in Table 9, **if the proposed Carlsbad desalination project performed at the same level as the Tampa Bay facility has performed over its seven year operational life, the marginal cost of water produced by the Carlsbad facility would be $3,507 per acre-foot.**

Assumptions for Carlsbad Case 1 in Table 9:

- Based on Tampa Bay Case 1 with capital cost overruns, 7-year average production and O&M costs
- Financing was assumed to be 30 Years at 5.2%
- The energy cost was adjusted to $0.116 per kWh, which is the likely minimum energy cost as determined by two independent studies[69]

- A modest 5% profit on O&M, but not capital costs was assumed to begin in year eight
- Warm intake water from the nearby Encina Power Station once-through cooling water discharge was assumed to continue through 2017
- A cost of $15 per metric ton of carbon dioxide emitted for power consumption was added as a carbon mitigation cost
- Federal. state, and local taxes for a private facility not included

**Table 9**
**Carlsbad Case 1**

| Ann Cap Cost | Avg Ann O&M | Energy Cost Adj | Temp Impact Adj | Carbon Offset Adj | Avg AF/Yr Produced | Profit | Marginal Cost/AF |
|---|---|---|---|---|---|---|---|
| $35,196,267 | $22,941,119 | $2,714,217 | $3,345,999 | $619,046 | 18,480 | $1,220,627 | **$3,507** |

As shown in Table 10, if the proposed Carlsbad project does not encounter the same operational problems experienced by the Tampa Bay facility, and functions and produces water at the rate of the post-rehabilitated Tampa Bay facility for its 30-year life, the marginal cost would be $2,175 per acre-foot.

Assumptions for Carlsbad Case 2:
- Based on Tampa Case 2 above with capital cost overruns, 2-year average production and O&M
- Financing was assumed for 30 Years at 5.2%
- The energy cost was adjusted to $0.116 per kWh
- A modest 5% profit on O&M, but not capital cost, was assumed to begin in year eight
- Warm intake water from the nearby Encina Power Station was assumed to continue through 2017
- A cost of $15 per metric ton of carbon dioxide emitted for power consumption was added as a carbon mitigation cost
- Federal, state, and local taxes for a private facility not included

**Table 10**
**Carlsbad Case 2**

| Ann Cap Cost | Avg Ann O&M | Energy Cost Adj | Temp Impact Adj | Carbon Offset Adj | Avg AF/Yr Produced | Profit | Marginal Cost/AF |
|---|---|---|---|---|---|---|---|
| $35,196,267 | $37,607,673 | $6,547,964 | $7,086,827 | $1,311,139 | 40,347 | $1,898,956 | **$2,175** |

Two additional cases provide marginal cost results if the proposed Carlsbad project does not incur capital cost overruns equivalent to the capital cost overruns experienced by the Tampa Bay project.

Assumptions for Carlsbad Case 3 in Table 11:

- Based on Tampa Bay Case 1 with 7-year average production and O&M
- $534 million capital cost with no cost overruns
- Financing was assumed for 30 years at 5.2%
- The energy cost was adjusted to $0.116 per kWh
- A modest 5% profit on O&M, but not capital cost, was assumed to begin in year eight
- Warm intake water from the nearby Encina Power Station was assumed to continue through 2017
- A cost of $15 per metric ton of carbon dioxide for power consumption emitted was added as a carbon mitigation cost
- Federal, state, and local taxes for a private facility not included

**Table 11**
**Carlsbad Case 3**

| Ann Cap Cost | Avg Ann O&M | Energy Cost Adj | Temp Impact Adj | Carbon Offset Adj | Avg AF/Yr Produced | Profit | Marginal Cost/AF |
|---|---|---|---|---|---|---|---|
| $24,503,730 | $22,941,119 | $2,714,217 | $3,345,999 | $619,046 | 18,480 | $1,220,627 | **$2,929** |

The Carlsbad Case 4 assumptions in Table 12 represent a suite of all best-case assumptions for the proposed facility. Under this scenario, the marginal cost is $1,910 per acre-foot. However, this does not include taxes on a private facility. It also assumes financing at low interest rate generally only available to public facilities.

Assumptions for Carlsbad Case 4 in Table 12:

- Based on Tampa Bay Case 2 with 2-year average production and O&M
- $534 million capital cost with no cost overruns
- Financing was assumed for 30 Years at 5.2%
- The energy cost was adjusted to $0.116 per kWh
- A modest 5% profit on O&M, but not capital cost, was assumed to begin in year eight
- Warm intake water from the nearby Encina Power Station was assumed to continue through 2017
- A cost of $15 per metric ton of carbon dioxide emitted for power consumption was added as a carbon mitigation cost
- Federal, state, and local taxes for a private facility not included

**Table 12**
**Carlsbad Case 4**

| Ann Cap Cost | Avg Ann O&M | Energy Cost Adj | Temp Impact Adj | Carbon Offset Adj | Avg AF/Yr Produced | Profit | Marginal Cost/AF |
|---|---|---|---|---|---|---|---|
| $24,503,730 | $36,607,673 | $6,547,964 | $7,086,827 | $1,311,139 | 40,347 | $1,898,956 | **$1,910** |

Another method of projecting marginal costs for the Carlsbad project is to combine the Carlsbad capital costs of $534 million with the recently released operating costs projections for a rehabilitated and modernized Santa Barbara seawater desalination facility discussed in the above section. The result is provided in Table 13 below, along with a range of financing costs and their impact on the marginal costs. A February 26, 2010, Research Update by Standards & Poor's assigned Poseidon Resources a BBB- credit rating.[70] A rating any lower would be considered junk bond status. Public agencies with tax power or rate assessment revenue streams generally obtain long-term financing for capital projects in the 5% range. Since Poseidon Resources is a private corporation with a BBB- credit rating, its ability to obtain financing at low public interest rates is in question. Therefore, a range of interest rates from 5% to 10% were included in the analysis.

**Table 13**
**Carlsbad Marginal Costs Analysis Using Santa Barbara Operating Costs**

| Interest Rate | Annual Cap Cost[71] | Actual Production, % of Design Capacity | Actual Production, afy | Marginal Cost per af for Cap Cost Only | Santa Barbara O&M Costs/afy | Total Marginal Cost per af |
|---|---|---|---|---|---|---|
| 5% | $23,887,708 | 100% | 56,007 | $427 | $1,470 | $1,897 |
| 5% | $23,887,708 | 90% | 50,406 | $474 | $1,470 | $1,944 |
| 5% | $23,887,708 | 80% | 44,806 | $533 | $1,470 | $2,003 |
| 7.5% | $32,844,475 | 100% | 56,007 | $586 | $1,470 | $2,056 |
| 7.5% | $32,844,475 | 90% | 50,406 | $652 | $1,470 | $2,122 |
| 7.5% | $32,844,475 | 80% | 44,806 | $733 | $1,470 | $2,203 |
| 10% | $43,113,726 | 100% | 56,007 | $770 | $1,470 | $2,240 |
| 10% | $43,113,726 | 90% | 50,406 | $855 | $1,470 | $2,325 |
| 10% | $43,113,726 | 80% | 44,806 | $962 | $1,470 | $2,432 |

**This costs evaluation method does not provide for any capital cost overruns, profit or taxes on the capital or O&M costs, or for any ongoing carbon offset costs to provide a carbon neutral project** as stated by Poseidon Resources on its website. Private facilities are subject to taxes that are generally not applicable to publicly owned and operated facilities. These can include property, sales, and income taxes. As evidence of the potential tax assessment on private facilities, Poseidon Resources has been negotiating with the City of Huntington Beach on tax assessment issues.[72] Taxes are costs that will be passed along to ratepayers and will increase the marginal costs of a project. These additional costs can be expected to increase the marginal cost by 5% to 10% or more.

**All of the various analytical approaches suggest a marginal cost for the Carlsbad facility of at least around $2,000 per acre-foot in the best case scenarios. The marginal cost ranges as high as around $3,507, which is based on the actual costs of the Tampa Bay facility, adjusted for conditions at the Carlsbad site, after seven years of Tampa Bay's 30-year operating life.**

## The Comparative Marginal Costs for Water Conservation and Recycling

Although not the primary focus of this analysis, for a comparison basis, well-accepted marginal costs are provide for a range of water conservation measures and water recycling programs. These are important as a comparison point for seawater desalination costs and a primary reason for developing marginal costs. A recent comprehensive study of the marginal costs of well-accepted conservation measures was funded by the CALFED Bay-Delta Program. It found that water conservation savings from a broad range of measures can be obtained for a cost of well under $1,000 per acre-foot.[73] The 2009 California Water Plan published by the Department of Water Resources lists the recycled water marginal costs for most California urban areas ranging between $300 and $1,300 per acre-foot.[74]

While it remains uncertain if the often optimistic and unproven marginal costs for seawater desalination in the analysis above can be obtained, the marginal costs for water conservation and recycling programs are well-proven with a large number of functioning projects in California.

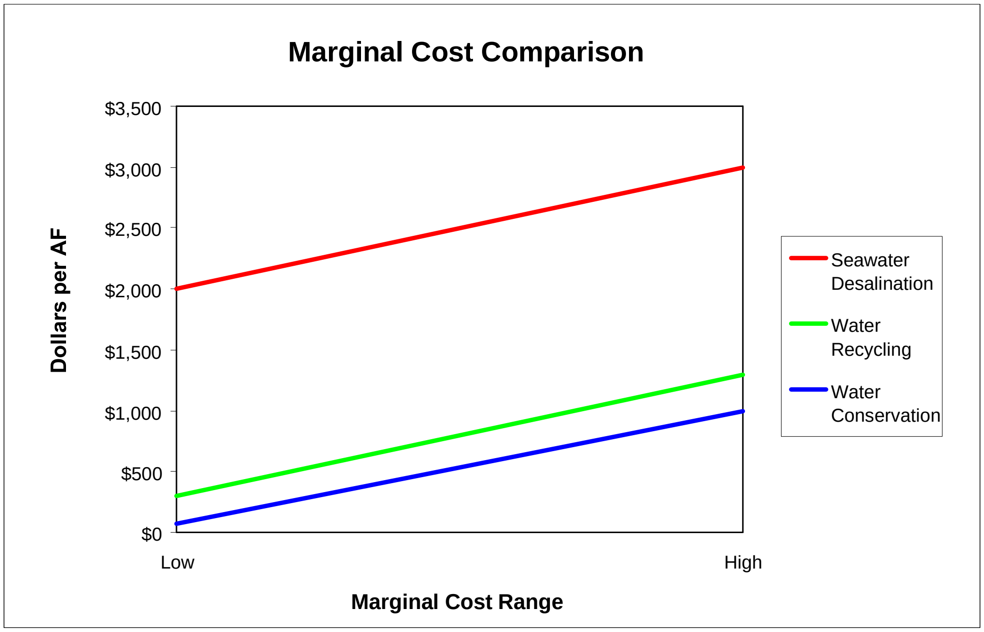
## Conclusion

It appears that realistic estimates of seawater marginal costs in California given current technology will range from a low of about $2,000 to $3,000 or more per acre-foot depending on local variables such as the site characteristics and cost, size of the facility, financing cost, energy cost, local intake water quality conditions, environmental mitigation costs, actual water production, and the cost of a connection and pumping to existing infrastructure.

This compares to much lower marginal costs of generally well under $1,000 per acre-foot for water conservation measures[75] and generally $300 to $1,300 per acre-foot for water recycling.[76] Both of these options appear to be far from fully utilized in California's urban areas.[77]

The relative marginal costs in California of seawater desalination, water recycling, and water conservation are shown in Figure 1 below.

**Figure 1**




While many agencies pursuing seawater desalination cite it as a drought-proof supply, as evidenced by the demand reductions by urban consumers in California during a recent series of dry years, it appears many water managers may underestimate demand elasticity during shortages. Behavioral-based demand reductions during shortages can occur at very low cost to ratepayers and society.

Many areas in California are now seriously evaluating and pursuing a suite of promising new water conservation measures, such as graywater use and local rainwater harvesting, which may be less costly and environmentally beneficial compared to seawater desalination. Low-impact development and integrated watershed and floodplain management practices are also gaining favor that can increase groundwater recharge and locally available water supplies while improving environmental conditions.

A better understanding of the real costs of the various water management options is important to rational decision making and appropriately prioritizing limited funding for the best alternatives for individual water users and society. The realistic costs of seawater desalination need to be more transparent and understood by the public. Proponents of seawater desalination projects should clearly delineate the costs of the projects in the categories identified in this paper. Also the costs of emerging water management alternatives such as graywater use and rainwater water capturing, low-impact development and integrated watershed and floodplain management practices should be better evaluated for identifying the most cost-effective options for improved water management in California.

**Acknowledgements**

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**About the Author:**

James Fryer has over 20 years of experience working on freshwater, estuarine, and marine conservation policies, programs, and projects. He has produced numerous papers and reports on water management policies, practices, and economics. He was the head of Marin Municipal Water District's water conservation programs in the 1990s. In subsequent work with the NGO community in the Florida Keys, he directed coral reef and water quality monitoring programs. He helped establish the Tortugas Ecological Reserve, a 191 square nautical mile, and largest marine protected area in U.S. continental waters while serving on the Florida Keys National Marine Sanctuary Advisory Committee. He developed a conservation planning GIS analysis of the Indian River Lagoon watershed, a 156-mile stretch of coastal lagoons and surrounding watershed in Southeast Florida, considered the most biologically diverse estuary in North America, and served on the Indian River Lagoon National Estuary Program Advisory Committee. He also assisted the Florida Dept. of Environmental Protection in the development of statewide water conservation plans for Florida. In 1997, he served on the U.S./South Africa Bilateral Commission sent to South Africa to assist the Mandela government with watershed and water resources planning. In 1996 he served as an advisor to the British Columbia Water and Wastewater Association for development of a regional planning effort. He has a M.S. in Environmental Management from the University of San Francisco where his thesis project was developing an Integrated Floodplain Management model for the San Francisco Bay-Delta watershed. He is an experienced river runner, scuba diver and sailor and recently returned to California after spending the previous five years on a global sailing voyage.

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**Endnotes**

1 "CALFED Water Use Efficiency Comprehensive Evaluation." CALFED Bay-Delta Program. 2006. p.144.

2 "California Water Plan Update 2009." DWR bulletin 160-09, Pre-final draft, Vol. 2, p.11-6.

3 More information on the potential for additional water conservation can be found at "CALFED Water Use Efficiency Comprehensive Evaluation." CALFED Bay-Delta Program, and "20X2020 Water Conservation Plan." February 2010. Available at: http://www.swrcb.ca.gov/water_issues/hot_topics/20x2020/docs/20x2020plan.pdf More information on the potential for increased recycled water use can be found in the "California Water Plan Update 2009." DWR bulletin 160-09, Pre-final draft, Vol. 2, p. 11-4, 11-5, 11-6.

4 See http://www.affordabledesal.com/home/test_data.html for analyses that indicates a seawater desalination cost range of about $800 to less than $1,000 per acre-foot of product water in 2006 dollars. The "California Water Plan Update 2009." DWR bulletin 160-09, Pre-final draft, Vol. 2, p.9-5 indicates a range of $1,000 to $2,500 per acre-foot for seawater desalination.

5 For more information on these issues see Residents for Responsible Desalination at: http://R4RD.org/

Also see: www.marinwatercoalition.org
www.desalresponsegroup.org
www.foodandwaterwatch.org www.environmentnow.org
http://www.surfrider.org/a-z/desal.php

6 See www.affordabledesal.com

[7] See: http://www.affordabledesal.com/home/test_data.html

[8] Personal communication with John MacHarg, March 3, 2010.

[9] Personal communication with John MacHarg, March 3, 2010.

[10] See: http://www.affordabledesal.com/home/participants.html

[11] See: http://www.affordabledesal.com/home/test_data.html

[12] Coleman, Matt. "Review of Energy Expense for Proposed Carlsbad Desalination Plant." p.1. California Coastal Commission staff report. http://documents.coastal.ca.gov/reports/2008/8/W4a-8-2008.pdf. p.34.

[13] "Seawater Desalination Pilot Program." MMWD Engineering Report, Kennedy/Jenks Consultants. January 26, 2007. p.188.

[14] See: http://www.affordabledesal.com/home/test_data.html

[15] Figures provided by and derived from operational records supplied by Tampa Bay Water in response to a request for public records in the fall of 2009. Records received from Tampa Bay Water include: Annual Desalination Budget Reports for FY 2003 through 2009, Desalination Product Water Production Report for 2003 through 2009, kWh energy usage per MG product water, Desalination Construction Cost by Major category spreadsheet, intake water temperature and salinity tables and graphs. There is more information on this issue in Tampa Bay section of this report.

[16] "Desalination Rehabilitation Study." Prepared for City of Santa Barbara by Carollo Engineers, March, 2009. p.4-3, 4-4.

[17] Derived from figures in MMWD staff Excel spreadsheet "Desalination Conceptual Cost Estimate" Updated October, 23, 2008 and based on costs in"Seawater Desalination Pilot Program." Marin Municipal Water District Engineering Report, Kennedy/Jenks Consultants. January 26, 2007.

[18] The 2006 capital cost figures were adjusted to 2009 dollars to provide a more level comparison basis with the capital costs of other facilities.

[19] The 2006 capital cost figures were adjusted to 2009 dollars to provide a more level comparison basis with the capital costs of other facilities.

[20] The Tampa Bay capital cost figure of $158 million ($110 million in 2002 and $48 million in 2007) was adjusted to $190.3 million in 2009 dollars to provide a more level comparison basis with the capital costs of other facilities.

[21] The 1991 capital cost figure of $34 million was adjusted to $59.6 in 2009 dollars to provide a more level comparison basis with the capital costs of other facilities. The original design capacity of 6.7 MGD was used to reflect the original capital cost per MGD design capacity.

[22] The distribution system improvement cost of $42 million was deducted from the total capital cost capital costs of $173.4 for a 10 MGD facility. These figures are from MMWD staff Excel spreadsheet "Desalination Conceptual Cost Estimate" Updated October, 23, 2008 and based on costs in "Seawater Desalination Pilot Program." Marin Municipal Water District Engineering Report, Kennedy/Jenks Consultants. January 26, 2007.

[23] The distribution system improvement cost of $22.6 million was deducted from the total capital cost capital costs of $111.2 million for a 5 MGD facility. These figures are from MMWD staff Excel spreadsheet "Desalination Conceptual Cost Estimate" Updated October, 23, 2008 and based on costs in "Seawater Desalination Pilot Program." Marin Municipal Water District Engineering Report, Kennedy/Jenks Consultants. January 26, 2007. Capital costs for the 5 MGD facility include some infrastructure and built in costs for future expansion up to 15 MGD capacity.

[24] Dundorf, Stephen; MacHarg, John; Seacord, Thomas. "Optimizing Lower Energy Seawater Desalination." The Affordable Desalination Collaboration. Abstract Manuscript for the International Desalination Association World Congress. August, 2006. P.17. Available at: http://www.affordabledesal.com/home/news.html

[25] "EIR for Carlsbad Desalination Facility." December 2005. p.4.7-14.

[26] Mack, Stephen F. & Roebuck, Robert L. "Santa Barbara's Desalination Facility: Going for the Long Term." Presented August 6, 1996 at AWWA Conference, Monterey, CA.

[27] www.dow.com/PublishedLiterature

[28] www.dow.com/PublishedLiterature

[29] See: http://www.affordabledesal.com/home/test_data.html

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31 Derived from figures in MMWD staff Excel Spreadsheet "Desalination Conceptual Cost Estimate" Updated October, 23, 2008 and based on costs in "Seawater Desalination Pilot Program." Marin Municipal Water District Engineering Report, Kennedy/Jenks Consultants. January 26, 2007.

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33 "Affordable Desalination Breaking the Energy Barrier." News Release by Affordable Desalination Collaboration, January 26, 2006. Available at http://www.affordabledesal.com/home/news.html

34 Dundorf, Stephen; MacHarg, John; Seacord, Thomas. "Optimizing Lower Energy Seawater Desalination." The Affordable Desalination Collaboration. Abstract Manuscript for the International Desalination Association World Congress. August, 2006. p.16. Available at: http://www.affordabledesal.com/home/news.html

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42 Reflects an average operating scheme of 23 years at 50% capacity and & 2 years at 100% capacity every 25 years.

43 Reflects an average operating scheme of 23 years at 50% capacity and & 2 years at 100% capacity every 25 years.

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45 "Final Environmental Impact Report, Marin Municipal Water District Desalination Project." URS, December, 2008. p.5-1.

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47 "Desalination, With a Grain of Salt – A California Perspective." Pacific Insitite. Appendix C, p 15.

48 Figures derived from operational records supplied by Tampa Bay Water in response to a request for public records in the fall of 2009. Records received from Tampa Bay Water include: Annual Desalination Budget Reports for FY 2003 through 2009, Desalination Product Water Production Report for 2003 through 2009, kWh energy usage per MG product water, Desalination Construction Cost by Major category spreadsheet, intake water temperature and salinity tables and graphs.

49 Figures provided by and derived from operational records supplied by Tampa Bay Water in response to a request for public records in the fall of 2009. Records received from Tampa Bay Water include: Annual Desalination Budget Reports for FY 2003 through 2009, Desalination Product Water Production Report for 2003 through 2009, kWh energy usage per MG product water, Desalination Construction Cost by Major category spreadsheet, intake water temperature and salinity tables and graphs.

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61 "Desalination Rehabilitation Study" Prepared for City of Santa Barbara by Carollo Engineers, March 2009. p.4-3.

62 Figures derived from operational records supplied by Tampa Bay Water in response to a request for public records in the fall of 2009. Records received from Tampa Bay Water include: Annual Desalination Budget Reports for FY 2003 through 2009, Desalination Product Water Production Report for 2003 through 2009, kWh energy usage per MG product water, Desalination Construction Cost by Major category spreadsheet, intake water temperature and salinity tables and graphs.

63 Capital cost from Poseidon Resources application to The California Debt Limit Allocation Committee. "Application for an Allocation of the State Ceiling on Qualified Private Activity Bonds for an Exempt Facility Project." July 30, 2009 Hearing Date. P.10.

64 Fryer, James. "Marginal Cost Analysis for the Proposed Carlsbad Project." November 4, 2009. Available at: http://documents.foodandwaterwatch.org/carlsbad-desal-analysis.pdf

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66 Coleman, Matt. "Review of Energy Expense for Proposed Carlsbad Desalination Plant." p.1. California Coastal Commission staff report. http://documents.coastal.ca.gov/reports/2008/8/W4a-8-2008.pdf. p.34.

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71 Based on $534 million in capital costs, 3% cpi/inflation, and in net present value terms in 2009 dollars.

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75 "CALFED Water Use Efficiency Comprehensive Evaluation." CALFED Bay-Delta Program. 2006. p.144.

76 "California Water Plan Update 2009." DWR bulletin 160-09, Pre-final draft, Vol. 2, p.11-6.

77 More information on the potential for additional water conservation can be found at "CALFED Water Use Efficiency Comprehensive Evaluation." CALFED Bay-Delta Program. Also "20X2020 Water Conservation Plan."

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More information on the potential for increased recycled water use can be found in “California Water Plan Update 2009.” DWR bulletin 160-09, Pre-final draft, Vol. 2, p. 11-4, 11-5, 11-6.

**FAC 8415 Desalination Plant** FY-14 SUC Recalculation

Reported Size: 471.833 KG (Thousands of Gallons/Day) V15.1

Sustainment:

| | | | | | | |
|---|---|---|---|---|---|---|
| O&M Cost Range | | $ 1.50 | to | $ 4.00 | per kgal produced | |
| Maintenance = | | 6% | | | of total O&M Cost | |
| Average total O&M * 6% = | | | $ 0.17 | | per thousand gallons | |
| Per day cost = | | 472 | * | $ 0.17 | $ 77.88 | |
| Per year cost | | 365 | * | $ 77.88 | $ 28,426.20 | |
| Per unit: | | $ 28,426.20 | divided by | 471.833 | $ 60.25 | per KG |
| | | | | | | |
| | | $ 60.25 | * | | 0 | |

Inflation from CY 2010

Sources: Seawater Desalination Costs, Water Reuse Association, Revision January 2012

Texas

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C:\FXM V16\FAC 8415 Desalination Plant

Texas Innovative Water 2010

A Seminar to Advance the Development and Management of Innovative Water Supplies in Texas

# How Much Does Seawater Desalination Cost?


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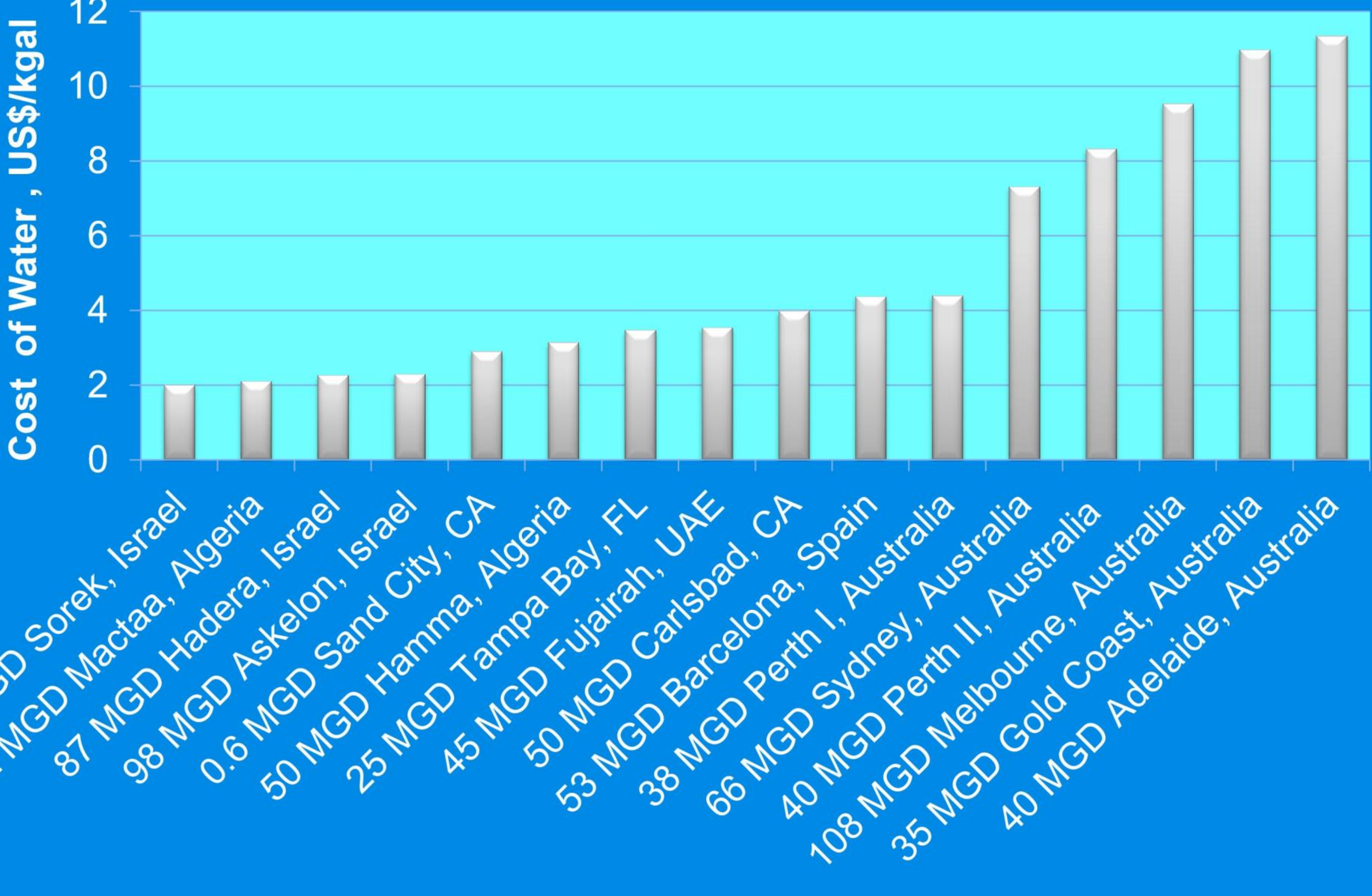
# Presentation Outline

- Overview of Current Desalination Cost Trends
- Low-Cost Bracket Desalination Projects – Key Features
- High-Cost Bracket Desalination Projects – What Factors Drive the High Costs?
- Key Cost Components

# Cost of Water of Recent Desalination Projects



# Costs of Recent US SWRO Projects

| Project | Status | Capital Cost (US$) | Annual O&M Cost (US$/kgal) | Cost of Water (US$/kgal) |
|---|---|---|---|---|
| 0.6 MGD Sand City, CA since 2010 | In Operation | [illegible] | [illegible] | [illegible] |
| 25 MGD Tampa Bay, FL since 2008 | In Operation | US$138 MM | US$1.54/kgal | US$3.48/kgal |
| 50 MGD Carlsbad, CA | In Financing | US$350 MM | US$1.75/kgal | US$4.00/kgal |
| 2.5 MGD Santa Cruz, CA | In Planning | US$59-64 MM | US$3.94/kgal | US$7.6-8.0/kgal |
| 2.5 MGD Brownsville Demo Project, TX | In Planning | US$22.5 MM | US$2.80/kgal | US$4.38/kgal |

| | | | | |
|---|---|---|---|---|
| 25 MGD-80 MGD<br>Coquina Coast, FL | In Planning | US$180 MM -<br>US$560 MM | US$1.99/kgal | US$4.47/kgal<br>(US$5.35-US$6.10<br>w/ conveyance) |

# Typical Cost and Energy Ranges
## (Medium & Large SWRO Plants)

| Classification | Cost of Water Production (US$/kgal) | SWRO System Energy Use (US$/kgal) |
|---|---|---|
| Low-End Bracket | 2.0 - 3.0 | 9.5 – 10.5 |
| **Medium Range** | **3.5 – 5.0** | **11.0 - 12.0** |
| High-End Bracket | 6.5 - 11.5 | 12.5 – 14.0 |
| Average | 4.0 | 11.5 |

# Common Features of Low-Cost Desalination Projects

- Point of Product Water Delivery within 5 Miles of Desalination Plant Site;
- RO System Design w/ Feed of Multiple Trains by Common High Pressure Pumps and Energy Recovery Systems;
- Turnkey (BOOT, BOO) Method of Project Delivery.

# Key Reasons for Cost Disparity Between High-End & Low-end Cost Projects

**(US$2.0 – 3.0 vs. US$6.5-11.5/kgal)**

- **Desalination Site Location** (NIMBI vs. Science Driven)
  - **Costly Plants Have Overly Long Product Water Delivery Pipelines**
  - **120 MGD Melbourne Plant – Cost of Plant/Delivery + Power Supply Systems =**

US$1.7 BB/1.1 BB (50 miles)

- 66 MGD Sydney SWRO Plant – Cost of Plant/Delivery System
  = US$560 MM/US$490 MM (10 miles of underground tunnel under Botany Bay).

## ➢ Environmental Considerations

- Complex Intakes & Diffuser Systems

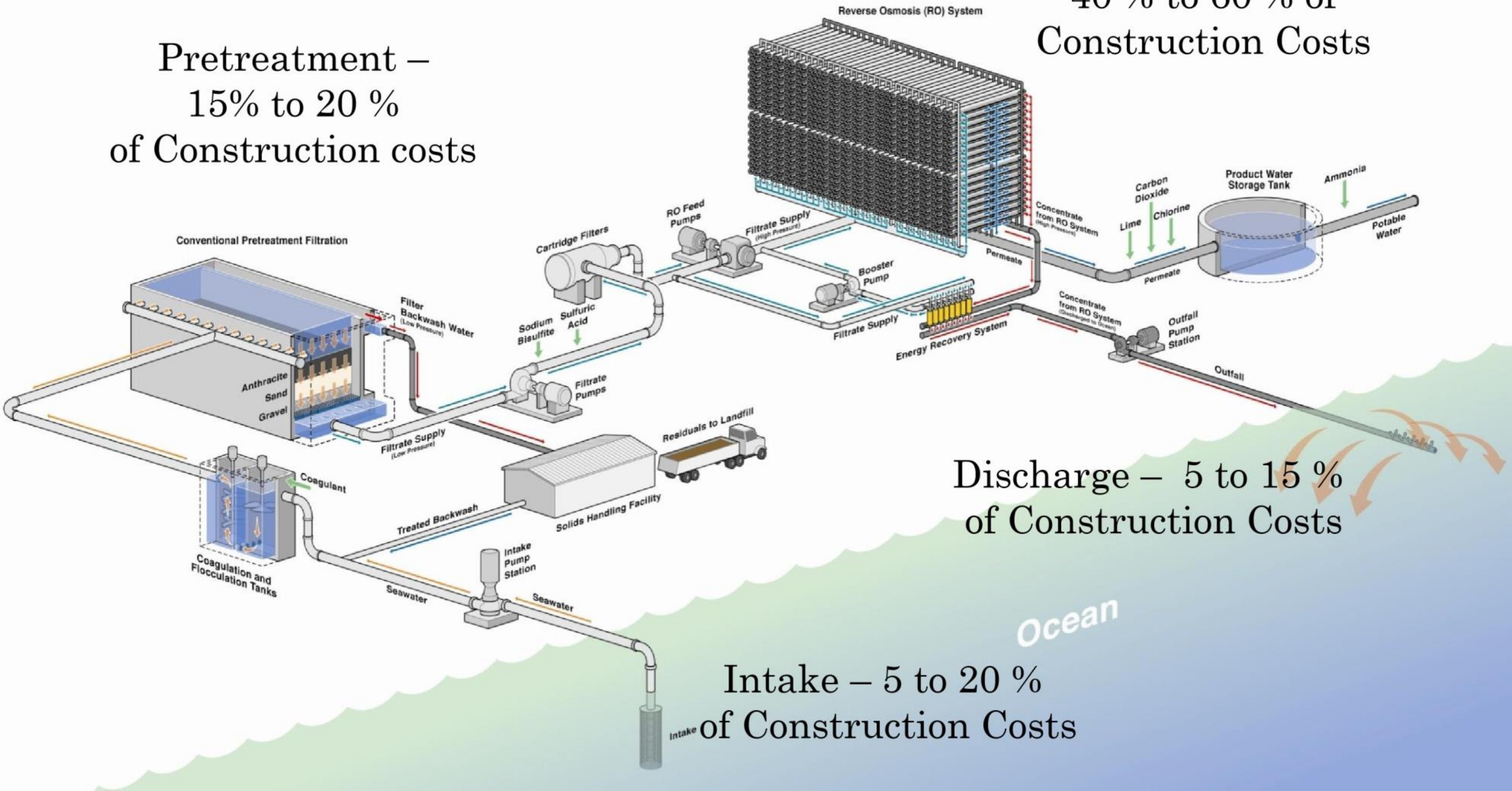
## ➢ Phasing Strategy

- Intake and Discharge System Capacity;
- Pretreatment & RO System Design;

## ➢ Labor Market Pressures

## ➢ Method of Project Delivery & Risk Allocation

# Seawater Desalination Plant – Construction Costs




RO System – 40 % to 60 % of Construction Costs

Pretreatment – 15% to 20 % of Construction costs

Discharge – 5 to 15 % of Construction Costs

Intake – 5 to 20 % of Construction Costs

# Intake Construction Costs
# Key Factors

- Very Dependent on Source Water Quality
- Usually US$0.5 – 1.5 MM/MGD (up to 3.0 MM/MGD for Complex Tunnel Intakes)
- Beach Well Intakes Are Usually Less Costly
- Horizontal and Slant Wells Comparable to Open Intakes
- Infiltration Galleries Often are More Expensive than Open Intakes

# Pretreatment Construction Costs

- Very Dependent on Source Water Quality & Type of Treatment Technologies
- Usually US$0.5 – US$1.5 MM/MGD
- High Quality Well Water Sources Require Only Cartridge Filtration (Low Cost Pretreatment)

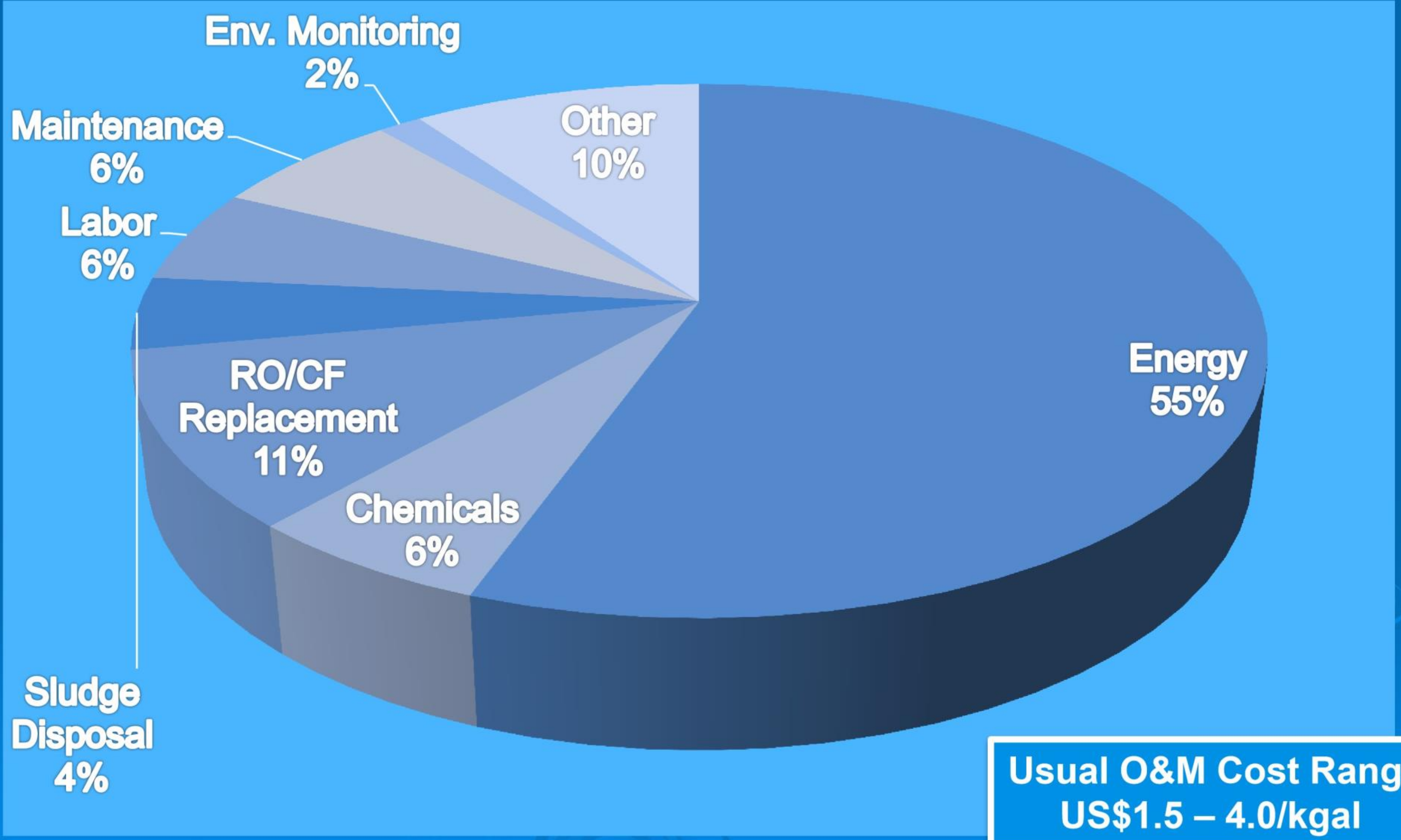
# SWRO System Construction Costs

- Dependent on Source Water Quality & Target Product Water Quality
- Usually Between US$1.5-4.0 MM/MGD
- Single-stage/Single Pass SWRO System is Least Costly

# Concentrate Disposal Construction Costs

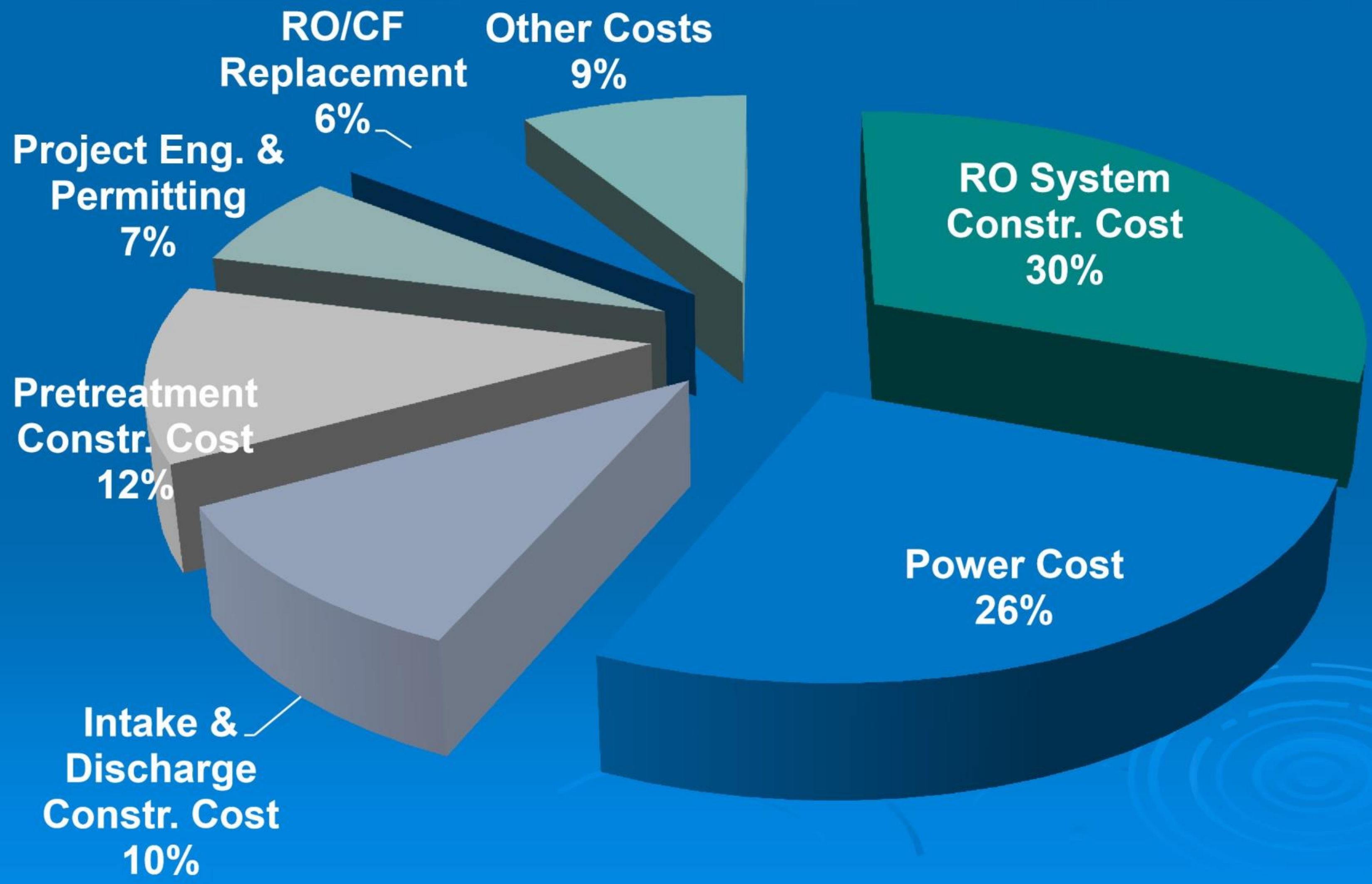
| Disposal Method | Construction Cost (US$ Million/MGD) |
|---|---|
| New Outfall w/Diffusers | 2.0 – 5.5 |
| Power Plant Outfall | 0.2 – 0.6 |
| Sanitary Sewer | 0.1 – 0.4 |
| WWTP Outfall | 0.3 – 2.0 |
| Deep Well Injection | 2.5 – 6.0 |
| Evaporation Ponds | 3.0 – 9.5 |
| Zero-Liquid Discharge | 5.5 – 15.0 |

# Typical O&M Cost Breakdown




**Usual O&M Cost Range**
**US$1.5 – 4.0/kgal**

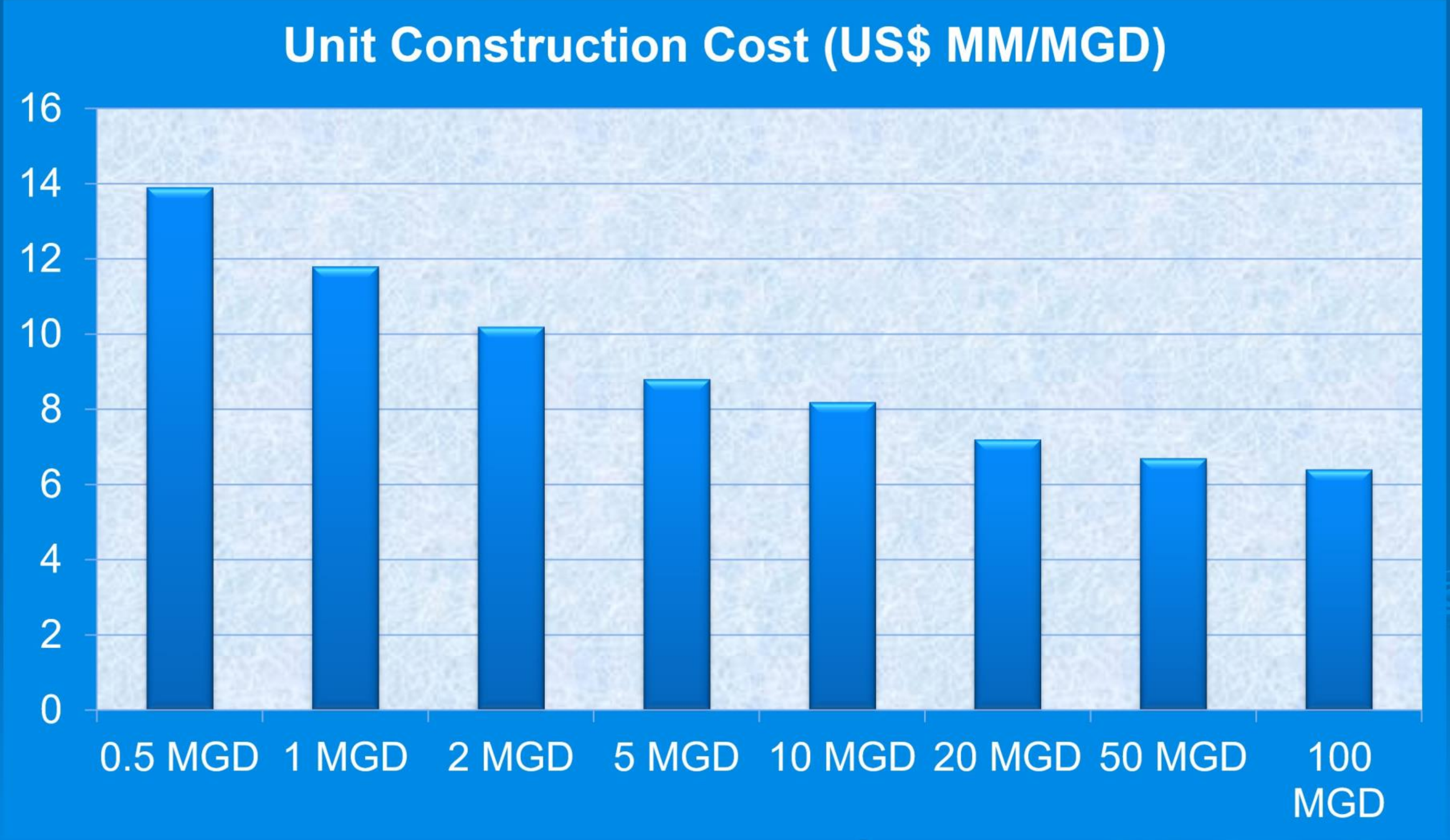
# Cost of Water Breakdown



# Key Factors Affecting Costs

- Plant Size – Bigger is Better
- Source Water Quality - TDS, Temperature, Solids, Silt and Organics Content.
- Product Water Quality – TDS, Boron, Bromides, Disinfection Compatibility.
- Concentrate Disposal Method;
- Power Supply & Unit Power Costs;
- Project Delivery Method & Financing;
- Other Factors:
  - Intake and Discharge System Type;
  - Pretreatment & RO System Design;
  - Plant Capacity Availability Target.

# Desalination Plant Construction Cost as Function of Capacity



# Product Water Quality & Costs

| Target WQ | Constr. Costs | O&M Costs | Cost of Water |
|---|---|---|---|
| TDS/Cl = 500/250 mg/L; Boron = 1 mg/L. | 1.0 | 1.0 | 1.0 |
| **TDS/Cl = 250/100 mg/L; Boron = 0.75 mg/L.** | **1.15-1.25** | **1.05-1.10** | **1.10-1.18** |
| TDS/Cl = 100/50 mg/L; Boron = 0.5 mg/L. | 1.27-1.38 | 1.18-1.25 | 1.23-1.32 |
| TDS/Cl = 30/10 mg/L; Boron = 0.3 mg/L. | 1.40-1.55 | 1.32-1.45 | 1.36-1.50 |

# Where Future Cost Savings Would Come From?

# "The Best" of Seawater Desalination Present Status & Future Forecasts

| Parameter | Today | Within 5 Years | Within 20 Years |
|---|---|---|---|
| Cost of Water (2010 US$/kgal) | US$2.0-3.0 | US$1.5-2.5 | US$1.0-1.5 |
| Construction Cost (Million US$/MGD) | 4.5-8.0 | 4.0-6.5 | 2.0-3.5 |
| Power Use of SWRO System (kWh/kgal) | 9.5-10.5 | 8.0-10.0 | 5.0-6.5 |
| Membrane Productivity (gallons/day/membrane) | 6,500-12,500 | 9,000-15,000 | 25,000-40,000 |
| Membrane Useful Life (years) | 5-7 | 7-10 | 10-15 |
| Plant Recovery Ratio (%) | 45-50 | 50-55 | 55-65 |

# Concluding Remarks

- Seawater Desalination is Economical Today and Will Become Even More Cost-Competitive in the Future;
- Typical Cost of Water is US$3.5 to US$5.0/kgal;
- The Future of Seawater Desalination Is Bright – 20% Cost of Water Reduction in the Next 5 Years;
- Long-term Investment In Research and Development Has the Potential to Reduce the Cost of Desalinated Water by 80 % In the Next 20 Years.

# Seawater Desalination Costs

## Questions?

# Investment and production costs of desalination plants by semi-empirical method

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***Abstract* - Energy consumptions and costs of desalting systems are among the main parameters affecting the choice of certain desalting system and desalted water final cost. The paper describes a semi-empirical method for determining production and investment costs taking into account plant capacity, availability, energy price and consumption, plant capital cost, membrane service life and other process variables. This study concerns the different desalting processes of seawater, namely distillation multi-stage multiflash, distillation multi-effect, vapour compression and the reverse osmosis. Results show that this method can give a good estimation of the investment and production costs for the concerned processes. Surely, this method can be useful especially in the maturation and the feasibility of any project in the field of desalination. So that most decisions of realization of any project can be taken in a relatively short time and therefore, costs of engineering can be reduced considerably.**

***Keywords* -** Desalination, Process, Economical, Plant

## 1. Introduction

The need of pure water throughout the world is in constant increase, as well as its insufficiency due to limited stocks and pollution. With more than 70% of the earth's surface covered with water, our planet is a "Water Planet". It is the most common substance in our life and is fundamental to all things living. About 97.4% (1350 × 106 km$^3$) of the water on the earth's surface is salty water leaving less than 3% of water as freshwater. Two per cent of the freshwater is stored as snow, polar ice caps and glacier (27.5 × 106 km$^3$) while 0.6% is stored below ground, soil moisture and swamp water (8.3 × 106 km$^3$) [1]. The world has been a six fold increase in water usage since 1950 and the demand for freshwater is increasing twice as fast as population growth. The world population will increase from 6 billion in year 2000 to 8 billion in 25years [1]. The only conclusion that can be drawn from the above facts is that life to continue on earth will need to use the abundant salty water to produce freshwater supplies capable of meeting the increasing demand. Desalination in the last few decades has proven to be the method to

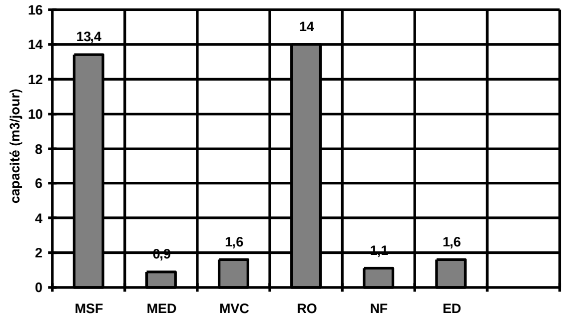


**Figure 1**. Plants of desalting brackish and seawater throughout the world, according process type [2].

Produce freshwater out of salty water with competitive cost compared to the cost of alternative sources. Because of that, different water desalting plants are used to generate large volumes of acceptable purity water, by processing brackish water, seawater and even waste water. The currently processes employed throughout the world are shown in figure 1.
The major task of desalination engineers is to choose the appropriate process with reduced energy consumption and specific investment cost, long service time and high availability with low amount of maintenance. The cost of producing a unit volume of product water has shown a continuous change over the last two decades. The method of estimation is applied to the plants of multi-stage flash (MSF-Once Through & Brine Recirculation), multi-effect distillation (MED-Horizontal Tubes & Vertical Tubes), vapor compression (VC-Mechanical & Thermal) and the reverse osmosis (RO).

## 2. Economical evaluation and study

This section develops and discusses a method that estimates investment and production costs for different type of processes. The cost of the produced water for each process is estimated including capital cost, energy cost, operation and maintenance cost, membrane replacement cost and filters replacement cost when used [3].

The data and the assumptions used in this section for the estimation of the capital investment and the production costs for each type of plant, are based on cost studies for specific site items for an approximate comparison plants concerning the costs *Cn* of item *n* and the units of the flow rates and energy rates, *Wn* and capital and erection costs for the main comparison of the year 1986 [4]. These assumptions can be resumed as follows:

- The major design parameters for various types of 1000 $m^3$/day desalting;
- For thermal desalting process plants, steam requirements are handled as a utility part of operating cost;
- Estimated cost of desalting seawater is based on plant life (about 30 years), production rates approximately 100%, capacity produced 2 × 1000 $m^3$/day, and stream factor (time that the plant is considered to be in service) nearly equals 85%.

### 2.1. Investment cost estimation

Total investment cost is defined as the sum of fixed capital cost and working capital cost; this includes the items listed below:

- Direct costs
- Indirect costs
- Contingencies
- Contractor's fee
- Start-up costs (a)

} Total Depreciable Capital Cost

- Land costs
- Site development

} Fixed Capital Cost

- Start-up costs (b) } Working capital

} Total Capital Cost

(a) Depreciable portion of start-up costs.
(b) Non-depreciable portion of start-up costs.

**Figure 2**. Different items of investment cost.

Greig and Wearmouth [4] consider that the total capitalized cost of the plant is to be the sum of capital cost, erection cost and the capitalized operational running costs (steam, electrical power, seawater, compressed air, chemicals and replacements materials). Therefore, the capitalized operational running cost for each type of plant is estimated with the method used for the approximate comparison for other sites according to the following equation:

$$C_t = C_c + C_e + C_r \quad (1)$$

$$C_{rn} = C_{an} \times I \quad (2)$$

$$C_{an} = 8760 \times W_n \times C_n \times A \quad (3)$$

$$I = \left[ \left(1 + \frac{i}{100}\right)^T - 1 \right] \Big/ \frac{i}{100} \quad (4)$$

$$C_{an} = 8760 \times W_n \times C_n \times A \times I \quad (5)$$

*Ct*: plant total capitalized cost; *Cc*: plant capital cost; *Ce*: plant erection cost; *Cr*: plant capitalized operational running cost; *Crn:* plant capitalized operational running cost of item *n* (steam or electrical power or seawater or compressed air or an individual chemical); *Can*: annual operating cost of the item *n*; *I*: represents worth factor; *i*: percentage interest rate; *T:* plant life time; *Wn*: the flow rate of energy rate of the item *n*; *Cn*: unit price of the item *n* for no specific site; *A*: stream factor of the plant.

### 2.2. Production cost estimation

An important task is to estimate the costs for operating the plant and/or facility, and for selling the products. Total production costs consist of manufacturing and general expenses. The manufacturing are also termed operating costs and is generally divided into direct and indirect portions. The time period that is defined for the basis of production costs is usually a year, although it can also be based on unit-of-product and 24 hours operating or daily basis and can be represented as the sum of the items shown in figure 3.

### 2.3. Investment cost calculation

Capital running costs for each type of plant is estimated according to Greig and Wearmouth [4]. Building and transport costs are not taken into account due to differences of desalting process types. Results are summarized in table 1.

### 2.4. Production cost calculation

The total production cost is the sum of direct and indirect costs. A semi-empirical method is used to estimate the production cost. It is based on observed results in different industries such as chemistry and petrochemical where data base has been built over a long period of time (15 to 20 years). Details of different calculation equations, according to Reidy [3] are listed in figure 4.

Results for each plant expressed as capital cost, energy cost, chemical cost and different other costs in $/$m^3$/year are listed in table 2.

### 2.5. Discussion

The economic results are mainly based on the investment and production costs for each type of plant calculated using the results obtained by the method proposed by Greig and Wearmouth [4]. As it is known, we have used the results (data in our case) obtained from the approximate comparison for calculation the running costs, however, the values of the capital and erection costs proposed in the main comparison are taken as data for our case. Justifying this choice by the importance given in our opinion to the running costs which may vary considerably from one country to another, like for example the energy and labour costs, which could represent a major and important part of the plant's capital cost during its whole life. The cost structure keeps, in the case of production cost, almost the same pattern and the same share of capital, energy, chemicals and furniture and others costs, which are in the range of those found in literatures and publications having potentially an expected errors. This can be in part explained, in the case of the investment cost, that its composition in figure 2 is reduced to the method [4] where assumptions are made to neglect some extra expense involved in constructing service facilities, storage facilities, loading terminals (this is very true for desalting plant), transporting facilities, and an other necessary utilities at a completely undeveloped site. The fixed capital investment for a new plant located at an undeveloped site may be much greater than that for an equivalent plant constructed as an addition or expansion to an existing plant. On the other hand, and in the case of the production cost, the multiplying factor for each item in the composition of production cost (figure 4) are not determined in the field of the desalination that is why errors in the estimation can be expected to be important in some cases.

- Raw materials
- Catalysts and solvents
- Utilities
- Maintenance supplies
- Maintenance labor & supervision *Direct Cost*
- Operating supplies
- Operating labor
- Quality control
- Royalties

- Depreciation
- Property taxes *Fixed Cost*
- Insurance
- Rent
- Indirect labour, supervision
- Fringe benefits
- Medical facilities
- Fire, safety, security *Plant* *Prod. Indirect*
- Waste treatment facilities
- Recreation facilities *Overhead Cost* *Cost*
- Salvage services, control laboratories
- Shipping & receiving facilities
- Storage & maintenances facilities

- Executive
- Clerical
- Engineering *Administration Cost*
- Legal
- Communications

-Sales expenses *General Cost*
-Advertising *Marketing cost*
- Product distribution
- Sales service

- Financing interest
- Research and developments

**Figure 3.** Different items of total production cost.

**Table 1**. Investment costs of different desalting seawater plants.

| Plant | MSF-OT | MSF-BR | MED-VT | MED-HT | MVC | TVC | RO |
|---|---|---|---|---|---|---|---|
| $\$/m^3/$year | 0.71 | 0.75 | 0.91 | 0.85 | 0.39 | 0.65 | 0.93 |

**Table 2**. Production costs of different desalting seawater plants.

| Plant | Production cost (%) | | | | Prod. Cost ($\$/m^3/$) |
|---|---|---|---|---|---|
| | Capital | Energy | Chem. Fournît. | Other | |
| MSF (OT) | 15 | 37 | 3 | 45 | 1.20 |
| MSF (BR) | 21 | 30 | 2 | 47 | 1.34 |
| MED (HT) | 18 | 29 | 13 | 40 | 1.38 |
| MED (VT) | 28 | 22 | 16 | 34 | 1.45 |
| MVC | 21 | 7 | 4 | 68 | 1.02 |
| TVC | 17 | 34 | 2 | 47 | 1.15 |
| RO | 12 | 3 | 34 | 51 | 1.81 |

It is to be noted that we can apply the same data, as in the production cost, for estimating the investment cost using the composition of the different items shown in figure 2. But the problem is that for the periods start up costs (1 and 2) and the working capital cost in the field of desalination are unknown period for us. So for the rest, we can consider that this can be in a great similitude to any other plant in the field of chemistry.

| *Direct cost* |
|---|
| Raw material=□(vol. incoming streams)□unit Price |
| Catalyst-solvents=□(vol.income.streams)□unit Price |
| Utilities: |
| Electricity= Power consumed □ Rate |
| Fuel= Fuel consumed □ Rate |
| Stream = Stream consumed □ Rate |
| Operating lab= Operat.labor [(a)] (hr/kg) □ (rate, \$/hr) |
| Operating supervision = 0.20 □ Operating labor cost |
| Quality control = 0.20 □ Operating labor cost |
| Maintenance labor = 0.027 □ fixed capital Cost |
| Maintenance labor = 0.018 □ fixed capital Cost |
| *Indirect costs* |
| *Fixed Cost* |
| Depreciation=(1-fs)(c) □ deprec.capit.cost /plant life |
| Property taxes = 0.02 □ fixed capital cost |
| Insurance = 0.01 □ fixed capital cost |
| *Plant overhead costs* |
| Fringe Benefits=0.22□(direct labor & supervis.)(e) |
| Overhead = 0.5 □ (direct labor & supervision)(e) |
| *General costs* |
| Administrative = 0.045 □ production cost |
| Commercial = 0.135 □ production cost |
| Financing= i □ (fixed capital cost + working capital) |
| Research = 0.0575□ production cost |
| ***Production cost = ∑ items above*** |

(a) expressed by modified Wessel equation; (b) fixed capital cost = depreciable capital cost + land development cost;
(c) salvage fraction of original cost (fs = 0.1);
(d) working capital cost = 0.20 × (fixed capital cost); (e) direct labor includes both operating and maintenance labor.

**Figure 4**. Direct and indirect calculation costs.

## 3. Conclusion and recommendations

We can say that the results found are interesting and encouraging mainly when some data of the plant are not available before the detailed engineering design stage. Such methods provide good order of magnitude estimates for early budgetary purposes. They can be taken as an introduction for the development of new techniques where the number of the many factors influencing the estimation of different costs may be reduced to a minimum number of variables. Consequently and in the case of the production cost, the different items are expressed in relationship with basically fixed capital cost, labour cost and production cost. For future purpose, it is suggested that a semi-empirical method for the estimation of the investment cost will be developed with an adequate number of items which will depend only for example on capital erection, and investment costs just like in the case of the production cost. And why not creating a data bank concerning the different items of the costs and through a sufficient and necessary period of time adjust the factors used in the production cost estimation to the field of desalination, and proposing an interesting model in the same way for the investment cost estimation.
At the end we hope that the developed methods will completely be empirical so when applying such methods in other countries will not require local rates and neither specific site parameters. Such model will meet at least the needs in the stage of the maturation and the feasibility of any project not more?

## 4. References


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America's Authority in Membrane Treatment

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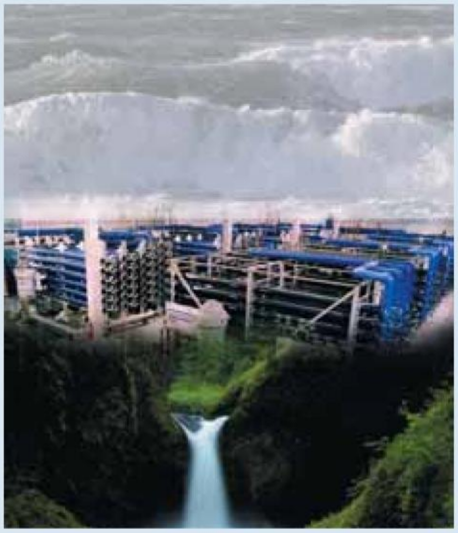
American Membrane Technology Association

*Improving America's Waters Through Membrane Treatment and Desalting*

# Membrane Desalination Costs

The growing demand for fresh water in many areas of the world, due to drought, water shortages, population increases and the desire for high quality drinking water, has spurred unprecedented interest in the process of desalting seawater or brackish water (less salty than seawater, but not fresh) to increase the reliability and quantity of water supplies. Long used on ships, island resorts and in water-short countries, the practice of employing desalting technology to produce large-scale domestic supplies is only a few decades old in the United States.



Currently, more than 1,300 desalting plants are operating in the United States, producing over 400 million gallons per day of high quality water, mostly for drinking, with an anticipated investment for the next 5 years of almost $3 billion. Worldwide membrane and thermal desalination capacity is over 11 billion gallons per day from over 12 thousand plants, worth $9.2 billion per year, growing at rate of 12% per year. Desalinated water has found many uses throughout the world. As shown in Figure 1, the largest of which is the production of acceptable quality drinking water. This water, in general, meets the US health and safety standards of the Environmental Protection Agency (EPA) and Food and Drug Administration (FDA) as well as standards established by other global Agencies, such as the World Health Organization (WHO).

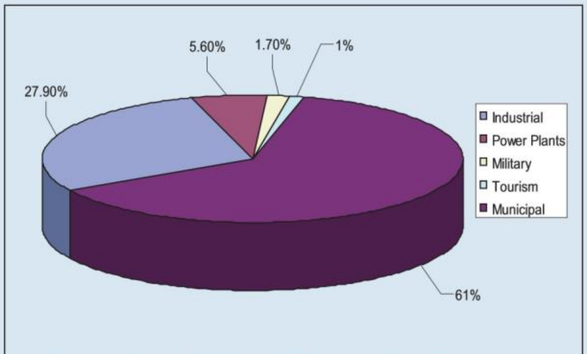



***Figure 1: Worldwide Distribution of Desalination Market Users***

Figure 2 shows the general cost reduction trend in the last few decades, in producing water using brackish and sea water sources.

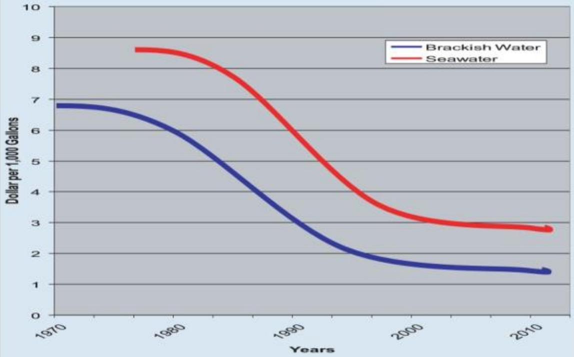



***Figure 2: Cost Reduction in Membrane Desalination***

Over the last 3 decades, pricing for desalting elements has been reduced substantially. As shown in Figure 3, due to technological improvements by suppliers, automation in the manufacturing process and competition, there have been significant reductions in seawater membrane costs. Similar trends have been present in brackish water modules.

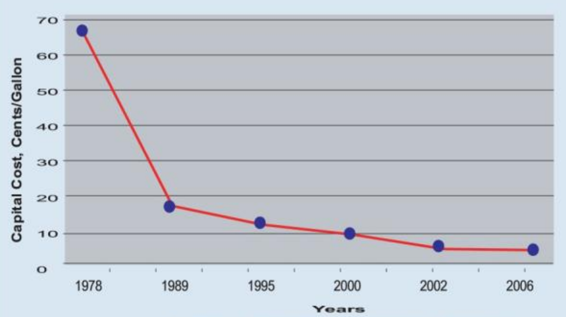



***Figure 3: Seawater Element Price Reduction***

Most US plants In coastal areas,desalt brackish waters, as local sources of fresh and brackish water are depleted. However there will be more large-scale seawater desalting plants built, most likely in California, Texas and Florida. Many growth opportunities exist in commercial, industrial and municipal applications for furthering the supply of good quality, low salinity water.

The most common objection to using desalted water to help meet the nation's growing water needs is that. "The process is too expensive." This is no longer valid since recent developments in both technology and processes have dramatically decreased the cost of desalting water using membrane technologies.

## Desalting Cost as a Portion of Total Supply

In most cases, desalted water is not the sole source of a community's supply. It is usually combined with water from less expensive sources. For instance, as shown in Table 1, if a community paying $2.50/1,000 gallons for its existing water decides to double its supply with desalted brackish water, in a worse case scenario, a typical family's monthly water bill would increase by about $3 per month. Similarly, if the augmented supply is 10% from desalted seawater, the monthly increase would be less than $6.60.

**TABLE 1: TOTAL WATER COSTS**

| SUPPLY TYPE | Consumer[1] $ per 1000 gallons | Total Family To Cost[2] $ per month |
|---|---|---|
| Existing Traditional supply | $0.90-2.50 | $10.80-$30.00 |
| New Desalted Water: | | |
| Brackish[3] | $1.50-3.00 | $18.00-$36.00 |
| Seawater[4,5] | $3.00-8.00 | $36.00-$96.00 |
| Combined supply[6] Traditional + brackish | $1.20-$2.75 | $14.40-$33.00 |
| Traditional + seawater | $1.11-$3.05 | $13.32-$36.60 |

1. Price includes all costs to consumers for treatmentand delivery.
2. Cost is based on a family of four using 100 gallonsper day per person, for a total monthly use of 12,000 gallons. Cost is based on the average of the "To Consumer" cost shown.
3. Brackish is moderately salty-1,000-5,000mg/Ltotal dissolved solids (TDS).
4. Seawater contains 30,000-35,000mg/L TDS.
5. Cost is for typical urban coastal community in theUSA. Costs for inland communities may be higher.
6. Combined supply costs are for the traditional supplyaugmented with 50% of desalted brackish water, or 10%. of desalted seawater.

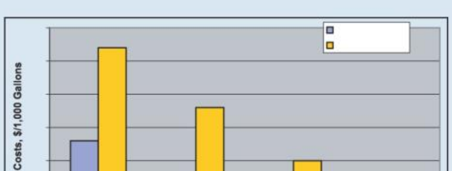
## Desalting Versus Traditional Water Development

In the US, most inexpensive traditional water resources have already been developed. New sources of supply will be more expensive than the existing ones. Of the potential new treatment options, in many cases, desalting a local resource is financially and environmentally competitive with the traditional methods such as building dams, aqueducts, canals and waste treatment plants. Cost comparisons are often made to existing water supplies. Actually, since desalted water represents a new source of supply, comparisons should be made to the cost of developing other new sources, such as surface water impoundments, remote deep well fields, dams and long distance pipelines.

In the last decade, desalting technology has improved significantly and costs have decreased by over 50 percent. At the same time, the cost of developing traditional water sources has escalated, as drinking water quality and environmental standards have become more stringent. Inflation affected prices and the distances from source to consumer have also increased. In many watershort areas, the costs for desalted water are already competitive with the tapping of new traditional supplies. As alternative energy sources and improved processes and equipment are developed, additional desalting cost reductions can be expected.

## Cost Factors and Graphs

The cost factors of desalting include capital costs and operating and maintenance costs. Costs can vary considerably from one locality to another based on a number of issues. In general, the amount of salt to be removed greatly affects the cost of desalting plant operation. The more salts to be removed, the more expensive the desalting process. The capacity of the facility also impacts costs, with larger plants generally being more economical. As shown in Figure 4, the larger the facility, the more cost efficient will be the utilization of equipment, labor and funds.



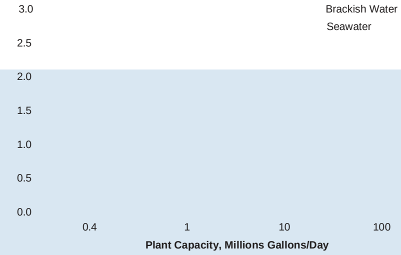




*Figure 4: Typical Operation and Maintenance Costs for Brackish and Seawater Desalination Plants*

Energy and recovery of capital are the main ingredients of the total cost of water, amounting to about 75% of the total, as shown in Figure 5. To these values, 10-15% can be added for profit, if the desalting project is contracted as a sale of water. The energy cost portion of the total cost greatly depends on the power/fuel pricing.

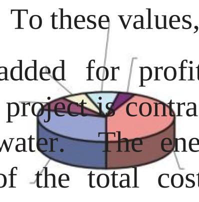



*Figure 5: Breakdown of Total Cost of Desalinated Water*

Other factors include the amount and type of pre and post treatment required, ancillary equipment selected, reliability, disposal of salts (concentrate), regulatory issues, land costs and conveyance of the water to and from the plant. Installing and operating a desalting plant involves a number of individual cost items, all of which are affected by local conditions. Figure 6 depict typical breakdowns of these costs.

15%

Process Equipment

49% ***Figure 6: Breakdown of Desalination Plant Capital Costs***

1. Indirect Costs Include: working capital, taxes,insurance, land, engineering and project management.
2. Outfall cost does not include concentrate dischargetreatment which sometimes could be a significant portion of the cost.

This material has been prepared as an educational tool by the American Membrane Technology Association (AMTA). It is designed for dissemination to the public to further the understanding of the contribution that membrane water treatment technologies can make toward improving the quality of water supplies in the US and throughout the world.

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# The Economics of Desalination

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Cost is a major factor in implementing desalination technologies and usually is site specific. This chapter provides an overview of factors that determine desalination cost, typical desalination cost estimation models, various cost factors, and approximate costs based on a review of case studies and available literature.

## Factors Affecting Desalination Costs

Several factors affect desalination cost. In general, cost factors associated with implementing a desalination plant are site specific and depend on several variables. Major cost variables are briefly described below. Details are provided in various documents (Cost Estimating Procedures 2003).

**Quality of Feedwater.** The quality of feedwater is a critical design factor. Low TDS concentration in feedwater (e.g. brackish water) requires less energy for treatment compared to high TDS feedwater (seawater). Low TDS allows for higher conversion rates and the plant can operate with less dosing of antiscalant chemicals. The pre-treatment of surface waters such as tidal waters will be more costly compared to brackish groundwater because of the potential existence of more contaminants in these waters.

**Plant Capacity.** Plant capacity is an important design factor. It affects the size of treatment units, pumping, water storage tank, and water distribution system. Large capacity plants require high initial capital investment compared to low capacity plants. However, due to the economy of scale, the unit production cost for large capacity plants can be lower.

**Site Characteristics**. Site characteristics can affect water production cost. For example, availability of land and land condition can determine cost. The proximity of plant location to water source and concentrate discharge point is another factor. Pumping cost and costs of pipe installation will be substantially reduced if the plant is located near the water source and if the plant concentrate is discharged to a nearby water body. Also, costs associated with water intake, pretreatment, and concentrate disposal can be substantially reduced if the plant is an expansion of an existing water treatment plant as compared to constructing a new plant.

**Regulatory Requirements.** These costs are associated with meeting local/state permits and regulatory requirements.

## Desalination Implementation Costs

Desalination plant implementation costs can be categorized as construction costs (starting costs) and operation and maintenance (O & M) costs.

### Construction Costs

Construction costs include direct and indirect capital costs. The indirect capital cost is usually estimated as percentages of the total direct capital cost. Indirect costs may include freight and insurance, construction overhead, owner's costs, and contingency costs. Below is a description of various direct and indirect costs associated with constructing a desalination plant.

**Direct Costs.**

- ***Land.*** The cost of land may vary considerably, from zero to a sum that depends on site characteristics and plant ownership (public vs. private).

- ***Production wells.*** The cost of well construction depends on plant capacity and well depth. Also, see auxiliary equipment below.

- ***Surface water intake structure.*** The cost of water intake structures depends on plant capacity and meeting environmental regulations. Also, see auxiliary equipment below.

- ***Process equipment.*** The process equipment includes water treatment units (membranes), instrumentation and controls, pre- and posttreatment units and cleaning systems. Process equipment costs depend on plant capacity and feedwater quality.

- ***Auxiliary equipment.*** Auxiliary equipment includes open water intakes, wells, storage tanks, generators, transformers, pumps, pipes, valves, electric wiring, etc.

- ***Buildings.*** Building costs include the construction of structures such as control room, laboratory, workshops, and offices. Construction cost is site-specific depending on site condition and type of building.

- ***Concentrate disposal.*** The cost of concentrate disposal system depends on the type of desalination technology, plant capacity, discharge location, and environmental regulations.

**Indirect Costs.**

- ***Freight and insurance.*** Freight and insurance (or premium) cost is typically estimated as 5% of total direct costs.

- ***Construction overhead.*** Construction overhead costs include labor costs, fringe benefits, field supervision, temporary facilities, construction equipment, small tools, contractor's profit and miscellaneous expenses. This cost is typically estimated as 15 percent of direct material and labor costs.

- ***Owner's cost.*** The owner's cost includes land acquisition, engineering design, contract administration, administrative expenses, commissioning and/or startup costs, and legal fees. It is estimated as approximately 10 percent of direct materials and labor costs.

- ***Contingency cost.*** This cost is included for possible additional services. It is generally estimated at 10 percent of the total direct costs.

**Operating and Maintenance Costs**

The operating and maintenance (O & M) costs consist of fixed costs and variable costs.

**Fixed Costs**. Fixed costs include insurance and amortization costs. Usually, insurance cost is estimated as 0.5 percent of the total capital cost. Amortization compensates for the annual interest payments for direct and indirect costs and depends on the interest rate and the life-time of the plant. Typically, an amortization rate in the range of 5-10 percent is used.

**Variable Costs.** Major variable costs include the cost of labor, energy, chemicals, and maintenance. Labor costs can be site-specific and also depend on plant ownership (public or private) or special arrangements such as outsourcing of plant operation. Energy cost depends on availability of inexpensive electricity (or other power source). For example, energy cost can be reduced if the desalination plant is co-located with a power generation plant. Chemical use depends mainly on feedwater quality and degree of pre-/posttreatment and cleaning process. The cost of chemicals is affected by type and quantity of such chemicals as well as global market prices and special arrangements with vendors.

The major maintenance cost pertains to the frequency of membrane replacement, which is affected by the feedwater quality. For low TDS brackish water, the replacement rate is about 5% per year. For high TDS seawater, the replacement could be as high as 20%. The cost for maintenance and spare parts is typically less than 2% of the total capital cost on an annual basis.

## Cost Estimation Models

Several models are available for estimating desalination costs. Model applications are mostly limited to site specific conditions and give approximate estimates. Nevertheless, cost models can be used as an indicator of potential costs for planning a desalination facility. Three typical cost models are described below.

### WTCost© Model

The Bureau of Reclamation, with the assistance of I. Moch & Associates and Boulder Research Enterprises has developed WTCost©, a computer program that estimates the capital and operation & maintenance costs (Cost Estimating Procedures 2003). The model provides estimates for the following desalination technologies: Brackish water reverse osmosis (BWRO), seawater reverse osmosis (SWRO), mechanical vapor compression (MVC), multiple effect distillation (MED), multi-stage distillation (MSF), nanofiltration (NF), and electrodialysis reversal (EDR). The model provides a set of default values for all input parameters, but default parameters can be overridden when more accurate information becomes available.

WTCost© model provides estimates of capital costs and indirect costs described above. Capital costs include start-up costs for desalination technologies, various pretreatment and posttreatment options, and concentrate disposal options (surface water discharge, disposal to sewer system, land application, evaporation ponds, deep well injection, and zero discharge (using concentrators). Other capital costs include feedwater intake infrastructure (seawater and brackish surface water, seawater and brackish well water), feedwater pipeline, general site development, auxiliary equipment, and buildings. The model gives estimates of indirect depreciating and non-depreciating capital costs. Depreciating costs include freight and insurance, interest during construction, construction overhead, owner's expenses, and contingency. Nondepreciating costs (costs that do not lose value or expense) include land and working capital costs (ready cash on hand to cover the day-to-day expense of operating the facilities).

WTCost© estimates annual costs. Annual costs vary directly with the quantity of water produced and are indexed to the price levels at the date of estimate. Annual cost estimations are provided for labor (for staff requirements and plant size), chemical costs (for type of desalination technology), energy (cost of electricity in $/kWh), type of desalination technology including plants co-located with power plants, replacement parts and maintenance materials, membrane replacement cost, insurance (assuming 5% of total capital costs), annual cost of capital, and plant factor (the percent of time the units will operate during the year at the percent design capacity.

### Desalination Economic Evaluation Program (DEEP)

The International Atomic Energy Agency (IAEA) has developed the Desalination Economic Evaluation Program (DEEP) to perform economic analysis of desalination using nuclear energy versus alternative sources of energy (International Atomic Energy Agency 2004). The model is applicable to largescale (>25 MGD capacity) desalination plants and is designed for research purposes, not industrial cost analysis. Information about DEEP is available on the IAEA Nuclear Desalination Unit's website at www.iaea.org. Currently, DEEP version 2.1 is available on CD-ROM at no charge from the IAEA, but license agreement and use permission is required. A brief description of DEEP follows.

DEEP is based on hybrid Microsoft Excel spreadsheet and Visual Basic methodology. There are three categories of input requirements: Model Data, User Input Data, and Default Data. Model Data refers to certain specified technical parameters that are built within the model and cannot be changed by the user. User Input Data are parameters that should be input by the model user. User Input Data are mostly site specific and include information such as plant location, type of technology, plant capacity, and feedwater salinity. Default Data are parameters that characterize plant performance (e.g. energy recovery efficiency) and economic parameters (e.g. interest rate). Default Data are specified by DEEP, but can be changed by the user as more accurate information becomes available. DEEP Output includes plant performance indicators such as recovery ratio, energy consumption, daily and annual water production, product water TDS, various cost factors that include levelized cost of water and power ($\$/m^3$ or \$/kWh), and breakdown of cost components for various scenarios.

**WRA RO Desalination Cost Planning Model**

Water Resources Associates (WRA) has developed the Reverse Osmosis Desalination Cost Planning Model (Water Resource Associates, Inc. 2005). The WRA model facilitates the cost analysis of a range of desalination project implementation options based on capital, O & M, and life cycle costs. The Version 2.0 model is Windows-based with userfriendly features. Major components of the model include: Master Data Input Form (for a user less knowledgeable about desalination process or its economic components), Advanced Input Form (which allows the user to customize the model by inputting 38 different default settings and make appropriate assumptions), Capital Cost Output, and O & M Cost Outputs. The model input requirements include 33 parameters or default values. The O & M cost output displays the annual O & M costs based on input or default values and a total annualized O & M cost based on the interest rate, inflation rate and life cycle period.

**Desalination Approximate Cost Estimates**

Desalination cost is affected by several factors such as type of technology, energy availability, geographic location, plant capacity, and feedwater quality. Other important factors include costs associated with transporting water from source to desalination plant, distribution of treated water, and concentrate disposal. Factors such as financing options and subsidies also affect the product water cost.

A 2003 Sandia National Laboratories Report provides a comprehensive review of literature and information on desalination costs (Table 1). It should be noted that because costs documented in various reports are not calculated in a consistent fashion and therefore they are approximate at best and do not represent a conclusive picture.

Table 2 shows the percent cost of various factors for desalination of brackish water and seawater in RO plants. These data are reported in the Sandia National Laboratories report compiling data from other sources (Miller 2003).

**Table 1.** Desalination Costs for Various Desalination Technologies ($/m$^3$ freshwater – multiply by 3.8 for $/1000gal)

| **Reference Sources** | **MSF (Seawater)** | **MEE (Seawater)** | **TVC (Seawater)** | **RO (Seawater)** | **RO (Brackish water)** | **ED ED(Brackish water)** |
|---|---|---|---|---|---|---|
| A | 1.10-1.50 | 0.46-85 | 0.87-0.92 | 0.45-0.92 | 0.20-0.35 | - |
| B | 0.80 | 0.45 | - | 0.72-0.93 | - | - |
| C | 0.89 | 0.27-0.56 | - | 0.68 | - | - |
| D | 0.70-0.75 | - | - | 0.45-0.85 | 0.25-0.60 | - |
| E | - | - | - | 1.54 | 0.35 | - |
| F | - | - | - | 1.50 | 0.37-0.70 | 0.58 |
| G | 1.31-5.36 | - | - | 1.54-6.56 | - | - |
| H | 1.86 | 1.49 | - | - | - | - |
| I | - | 1.35 | - | 1.06 | - | - |
| J | - | - | - | 1.25 | - | - |
| K | 1.22 | - | - | - | - | - |
| L | - | - | - | - | 0.18-0.56 | - |
| M | - | - | 0.46 | - | - | - |
| N | - | - | - | 1.18 | - | - |
| O | - | 1.17 | - | - | - | - |
| P | - | - | 0.99-1.21 | - | - | - |
| Q | - | - | - | 0.55-0.80 | 0.25-0.28 | - |
| R | - | - | - | 0.59-1.62 | - | - |
| S | - | - | - | 1.38-1.51 | - | - |
| T | - | - | - | 0.55-0.63 | - | - |
| U | - | - | - | 0.70-0.80 | - | - |
| V | - | - | - | - | 0.27 | - |
| W | - | - | - | 0.52 | - | - |

Source: (Miller 2003). Other sources for cost estimates are documented in Appendix 1.

**Table 2.** Percent Distribution of Cost Factors

| | **Brackish water**(%) | **Seawater**(%) |
|---|---|---|
| Fixed costs | 54 | 37 |
| Electric power | 11 | 44 |
| Labor | 9 | 4 |
| Membrane-replacement | 7 | 5 |
| Maintenance and parts | 9 | 7 |
| Consumables (chemicals) | 10 | 3 |

Source: Miller 2003

Several observations can be made from these data.

1) For both, brackish water and seawater, fixedcosts are a major factor;
2) The major difference in cost betweendesalination of brackish water and seawater is energy consumption, while the remaining factors are decreased proportionally, but remain about the same; and
3) Costs associated with membrane replacement,maintenance & parts and consumables are relatively small. These costs depend on the status of technology and may be further reduced as technology evolves, but will not have significant impact on the overall cost of desalination.

Treatment costs are affected by salinity and overall water quality. High salinity water (e.g. seawater) consumes more energy and is therefore more costly to desalinate. It can be noted that cost efficiency of seawater desalination is a critical parameter in order to make it economically viable. From a water source perspective, desalination of brackish groundwater is the least costly. Surface waters (e.g. tidal waters) contain higher salinity and other impurities. Treatment of high salinity water will require more pre-treatment and perhaps a combination of various technologies, therefore making it more costly.

Desalination plant capacity is a major cost factor. Literature shows that in general, large capacity plants require a high initial capital investment compared to low capacity plants. Also, the increase in cost of product water (per 1000 gallons) is proportional to energy cost (per KwHour). However, due to the economies of scale, operation and management costs, the unit production costs for large capacity plants can be lower (LBGGuyton Associates 2003, Younos 2004).

Concentrate disposal is a major economic factor and is affected by several factors that include site characteristics (geologic features, soil conditions, proximity to potential disposal site), regulatory requirements, public approval, and the type of concentrate disposal method. Based on those limitations, concentrate disposal cost can range from 5 to 33 percent of the produced water cost (Tsiourtis 2001).

In general, surface water disposal is the most common and affordable option when costs associated with concentrate transport, post-treatment, and outfall structures are considered. However, disposal costs for inland desalination plants are generally higher than those for coastal plants because inland plants cannot dispose to surface waters unless the concentrate can be treated to an acceptable quality. The second common and economic concentrate disposal method is combining the concentrate with effluent from wastewater treatment plants. Costs associated with land application techniques (evaporation ponds, spray irrigation, and percolation) depend on the site characteristics. The cost of deep well injection depends on the volume of the concentrate to be disposed of and is considered most expensive at very small volumes. The Zero liquid discharge (ZLD) method is the most expensive option due to the high energy requirement, whereas with other techniques the energy associated cost is insignificant (Mickley 2001).

Table 3 shows design parameters and capital cost factors for various concentrate disposal options. This table can be used to compare available options and to determine the most appropriate method of disposal for a selected desalination plant (Mahi 2001).

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**Table 3 Design Variables and Capital Cost Items for Different Methods of Disposal**

| | Methods of Disposal | | | | | | |
|---|---|---|---|---|---|---|---|
| | Surface Water Disposal | Sewage Treatment Plant | Deep Well Injection | Percolation | Spray Irrigation | Evaporation Pond | Zero Discharge |
| **Design Variable** | | | | | | | |
| Distance | Y | Y | Y | Y | Y | Y | Y |
| Volume | Y | Y | Y | Y | Y | Y | Y |
| Depth | — | — | Y | — | — | — | — |
| Number of tubing transitions | — | — | Y | — | — | — | — |
| Evaporation rate/ hydraulic loading | — | — | — | Y | Y | Y | — |
| Land availability, type, cost | — | — | — | Y | Y | Y | — |
| Storage time | — | — | — | Y | Y | — | — |
| Sprinkling spacing | — | — | — | — | Y | — | — |
| Reject flow | — | — | — | — | — | — | Y |
| Energy cost | — | — | — | — | — | — | Y |
| **Capital Cost Item** | | | | | | | |
| Transport system (pipe, pump) | Y | Y | Y | Y | Y | Y | Y |
| Treatment system (includes blending) | Y | Y | — | Y | Y | — | — |
| Outfall structure | Y | — | — | — | — | — | — |
| Injection well (depth, pump, materials) | — | — | Y | — | — | — | — |
| Monitoring wells | — | — | Y | Y | Y | Y | — |
| Land, land preparation | — | — | — | Y | Y | Y | — |
| Distribution system (pipe, pump) | — | — | — | Y | Y | — | — |
| Wet weather storage | — | — | — | Y | Y | — | — |
| Alternate disposal system | — | — | Y | — | — | — | — |
| Subsurface drainage system | — | — | — | (Y) | Y | — | — |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Disposal fee | — | Y | — | — | — | — | — |
| Skid mounted system | — | — | — | — | — | — | Y |

Methods with 'Y' must consider the design variable or cost item when used for concentrate disposal.

Source: Mahi 2001

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# Desalination: Can it be greenhouse gas free and cost Competitive?

MEM Masters Project


by: !          John Frederick “JF” Thye
advisor: !  Marian Chertow


date: !       9 May 2010


- Yale School of Forestry and Environmental Studies

# Table of Contents

# Executive Summary

This paper reviews the current status of global water scarcity, water price, and desalination processes, as well as their efficiencies and associated economics. Given rapidly growing desalination energy demands and the seriousness of the associated greenhouse gas emissions, this paper's goal is to determine the current and future technological and economic competitiveness of high efficiency desalination technologies and non-fossil fuel powered renewable energy system (RES) integration with commercial desalination plants.

This paper estimates the world average cost of fresh water, including sanitary services, to be approximately USD 1.14/m^3, derived from from 2008 GWI and 2009 OECD report data. Recent published levelized desalination plant cost structures show water delivery between USD 0.61/m^3 and USD 3.00/m^3. In comparison to operating desalination plants, renewable energy desalination system (REDS) water costs are more difficult to estimate. Currently, the most cost competitive technology matchup, the "Wind-Reverse Osmosis" REDS, is thought to have hypothetical costs between USD 1.25/m^3 and USD 1.50/m^3. All REDS models, should be noted, are still officially in a theoretical model or pilot project stage. Cost data on these constructs is therefore limited and incomplete.

The buzz around desalination technologies is fierce, as governments and investors are competing in a race to create the next great breakthrough technology. In the near term, most promise is shown by combinations of wind or solar energy with desalination technologies that are in the osmosis category, such as reverse osmosis (RO) or forward osmosis (FO). This is especially true if FO is able to respond well to variable power inputs.

FO is being pioneered by the Modern Water company and Oasys, who seem to be the current category leaders. Rumors about carbon nanotubes whisper of their serious potential, particularly interesting because of the technology's high flux rate and seeming ability to cooperate well with varying flow rates and power on-off cycling, but the technology is still in the R&D stage.

# Introduction

Clean water resources are rapidly being reduced around the world through human consumption, yet water is one of the most abundant elements on earth. Three-fourths of the planet's surface is covered by water, but only three percent is fresh water fit for human consumption, held in ground water, rivers, and lakes. Less than one percent of fresh water is actually within human reach.[1]

97% of the earth's water is in the ocean, where it maintains a salt content too high for human ingestion. In order to tap this seemingly boundless resource, desalination technologies that remove salt from brackish and seawater sources have been deployed in limited capacity since ancient times. Major advances over the past 40 years have led to a steep increase in desalination technology deployment, and technologies are continuously evolving for commercial and household consumption.

[1] Eltawil, 2009

The separation of salts from seawater remains energy intensive, however. Since the primary direct and indirect energy source for desalination has been fossil fuels (where indirect energy is electricity produced from fossil fuel power plants), the concern over climate change has steered much attention to how renewable energy sources (RES) could be coupled with desalination technologies. Water resource planing committees and venture capital investors therefore consider the economically viable synergy between RESs and desalination technologies that can draw on a virtually infinite water source, the ocean, one of the great technological races of our time to solve the world-wide water shortage crisis.

Combining renewable energies with desalination also has an inherent advantage beyond basic potable water production. Water is an excellent storage medium and can be held in vast quantities for extended periods of time. Therefore, it is possible to produce water and store excess production when a large amount of power supply is available. Consequently, when power is not available, no wind to spin a turbine or sun to generate solar electricity, stored water serves as an intermediate source. This alleviates the need for expensive large-scale back-up energy systems that plague most commercial applications of RESs.

This paper reviews the current status of global water scarcity, water price, and desalination processes, as well as their efficiencies and associated economics. Given rapidly growing desalination energy demands and the seriousness of desalination associated greenhouse gas emissions, this paper’s goal is to determine the current and future technological and economic competitiveness of non-fossil fuel RES integration with commercial desalination plants.
Commercial fresh water production is generally considered to be able to provide fresh water for population sizes between multiple families to large municipalities. In summary, a successful integration between a RES and a desalination technology solves three preeminent challenges:

1. Virtually limitless access to water with zero fossil fuel inputs.
2. The integrated coupling of variable wind and solar power inputs with desalination plants, which have traditionally been designed for constant power inputs from fossil fuel plants.
3. The ability to store fresh water during high production periods, which is tapped during times when renewable energy is not available (no wind or sun), creating a constant supply availability to consumers.

Limitations to my research are due to incomplete economic and technological performance data, which makes true technology comparisons challenging. The performance of RES-desalination is site-specific, so the same system will perform differently depending on location, weather condition, water temperatures, as well as particle, chemical and salinity levels. Though some systems have already run for multiple years, many of the more promising new concepts are still in pilot phases, experimental lab settings, or in the theoretical constructs stage, modeled after virtual field conditions.

## A note on this paper’s format:

Sections describing technologies and case studies are writing in a bullet point format. The objective is to distill the most essential technical attributes and considerations as clearly as possible. Standard text sections throughout the paper serve to introduce and discuss linking concepts.

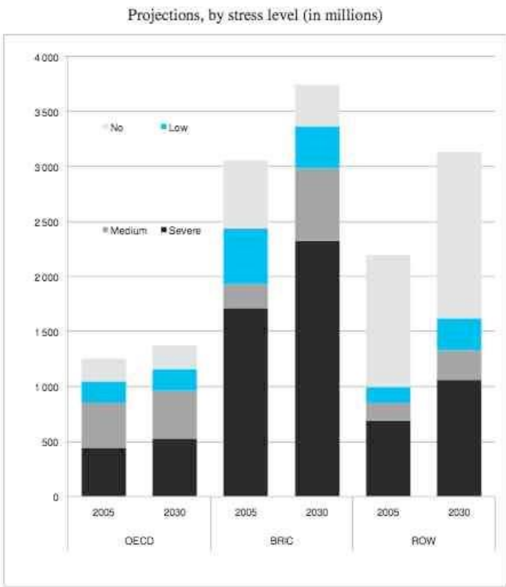
# Global Water Economics

The price of water can be measured by its demand and economic cost. Water scarcity is a demand side analysis driven by the degradation of social fabric and quality of life associated with the lack of clean water. In essence we may conclude that access to a minimum amount of fresh water is a basic human right with zero demand elasticity and and infinite price. However, beyond the minimum standards, the water demand curve is downward sloping with regional specific slopes and characteristics. These are driven by the culture and industry that make up water demand.

## Global Water Scarcity

As depicted in the Figure below, in 2005, 2.8 billion people lived in areas under severe water stress, which is defined in two ways.[2] The Falkenmark indicator defines it as less than 500 m^3 per capita per year, while the WTA (Withdrawal per Total Available Water Resource) defines severe water stress as more than 40%. By 2030, the OECD Environmental Outlook estimates that this number will increase by about 1 billion, to 3.9 billion (47% of the world population), without taking climate change into consideration.

[2] OECD, 2009a




*Source*: OECD Environmental Outlook baseline in OECD (2007), *Environmental Outlook to 2030*, OECD, Paris. The OECD baseline used for the *Environmental Outlook* is policy neutral, *i.e.* it assumes no new policies and projects current policies into the future to show what the world will be like in 2030 if currently existing policies are maintained, and no new policies introduced to protect the environment.

| Water-scare countries in 1955 | Countries added to scarcity category by 1990 | Countries added to scarcity category by 2025 under all UN population growth projections | Countries added to scarcity category by 2025 only if they follow UN medium or high projections* |
|---|---|---|---|
| Malta | Qatar | Libya | Cyprus |
| Djibouti | Saudi Arabia | Oman | Zimbabwe |
| Barbados | United Arab Emirates | Morocco | Tanzania |
| Singapore | Yemen | Egypt | Peru |
| Bahrain | Israel | Comoros | |
| Kuwait | Tunisia | South Africa | |
| Jordan | Cape Verde | Syria | |
| | Kenya | Iran | |
| | Burundi | Ethiopia | |
| | Algeria | Haiti | |
| | Rwanda | | |
| | Malawi | | |
| | Somalia | | |

*Cyprus will have more than 1,000 cubic meters of renewable fresh water annually per person in 2025 if it follows either the UN low or medium population growth projection. Zimbabwe, Tanzania and Peru can avoid falling below 1,000 cubic meters per capita only if they follow the UN low projection.

***Figure 1** (left): Regional populations living under water stress as per WTA indicator (OECD countries: Organization of Co-operation and Development; BRIC: Brazil, Russian Federation, India, China; ROW: Rest of the world (countries which are neither OECD nor BRIC).*[3]

***Figure 2** (right): Countries experiencing water scarcity in 1955, 1990, and 2025 (projected), based on availability of less than 1,000 cubic meters of renewable water per person per year.*[4]

BRIC countries will see the highest increase in water scarcity in certain population pockets, while the country water scarcity figure above projects which countries are expected to experience nationwide severe water scarcity. Many oil rich countries, like Saudi Arabia, are already dependent on desalination for much of their fresh water capacity.

Climate change is expected to significantly affect the capacity of natural water systems to meet anthropogenic and ecological needs. The main water-related impacts from climate change are expected to be felt by shifting, and more variable, hydrological regimes, i.e. changes in water distribution around the world, changes in seasonal and annual variability, and an increase in the frequency and/or intensity of extreme events. Rising sea levels will threaten the world's megadeltas, while the vast populations dependent on glacial melt (one-sixth of the world's population) are losing their "water towers": the high altitude glacial reservoirs (e.g. Peru).[5]

[3] OECD, 2009a

[4] National Council for Science and the Environment 2005 (http://www.cnie.org/pop/pai/water-14.html)

[5] EEA, 2008

## Global Water Prices

The Figure below shows the price per cubic meter of water and wastewater services faced by a households consuming 15 m^3 per month in 90 selected countries and eight regions. OECD defines the price of water indicator by the price paid by final (domestic) users. The data was adjusted using purchasing power parities for private consumption. This indicator choice over other possible measurements of "average tariffs" was motivated by the intention to ensure comparability across countries, given the extreme variability of tariff levels and structures not just across countries, but across different providers within each country.

Though water and wastewater bills differ between countries, clusters of countries reveal interesting average cost comparisons. OECD countries, on average, have a water cost approximately USD 0.50/m^3 higher than Central and South-East Europe, and USD 2/m^3 higher than most of the rest of the world. Within the OECD two counties are below the USD 1.00/m^3 cost, ten countries are below USD 2.00/m^3, and nine are around USD 3.00/m^3. Denmark (USD 4.41/m^3) and Scotland (USD 9.45/m^3) submitted much higher values. The OECD report assumes that these countries have made efforts to incorporate as much of the economic and other costs of waste water service provision and use into their tariffs, which other countries may not have to the same extent. US urban water cost, in comparison, are USD 0.55/ m^3, and less than USD 0.05/m^3 for agricultural use.

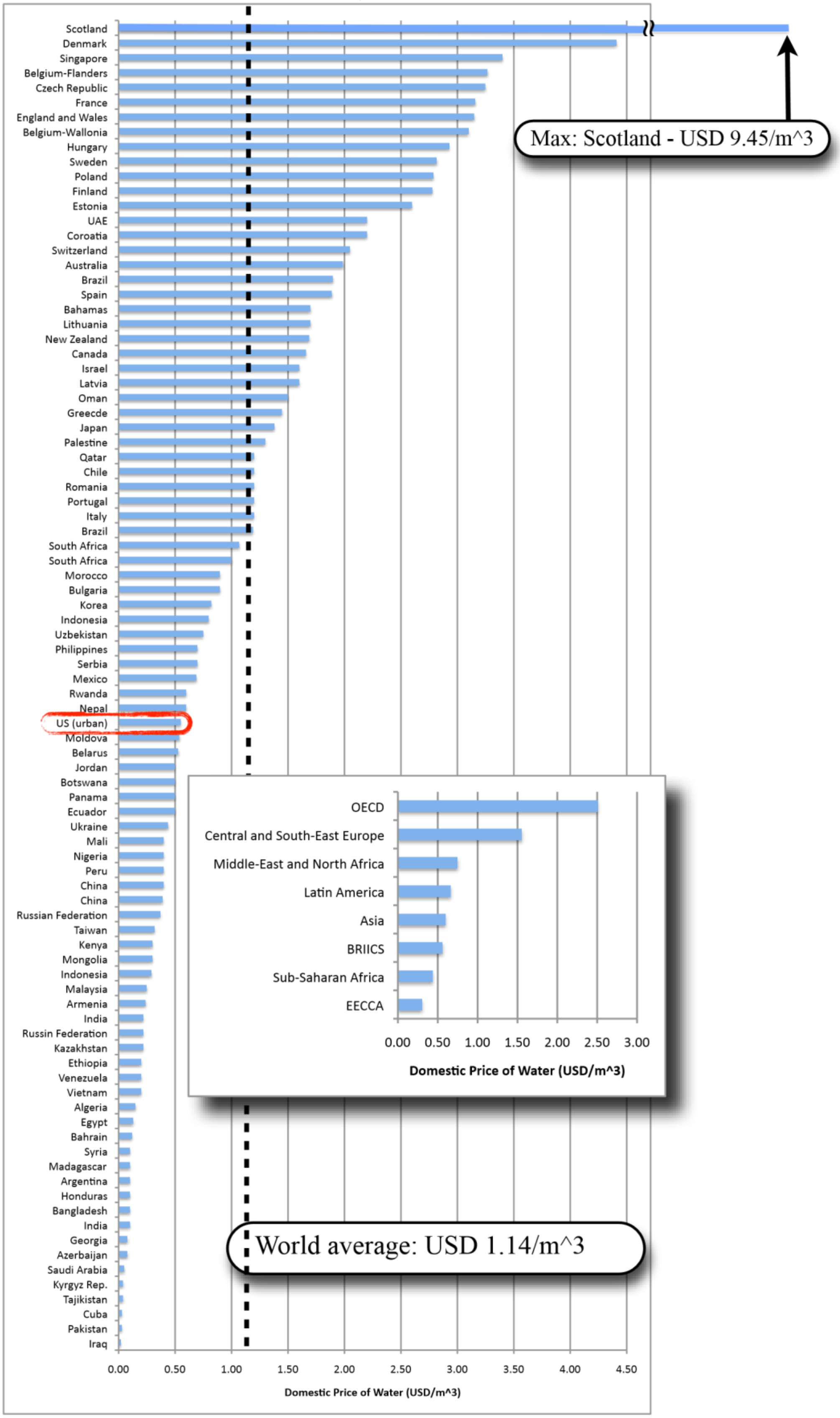
***The world average cost of fresh water, calculated via the above analysis, and depicted graphically in the following figure, is roughly USD 1.14/m^3.***

The OECD report argues that one should refrain from going too far in comparing water pricing levels across countries, which may really be of little use, sine averaging out local pricing levels can lead to price distortions. Within and across countries, prices might differ widely (e.g. the United States) because costs vary depending on the quality of available natural resources and other circumstances.

However, these rough numbers do provide a baseline against which desalination costs must be able to compete to be economically viable.

***Figure 3 (next page)****: Domestic Price of water and wastewater services in USD/m^3 2009 adjusted for consumption purchasing power parity including taxes. The water and wastewater bill is computed based on an assumed national consumption of 15 m^3 per month per household. The data reported is estimated from information provided by utilities on average revenue per cubic meter, i.e. total annual revenue divided by the total volume of annual water sales, in different* *selected countries and regions around the world. (EECCA: Eastern Europe, Caucasus and Central Asia).*[5]

[5] Derived by JF Thye from data presented in GWI, 2008 and OECD, 2009a


Scotland
Denmark
Singapore
Belgium-Flanders
Czech Republic
France
England and Wales
Belgium-Wallonia
Hungary
Sweden
Poland
Finland
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UAE
Coroatia
Switzerland
Australia
Brazil
Spain
Bahamas
Lithuania
New Zealand
Canada
Israel
Latvia
Oman
Greecde
Japan
Palestine
Qatar
Chile
Romania
Portugal
Italy
Brazil
South Africa
South Africa
Morocco
Bulgaria
Korea
Indonesia
Uzbekistan
Philippines
Serbia
Mexico
Rwanda
Nepal
US (urban)
Moldova
Belarus
Jordan
Botswana
Panama
Ecuador
Ukraine
Mali
Nigeria
Peru
China
China
Russian Federation
Taiwan
Kenya
Mongolia
Indonesia
Malaysia
Armenia
India
Russin Federation
Kazakhstan
Ethiopia
Venezuela
Vietnam
Algeria
Egypt
Bahrain
Syria
Madagascar
Argentina
Honduras
Bangladesh
India
Georgia
Azerbaijan
Saudi Arabia
Kyrgyz Rep.
Tajikistan
Cuba
Pakistan
Iraq
0.00 0.50 1.00 1.50 2.00 2.50 3.00 3.50 4.00 4.50
Domestic Price of Water (USD/m^3)
Max: Scotland - USD 9.45/m^3
OECD
Central and South-East Europe
Middle-East and North Africa
Latin America
Asia
BRIICS
Sub-Saharan Africa
EECCA
0.00 0.50 1.00 1.50 2.00 2.50 3.00
Domestic Price of Water (USD/m^3)
World average: USD 1.14/m^3

# History of Desalination

Desalination technologies treat seawater and brackish waters to produce freshwater, and in the process discharge a saltier wastewater concentrate stream. Global desalination water production capacity has increased exponentially since 1960, as shown in the Figure. Current online production capacity is estimated to exceed 42 million m^3/day[7], of which 37 million m^3/day are considered operational. This adds up to approximately 0.3 percent of average total anthropogenic freshwater use per day.[6]

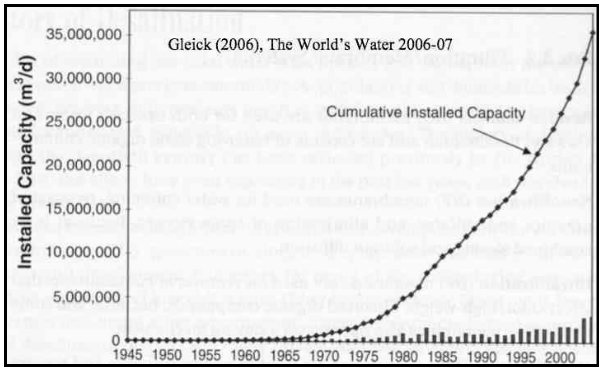
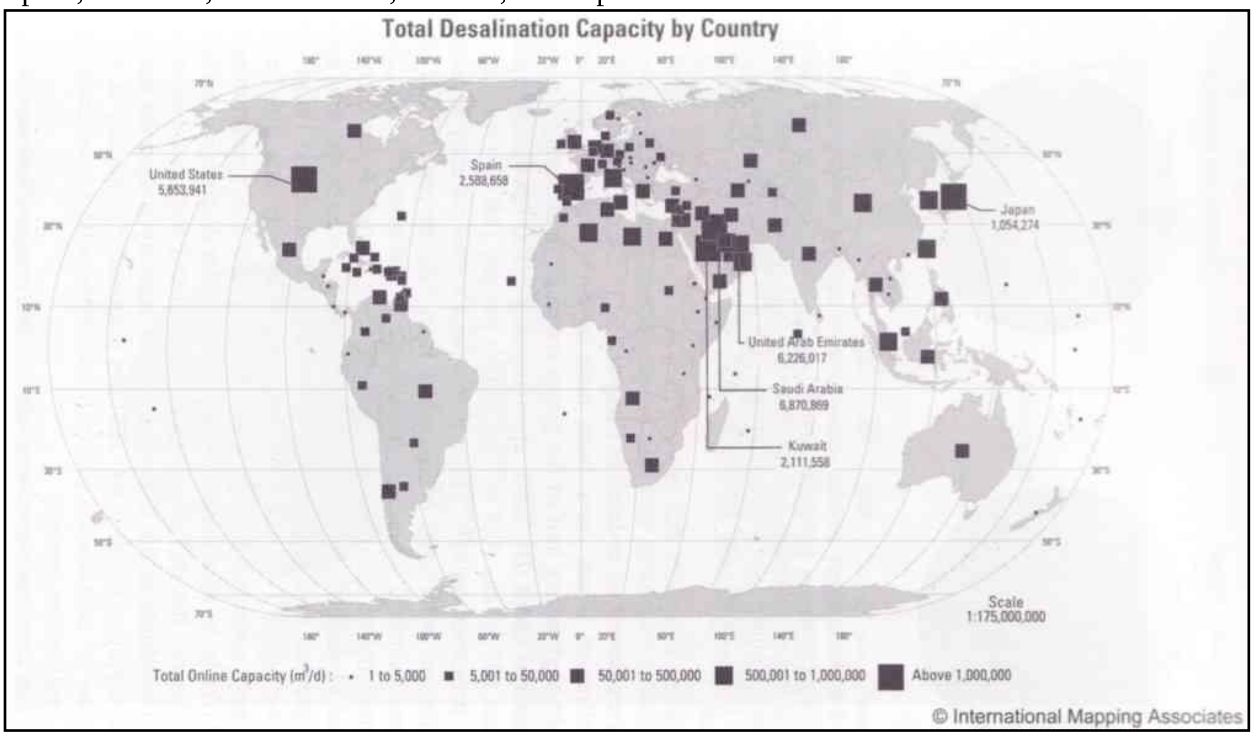



***Figure 4***: *Time-series of global desalination capacity to 2005.*

47 percent of the current online global desalination capacity is located in the Middle East. North America, Europe, and Asia each have about 15 percent of desalination capacity. The figure below illustrates the countries with the largest capacities, over 1 million M^3/day. These include the US, Spain, the UAE, Saudi Arabia, Kuwait, and Japan.

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[7] GWI, 2006b

***Figure 5***: *Global online desalination capacity.*[7]

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[6] Cooley et al., 2006

[7] GWI, 2006b

60% of global desalination capacity uses seawater, though this varies by country. In the US, for example, seawater desalination accounts for only 8%, with the majority of US desalination (77%) treating brackish water. As the figure below indicates, currently 18 countries have an installed capacity of more than one percent of the global total, of which the oil-rich nation of Saudi Arabia has the highest capacity with 6.9 million m^3/day, and the US and United Arab Emirates the second and third highest.

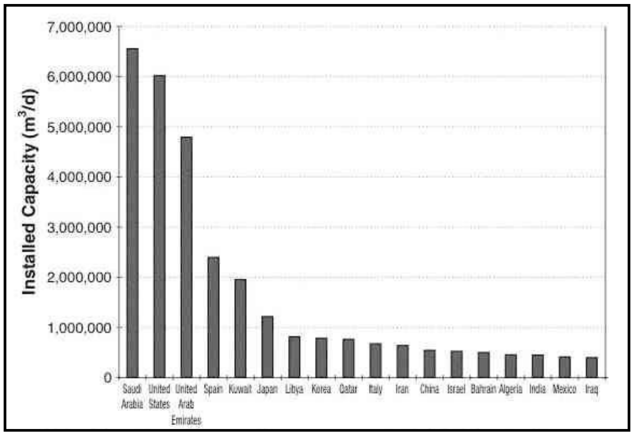


***Figure 6****: Countries with more than 1% of global desalination capacity, January 2005. Total installed capacity in cubic meters per day.*[8]

Most of US desalination plant installations operate on the arid west coast and have benefited from a history of government subsidies and grants. The most significant US federal funding for desalination R&D, topping USD 180 million in 1966, was deployed between 1965 to 1973. Currently R&D is heavily funded through venture capital activity and financed through private, municipal, state, and sovereign wealth funds. The present private funding climate is a sign that the investment community and capital markets have recognized the urgency of water scarcity and the depletion of traditional clean water sources.

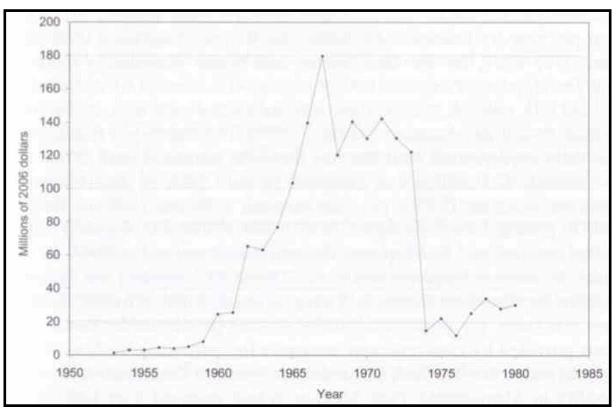


***Figure 7****: Yearly US federal funding for desalination R&D between 1953 to 1980, as appropriated in constant 2006 USD. Based on data from the US General Accounting Office (1979) and the Bureau of Labor Statistics Consumer Price Index.*[9]

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[8] Gleick et al., 2006-2007

[9] NRC, 2008

# Desalination Water Quality Standards

Water salinity is defined and categorized by salt concentration and ranges from fresh, to brackish, to saline water. Most non-seawater resources have salinity up to 10 ppt (parts per thousand). Seawater salinity ranges from 35 to 45 ppt in total dissolved salts (TDS).[10] The figure below summarizes the parts per thousand salinity definitions for water. Of note is that seawater salinity has to be reduced approximately one hundred fold to be considered fresh drinking water. This ratio foreshadows the large amount of work, or energy, demanded to produce fresh water.

| Fresh water | Brackish water | Saline water | Brine |
|---|---|---|---|
| < 0.5 | 0.5 – 30 | 30 – 50 | > 50 |

***Figure 8**: Water salinity based on dissolved salts in parts per thousand (ppt).*[11]

The World Health Organization (WHO) states that a permissible salinity limit for potable drinking water is 0.5 ppt and 1.0 ppt under limited consumption.[12] The US Environmental Protection Agency (EPA) states that drinking water with TDS greater than 500 mg/L (0.5 ppt) can be distasteful. Brackish water has a salinity between that of fresh and and saline sea-water, and usually results from mixing of seawater with fresh water, as in estuaries, or in brackish fossil aquifers. In addition to removing salt, some desalination processes, like reverse osmosis, can remove many forms of minerals, suspended solids, viruses and organic compounds, such as algae and bacteria.[13]

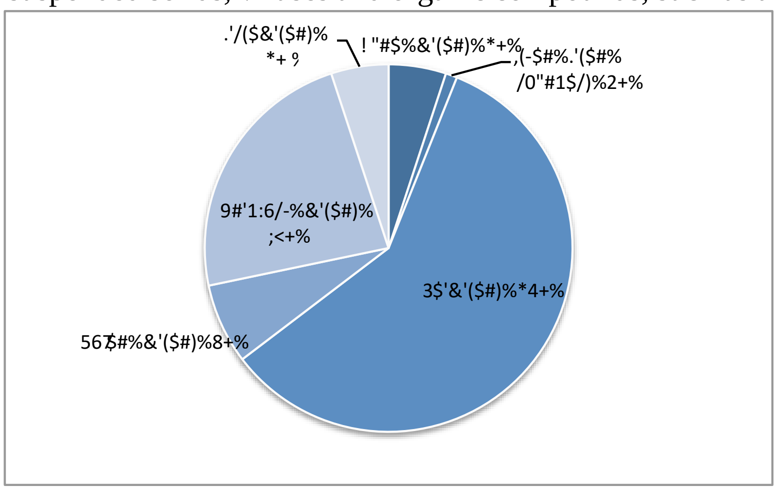


***Figure 9**: Global installed desalination capacity by feed water sources.*[14]

The figure above summarizes global feed water sources used by desalination plants. Of note is that currently 59% of operational desalination capacity uses seawater as a a primary source. Since seawater has the highest salt concentrations, it also requires the most energy to produce fresh water. However, its advantages are its virtually infinite abundance, as well as the proximity of desalination plants to the ocean, which allows for the dilution of the high density salt streams that

[10] Stumm and Morgan, 1996

[11] NRC, 2008

[12] WHO, 2003

[13] California Ocean Resources Management Program, 1997; Pantell, 1993

[14] IDA

are discharged from desalination plants as brine. The ecological impact of these waste streams are not within the scope of this paper, but should be carefully considered in the siting of any plant.

# Desalination Technologies Review

Desalination plants and RESs are two completely different technology concepts that can be combined in a multitude of ways. Not all combinations of RES-powered desalination systems are practical or economic. To find optimal combinations between the systems, both technologies have to be evaluated for their behavioral and performance characteristics, which are then matched to create seamless interconnectivity.

RES and desalination technology matches are very site-specific, and optimal technology combinations are selected based on requirements and conditions, which include:

- geographic conditions
- topography of the site
- capacity requirements and plant size
- type and cost of fossil fuel energy available
- condition of local infrastructure, including ability to plug into the electricity grid
- feed water salinity and temperature

This section summarizes the key operational aspects of the current eight most popular desalination technologies, their strengths and weaknesses, their capacities, as well as their economics. The section is purposefully written in bullet points and tables in order to break out the most essential facts that carry weight in matching desalination systems to RESs.

## Desalination System Key Operational Aspects

Desalination technologies are categorized into two main groups, thermal and membrane desalination. These are then broken down into subgroups that process salt water in technically very different ways. The following section discusses the operational aspects of the current eight most prominent desalination technologies, Multi-stage flash (MSF), Multi-effect Distillation (MED), Mechanical Vapor Compression (MVC) and Thermal Vapor Compression (TVC), Solar Distillation (SD), Reverse Osmosis (RO), Electro-dialysis (ED) and Electro-dialysis Reversal (EDR):

1. **<u>Thermal desalination includes:</u>**

▸ **Multi-stage flash (MSF)**

- MSF is the most dominant in the thermal category, at 90% of all thermal production and 42% total world desalination production.[15]
- It is the most robust of all desalination technologies, able to process water at a very high rate with little maintenance.[18]
- MSF is capable of very large yields. Currently the largest plants are operating and under construction in Saudi Arabia and the United Arab Emirates, having design capacities of 600,000 to 880,000 m^3/day (Saudi Arabia's Shuaiba III, Ras Al-Xour and Al Jobail II Ex plants being the largest at 730,000 to 880,000 m^3/day and The UAE's Jebel Ali M plant operating at a 600,000 m^3/day capacity).[16][17]
- Globally MSF is among the most commonly used desalination technology.
- It operates using a series of 4 to 40 chambers, or stages, each with successively lower temperature and pressure, to rapidly vaporize water, which is condensed afterwards to form fresh water.
- MSF operates at top brine temperatures of 90-120 degC. Higher temperature than this induces scaling, the precipitation and formation of hard mineral deposits such as manganese oxides, aluminum hydroxide, and calcium carbonate.
- Cost of plant depends on the performance ratio, water production over levelized cost.
- Capital and energy costs are the highest of all desalination technologies.

▸ **Multi-effect distillation (MED)**

- This is a thin-film evaporative technology, where vapor produced by 8-16 chambers (the "effect") subsequently condenses into distillate in the following chamber group

[15] IDA, 2002

[18] He et al.

[16] Pacific Institute, 2005

(the “second effect”) by reducing ambient pressure. MED plants utilize low grade input steam to produce the distillate through repetitive steps of evaporation and condensation, each at a lower temperature and pressure.[18]

- Operates at lower temperatures than MSF. The newest max out at 70 degC.
- MED is actually the first desalination technology used for seawater, and was developed by the chemical industry.
- Units are generally built at capacities of 600 to 30,000 m^3/day.
- Cost of plant depends on the performance ratio, water production over levelized cost.
- Capital costs are slightly lower than MSF, but and energy costs are generally the same as MSF and therefore significant.

▸ **Mechanical Vapor Compression (MVC) and Thermal Vapor Compression (TVC)**

- VC was used since late 19th century.
- It operates at small and medium scale capacities between 20 to 25,000 m^3/day.
- Units are very compact and transportable, making them attractive for the military.
- *Mechanical vapor compression (MVC)*:
  - The high pressure blower of the MVC plant are fluid flow machines with similar characteristics to wind turbine mechanics, aligning them theoretically well for a RES-desalination technology match on a stochastic interconnectivity basis. There is therefore a natural affinity between the technologies. By variation of the compressor speed and the evaporation temperature, the power consumption can be adapted to rapid changes in energy input (i.e. wind conditions).
- *Thermal vapor compression (TVC)*:
  - The hot feed water enters evaporator, where it is heated (rather than compressed as in the MVC) to boiling point and some of it evaporated. The vapor formed goes to compressor where pressure and saturation temperature is raised. Compressed vapor is fed back to evaporator to be condensed, providing the thermal energy to evaporate the seawater in a separate loop.
- Power consumption is significant and depends on this pressure difference. The compressor therefore represents main energy consumption in the system.

▸ **Solar Distillation (SD)**

- In and SD solar radiation is trapped in solar still, a shallow basin lined with black energy absorbent material with a transparent roof acting as condenser. This technology therefore operates under principals of greenhouse effect. Vapor produced by seawater is condensed on the cool surface of the roof.
- SD is simple and robust in operation and was deployed mainly in 1960s and 70s.
- It has been used in small scale applications, producing approximately 2.5 liters per m^2 of panel surface, at a thermal efficiency of 50%.

[18] IDE-Tech: http://www.ide-tech.com/files/990b0fa01310a9c82f841f2183e9ebcb/downloadchapter/2010/01/MED%20Brochure.pdf

- Though electricity retirements for pumping are minimal, construction costs and large land area requirements have led to the fall of its popularity.

2. **Membrane desalination:**

▸ **Reverse Osmosis (RO)**

- RO is the most dominant membrane desalination technology, at 88% of all membrane production and 46% total world production capacity.[19] It is also said to be the most commonly deployed technology, not taking capacity into account.
- RO has four subsystems: 1) pre-treatment; 2) high pressure pump; 3) membrane modules; and 4) post-treatment.
- Feed water pre-treatment involves filtration, sterilization, and addition of chemicals to prevent scaling and biofouling. Pre-treatment is critical due to membrane sensitivity.
- The desalination event happens when water is forced across a membrane surface at 17-27 bar for brackish water (BWRO) and 55-82 bar for sea water (SWRO). The *product*, or *permeate,* water passes through the membrane, having the majority of its dissolved solids removed. The salt concentrated *reject stream*, or *brine*, emerges at high pressure. In large plants the brine pressure energy is recovered by a turbine or Clark Pump (common in new stand-alone RES-desalination hybrids), recovering 20%-40% of energy.
- Membranes are designed to yield a permeate water of approximately 500 ppm TDS.[20][21]- Two types of RO membranes are used: 1) Spiral wound (SW); and 2) Hollow fiber (HF). Their use is dependent on cost, feed water quality and product water capacity.
- RO systems are available in a wide range of capacities due to their modular design with the largest operational plant having a capacity of 320,000 m^3/day in Israel at Ashkelon. The smallest capacity is approximately 0.1 m^3/day for marine and household purposes.
- RO systems may have one to hundreds of thousands of modules in racks  and therefore exhibit an attractive scalability. Reverse osmosis is, with regard to pretreatment, membrane fouling, after-treatment and efficiency of the high pressure pumps, a process that is rather sensitive to a stop- and-go operation.
- Generally, RO has low capital cost, but significant maintenance costs due to the high cost of membrane replacement. The Cost of energy (which is all electrical) used per m^3 is significant, but less than MSF and MED. The majority of RO energy is required to drive the high pressure feed water pump system.

▸ **Electro-dialysis (ED) and Electro-dialysis Reversal (EDR)** - ED and EDR are low cost method for brackish water desalination.

- Both technologies are *Economically unattractive for seawater* due their drastically increased energy costs at higher ppm total dissolved salts (TDS).

[19] IDA, 2002

[20] Loupasis, 2002

- The process works by transporting ions through a membrane by an electrical field that is applied across the membrane, creating a region of low salinity water.
- ED and EDR produce water around 20 ppm TDS.[22]
- EDR induces a membrane self-cleaning process by inhibiting the deposition of inorganic scales and colloidal substances. [23]
- ED went commercial in 1954 and EDR in the 1970s, and 31% of US desalination capacity is ED/EDR.
- ED and EDR is economically attractive only for low salinity brackish water.

[22] Loupasis, 2002

[23] ibid

## Global Installation of Desalination Technologies

The figure below is an incomplete summary of globally deployed desalination technologies, as the United Arab Emirates, Israel and Japan, who individually have some of the world's largest country-wide desalination capacities, are not included. However, the table demonstrates that MSF is by far the most popular installed technology, measured by capacity. MSF is the primary technology used in Saudi Arabia. Of note is that oil rich nations, such as Saudi Arabia and Kuwait, have higher MSF installations, while nations with smaller or no oil reserves prefer RO, expect for Italy, who has a fairly large MSF installation of of 55% total capacity.

| Country | MSF | MED | VC | RO | ED | Total | % |
|---|---|---|---|---|---|---|---|
| Saudi Arabia | 2700 | | 50 | 1000 | 94 | 3844 | 48.8 |
| USA | 50 | 50 | 130 | 1600 | 280 | 2110 | 26.8 |
| Kuwait | 350 | | | 50 | | 400 | 5.1 |
| Libya | 400 | | | 130 | 67 | 597 | 7.6 |
| Spain | 56 | | 40 | 230 | 45 | 371 | 4.7 |
| Italy | 200 | | 75 | 40 | 50 | 365 | 4.6 |
| Algeria | 60 | | 30 | 80 | 16 | 186 | 2.4 |
| Total | 3816 | 50 | 325 | 3130 | 552 | 7873 | 100 |
| Percent (%) | 48.5 | 0.6 | 4.1 | 39.8 | 7.0 | 100 | |

***Figure 10**: Installed Desalination Plant Capacity (000s m^3/day).*[24]

## Desalination System Operational Economics

This paper explores the private costs of desalinated water production. These are costs that are internalized within the operation of the project and are borne by the operator. They include the initial investment cost plus the operating and maintenance costs, which break up into wages, interest payments, energy, and equipment upgrades. As a rule of thumb, seawater desalination costs are 3 to 5 times higher than brackish water costs.[25]

Public costs, on the other hand, are real costs externalized by the plant operator. These are borne by the public at large, and may include operational nuisances or environmental damages caused by the desalination process. Public costs may include environmental impacts from brine discharge, feed water intake, or wind turbine or solar panel nuisances. These costs vary by project and range from zero to very significant, depending on location. Public costs are not discussed in this paper, as they are still widely debated. Public benefits, beyond the basic demand for clean water, are also not discussed in detail, as the paper's objective is to quantify the private costs and technical capabilities of modern desalination plants and their coupling costs to RES.
Factors that have the largest effect on the cost of desalination:

[24] Loupasis, 2002

[25] ibid

1. Feed water quality (i.e.. the salinity level) [26]
2. Product water quality specifications [27]
3. Energy costs
4. Economies of scale

Costs of desalinated water production have dropped considerably over the years as a result of reduced property plant and equipment (PP&E) costs, improved desalination efficiency, and improvements in system design, robustness, and operational ease. Input energy prices have risen, however, countering decreasing operational costs. Even so, total net levelized project costs have experienced a significant downward trend with time. As conventional water prices rise due to pollution and overexploitation of water resources, desalinated water is becoming a viable alternative water source.

The figures below compare the total capital and operations cost per m^3 of water for 100,000 m^3 seawater RO, MSF, MED (the three most popular commercial world-wide desalination technologies) desalination plants. The left figure below shows levelized costs, while the right figure summarizes the percentile costs breakouts for RO, MSF, MED.

Of note is that RO has no thermal energy costs, as only electric energy is used. This is a powerful aspect of the technology that enables effective coupling with RESs. RO electrical energy costs are high at 38% total costs and USD 0.23/m^3, while MSF and MED only have 21% and 8% total electricity costs, USD 0.19 and USD 0.06/m^3 respectively.

For MSF and MED electricity meets only part of the plant's energy requirements, while thermal energy inputs represent anther 30% and 38% of total production cost respectively. In comparison, energy costs are not only lower for RO, but represent a smaller portion of the production cost. However, the variable cost of labor is slightly higher for RO, by approximately 6% of project cost and USD 0.02/m^3. This is a reflection of the membrane maintenance requirements and lack of RO plant robustness.

Besides the RO pure electricity energy requirement, another vital point for considering RO matching with a RES, is that RO is an overall cheaper technology by approximately USD 0.30/m^3 compared to MSF and USD 0.10/m^3 compared to MED.

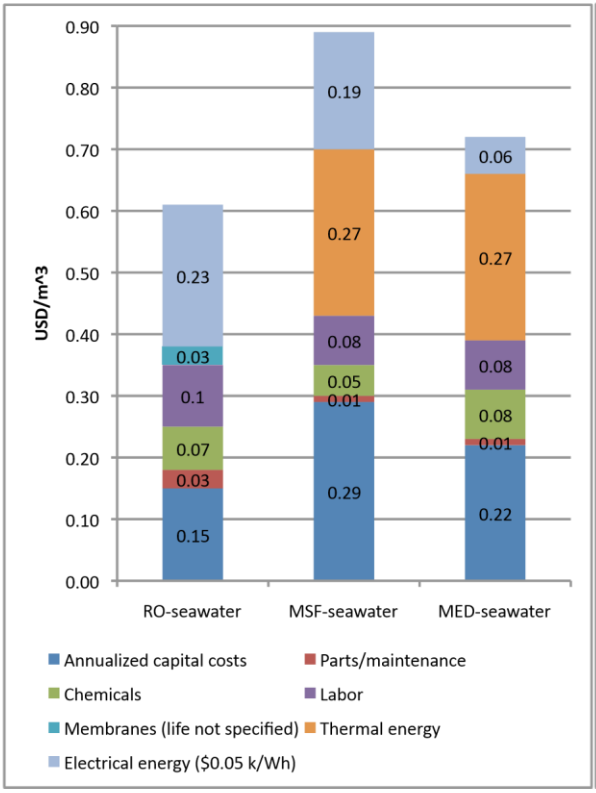
Additionally, as shown in the figure below, RO annualized capital costs have a lower percentile and total cost. They are lower for RO compared to other traditional desalination technologies for a number of reasons. First, RO depend on electric energy prices usually set by the open market on the grid, which arguably is cheaper than owning your own power plant (required for MSF and MED) due to the grid's ability to diversify operator risk and create market and price efficiency.

[26] Alatiqi et. al., 1999

[27] Dore, 2005

Second, MSF and MED desalination technologies have a larger upfront construction cost, compared to RO membrane banks and pump systems.

A serious consideration in RO financing and RES matching is that, net of the electricity cost, the annualized capital cost (25% total cost) is the next largest cost item per m^3. A study by Zejli on Moroccan RO-wind projects, discussed later in the paper, finds that in a RO-wind match the project's total economic cost is actually more sensitive to annualized capital cost variability than to changes in wind patterns and RES electricity inputs.[28]



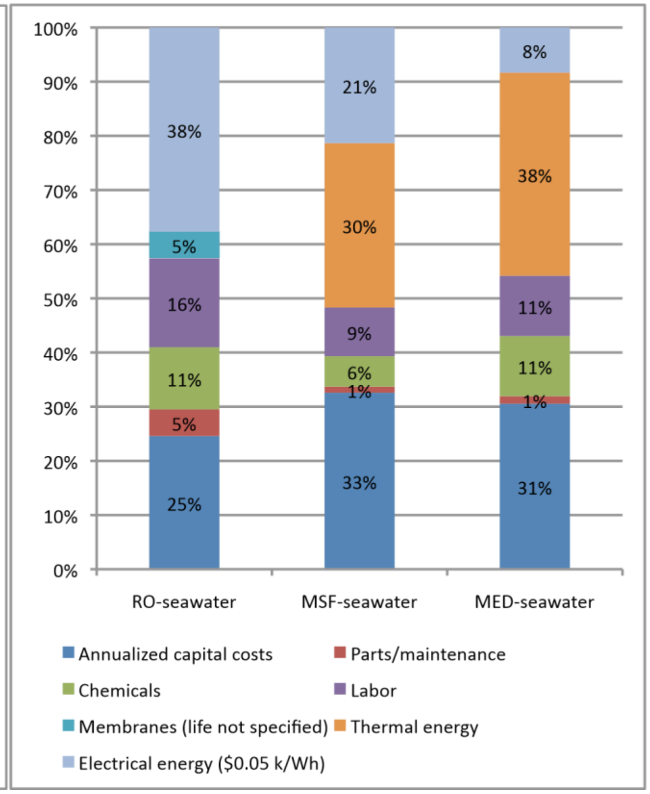




***Figure 11*** *(left): Comparative total capital and operations cost data for 100,000 m^3 of seawater by reverse osmosis, multistage flash, and multi-effect distillation.*[29]

***Figure 12*** *(right): Comparative percentile capital and operations cost for 100,000 m^3 of seawater by reverse osmosis, multistage flash, and multi-effect distillation.*[30]

The figure below highlights additional desalination plant cost data presented by Loupasis.[31] A significant conclusion from this table is the large spread of total costs per m^3 of permeate in the last column, as well as the difference in cost for RO sea- and brackish water. Loupasis costs are generally higher than the NRC-based costs in the figure above, presumably because Loupasis's the

[28] Zejli et al., 2004

[29] Derived by JF Thye from data presented in NRC, 2008

[30] Derived by JF Thye from data presented in NRC, 2008

[31] Derived by JF Thye from data presented in Loupasis, 2002

data is six years older. The table also underscores the variability of project costs due to geographic location, technology, time horizon, and source water that was alluded to earlier.

| | Investment in plant capacity | | Energy | | Consumable | | Labour | | Maintenance | | O&M | | **Total Cost, w/o Investment** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | USD/m^3 day | | USD/m^3 | | USD/m^3 | | USD/m^3 | | USD/m^3 | | USD/m^3 | | USD/m^3 | |
| Process | low | high | low | high | low | high | low | high | low | high | low | high | **low** | **high** |
| MSF | 1,000 | 2,000 | 0.60 | 1.8 | 0.03 | 0.09 | 0.03 | 0.20 | 0.02 | 0.06 | 0.68 | 2.15 | **1.36** | **4.30** |
| MED | 900 | 1,800 | 0.38 | 1.12 | 0.02 | 0.15 | 0.03 | 0.20 | 0.02 | 0.06 | 0.45 | 1.53 | **0.90** | **3.06** |
| VC | 900 | 2,500 | 0.56 | 2.4 | 0.02 | 0.15 | 0.03 | 0.20 | 0.02 | 0.08 | 0.63 | 2.83 | **1.26** | **5.66** |
| SWRO | 800 | 1,600 | 0.32 | 1.28 | 0.09 | 0.25 | 0.03 | 0.20 | 0.02 | 0.05 | 0.46 | 1.78 | **0.92** | **3.56** |
| BWRO | 200 | 500 | 0.04 | 0.4 | 0.05 | 0.13 | 0.03 | 0.20 | 0.004 | 0.02 | 0.12 | 0.75 | **0.24** | **1.50** |
| ED | 266 | 328 | 0.06 | 0.4 | 0.05 | 0.13 | 0.03 | 0.20 | 0.006 | 0.009 | 0.15 | 0.74 | **0.30** | **1.48** |

***Figure 13**: Total specific costs of the major desalination processes (assume USD/Euro exchange rate was approximately 1:1 in 2002).*[32]

Desalination plants in California have shown a significant degrease in cost from $1.60/m^3 in 1990 to $0.63/m^3 in 2002.[33] In 2004 Abu Dhabi completed a 190,000 m^3/day MSF plant with which they claim to produce water at $0.70/m^3,[34] though certainly cheap local oil supply subsidizes this low cost.

The figure below is a compilation of seawater desalination project costs per m^3 of freshwater production in 2009 USD. This cost data is derived from projects built since 2000 and is therefore partly influenced by the decrease in technology costs and the increase of energy costs. However, the graph depicts the importance of project scalability, demonstrating a dramatic decrease of cost between zero and 20,000 m^3/day of permeate. Therefore, in considering RES-desalination technology matches at commercial capacity levels we need to consider the dramatic marginal savings that occur over 10,000 m^3/day. The Mechanical Vapor Compression Curve (MVC) is a serious contender to the RO curve, as MVC costs are significantly below RO costs at 20,000 m^3 by approximately USD 0.75/m^3.

***However, as the technology review above demonstrated, MVC plants are currently limited in capacity to under 25,000 m^3, making RO the most cost effective desalination capacity currently available for yields above 40,000 m^3/day.***

[32] Derived by JF Thye from data presented in Loupasis, 2002

[33] Chaudhry, 2004

[34] Awerbuch, 2004

| Type of system: capacity in m^3/day | Unit product cost, $/m^3 |
|---|---|
| MVC | |
| 114 | 5.00 |
| 492 | 3.22 |
| 4,013 | 2.48 |
| 4,542 | 2.43 |
| 19,987 | 0.46 |
| RO | |
| 114 | 2.37 |
| 4,013 | 1.98 |
| 4,542 | 1.29 |
| 37,816 | 1.09 |
| 39,974 | 0.83 |
| 45,425 | 0.68 |
| 113,562 | 0.55 |
| MSF | |
| 26,990 | 1.57 |
| 31,987 | 1.44 |
| 37,816 | 1.25 |
| MEE | |
| 22,712 | 1.24 |
| 37,816 | 1.08 |
| TVC | |
| 22,145 | 1.55 |

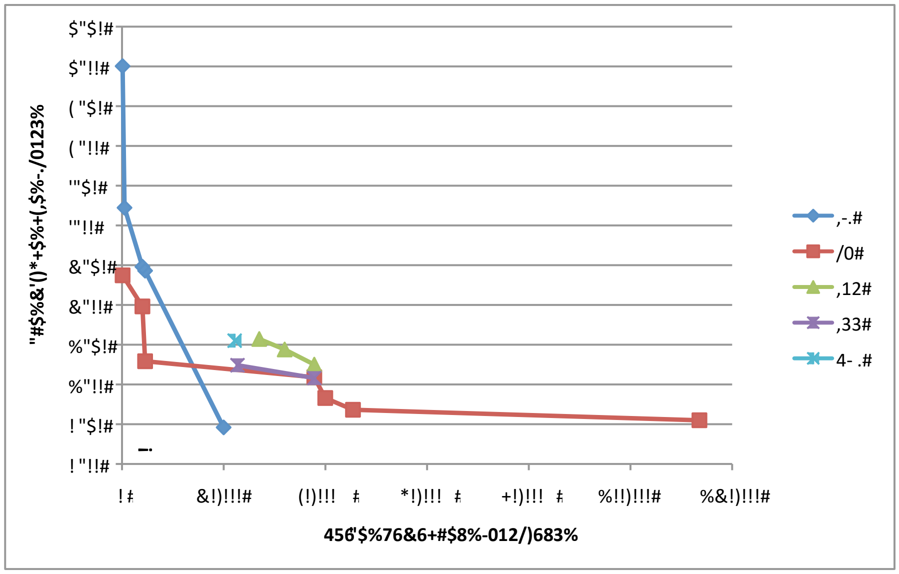


***Figure 14**: Unit product costs for seawater desalination processes.*[35]

Appendix III includes a summary of reported first year cost of product water from RO Plants.[36]

## Desalination System Energy Economics

The Figure below, reveals that VC, RO, and ED have the lowest energy requirements per m^3 of permeate. For compatibility with a REDS this technology characteristic is critical. ED technology can only be deployed in brackish water, leaving us to compare the next two most efficient technologies, VC and RO. As a baseline comparison, the theoretical minimum energy requirement for desalination is 0.83 kWh/m^3.[37]

[35] Derived by JF Thye from data presented in Eltawil et. al., 2009

[36] Gleick et al., 2006-2007

[37] NRC, 2008

| Process | Feed Water Type | Energy Source | Product Water Quality (ppm TDS) | Typical Max Plant Capacities ($m^3$/day) | Typical Energy Requirements ($kWh_e/m^3$) |
|---|---|---|---|---|---|
| Multi-Stage Flash Distillation (MSF) | Seawater | Steam | ~10 | 5,000-60,000 | 10-14.5 |
| Multiple-Effect Distillation (MED) | Seawater | Steam | ~10 | 5,000-20,000 | 6-9 |
| Vapor Compression (VC) | Seawater | Electricity | ~10 | 2,400 | 7-15 |
| Sea Water Reverse Osmosis (SWRO) | Seawater | Electricity | ~350-500 | 128,000 | 4-6*<br>7-13** |
| Brackish Water Reverse Osmosis (BWRO) | Brackish | Electricity | ~350-500 | 98,000 | .5-2.5 |
| Electrodialysis (ED) | Brackish | Electricity | ~350-500 | 45,000 | .7-2.5 |

Note: *with energy recovery **without energy recovery

***Figure 15****: Characteristics of the major desalination processes.*[38]

Traditionally, VC plants have operated under smaller maximum plant capacities than RO (2,400 m^3/day for VC vs. plants up to 100,000 to 200,000 m^3/day for RO). Compared to VC, RO is also 1 to 9 kWh/m^3 of water more energy efficient with seawater as feedstock. Assuming a commercial electricity cost of 0.05 $/kW, RO can be approximately 0.05 $/m^3 to 0.45 $/m^3 cheaper than VC just by energy demand costs, highlighting RO as the clear frontrunner in energy efficiently.

## Summary of Pros and Cons of Desalination Technologies

This sections tabulates that advantages and disadvantages of desalination technologies. Bolded sentences mark significant technology characteristics that note compatibility (in the Pros column) and non-compatibility (in the Cons column) for RES matching. The water recovery and total dissolved solids (TDS) column is included to evaluate the system's productivity and versatility. High water recovery means a low brine stream and high permeate to brine ratio.

Energy efficiency is improved by higher water recovery percentiles. Energy efficiency is a fundamentally important characteristic for matching, as high efficiencies allow for use of smaller RES plants, which lowers the project and ultimately water production cost.

| Process | Recovery and TDS | Pros | Cons |
|---|---|---|---|

[38] Loupasis, 2002

| | | | |
|---|---|---|---|
| **RO** | • 30–60% recovery possible for single pass (higher recoveries are possible for multiple pass or waters with lower salinity)<br>• <500 mg/L TDS for seawater possible and <less 200 mg/L TDS for brackish water | • **Lower energy consumption**<br>• **Relatively lower investment cost**<br>• No cooling water flow<br>• **Simple operation and fast start-up**<br>• High space/production capacity<br>• Removal of contaminants other than salts achieved<br>• Modular design<br>• Maintenance does not require entire plant to shutdown<br>• Energy usage proportional to salts removed not volume treated<br>• Higher membrane life of 7–10 years<br>• **Operational at low to moderate pressures** | • Higher costs for chemical and membrane replacement<br>• Vulnerable to feed water quality changes Adequate pre-treatment a necessity Membranes susceptible to biofouling<br>• Mechanical failures due to high pressure operation possible<br>• Appropriately trained and qualified personnel recommended<br>• Minimum membrane life expectancy around 5–7 years |
| **ED/EDR** | • 85–94% recovery possible<br>• 140–600 mg/L TDS | • Energy usage proportional to salts removed not volume treated<br>• Higher membrane life of 7–10 years Operational at low to moderate pressures | • **Only suitable for feed water up to 12,000 mg/L TDS**<br>• Periodic cleaning of membranes required Leaks may occur in membrane stacks<br>• Bacterial contaminants not removed by system and post-treatment required for potable water use |
| **MSF** | • 25–50% recovery in high temperature recyclable MSF plant<br>• <50 mg/L TDS | • Lends itself to large capacity designs<br>• Proven, reliable technology with long operating life Flashing rather than boiling reduces incidence of scaling<br>• Minimal pre-treatment of feed water required High quality product water Plant process and cost independent of salinity level<br>• Heat energy can be sourced by combining with power generation | • **Energy intensive process**<br>• Large capital investment required<br>• Larger footprint required (land and material)<br>• Corrosion problems if materials of lesser quality used<br>• Slow start-up rates<br>• Maintenance requires entire plant to shut-down<br>• High level of technical knowledge required<br>• Recovery ratio low |
| **MED** | • 0–65% recovery possible<br>• <10 mg/L TDS | • Large economies of scale<br>• Minimal pre-treatment of feed water required<br>• Very reliable process with minimal requirements for operational staff<br>• Tolerates normal levels of suspended and biological matter<br>• Heat energy can be sourced by combining with power generation<br>• Very high quality product water | • **High energy consumption**<br>• High capital and operational cost<br>• High quality materials required as process is susceptible to corrosion<br>• Product water requires cooling and blending prior to being used for potable water needs |
| **VC** | • VC (Vapor Compression Desalination) - mechanical and thermal<br>• 50% recovery possible<br>• <10 mg/L TDS | • Developed process with low consumption of chemicals economic with high salinity (>50,000 mg/L)<br>• Smaller economies of scale (up to 10,000 m3/d)<br>• **Relatively low energy demand**<br>• Lower temperature requirements reduce potential of scale and corrosion Lower capital and operating costs Portable designs allow flexibility<br>• **Ability to rapidly adjust to flux changes.** | • **Limited to smaller sized plants**<br>• Start-up require auxiliary heating source to generate vapor<br>• **Compressor needs higher levels of maintenance** |

***Figure 16 (previous page):*** *Desalination characteristics comparison table with recovery and total dissolved solids (TDS) treatment capability, and pros and cons of desalination processes.*[39]

As a result, an initial review of the desalination technology characteristics table above indicates that RO, from an engineering perspective, is a leader in RES matching due to its lower energy consumption, lower investment cost, simple operation, fast start-up capability, and operational ability at low to moderate pressures, all of which indicate a superior ability to handle low to high electric energy inputs from stochastic renewable energy sources.

The VC technology is also attractive for RES matching due to its relatively low energy demand and ability to rapidly adjust to flux changes. However, VC is limited to smaller plant sizes and its compressor requires higher levels of maintenance (i.e. exhibits a low level of robustness).

Appendix I includes a more detailed comparison table between distillation (MSF and MED) and RO desalination processes.[40]

[39] Eltawil, 2009 with added comments by JF Thye

[40] Al-Mutaz, 2000

# RES Economics

Figure 17, on the next page, is a summary of RES 2005 estimated- and 2020 projected costs. The wind electricity per kWh costs are highlighted with a red circle because they are clearly much lower than other renewable energy sources. It should be said, that the wind cost numbers are optimistic, as the US wind industry estimates the current cost of on-shore wind power to be between 5 to 7 cents/kWh (including subsidies such as production tax credits and renewable energy certificates), depending on wind resource conditions (i.e. flat and windy central plains vs. hilly and less predictable New England terrain).[41] However, even the revised wind cost numbers are still competitive with expensive coal. In comparison, solar thermal electricity is approximately twice as expensive as wind energy, and PV electricity is currently three times more expensive than wind per kWh.[42] Though PV and solar thermal are expected to become cheaper, wind energy remains an economic front runner at approximately twice to three times the US grid cost.

[41] http://www.awea.org/faq/wwt_costs.html#How%20much%20does%20wind%20energy%20cost

[42] Jefferies, 2009

| Technology | Current Cost (US cents/kWh) | | Projected future costs beyond 2020 (US cents/kWh) | |
|---|---|---|---|---|
| | Min | Max | Min | Max |
| Biomass Energy | | | | |
| Electricity | 5 | 15 | 4 | 10 |
| Heat | 1 | 5 | 1 | 5 |
| Wind electricity | | | | |
| Onshore | 3 | 5 | 2 | 3 |
| Offshore | 6 | 10 | 2 | 5 |
| Solar thermal electricity | | | | |
| Insulation of 2,500 kWh/m^2/year | 12 | 18 | 4 | 10 |
| Hydro-Electricity | | | | |
| Large scale | 2 | 8 | 2 | 8 |
| Small scale | 4 | 10 | 3 | 10 |
| Geothermal energy | | | | |
| Electricity | 2 | 10 | 1 | 8 |
| Heat | 0.5 | 5 | 0.5 | 5 |
| Marine energy | | | | |
| Tidal barrage (e.g. the proposed seven barrage) | 12 | 12 | 12 | 12 |
| Tidal stream | 8 | 15 | 8 | 15 |
| Wave | 8 | 20 | 5 | 7 |
| Grid connected photovoltaics, according to incident solar energy (insulation) | | | | |
| 1,000 kWh/m^2/year (e.g. UK) | 50 | 80 | 8 | 8 |
| 1,500 kWh/m^2/year (e.g. Southern Europe) | 30 | 50 | 5 | 5 |
| 2,500 kWh/m^2/year (most developing countries) | 20 | 40 | 4 | 4 |
| Stand alone photovoltaics | | | | |
| 2,500 kWh/m^2/year (incl. batteries) | 40 | 60 | 10 | 10 |
| Nuclear Power | | | | |
| Average grid supply | 4 | 6 | 3 | 5 |
| Electricity grid supplies fossil fuels (incl. T&D) | | | | |
| Off-peak | 2 | 3 * | | |
| Peak | 15 | 25 | | |
| Average | 8 | 10 | | |
| Rural electrification | 25 | 80 | | |
| Cost of central grid supplies, excl. transmission and distribution | | | | |
| Natural gas | 2 | 4 * | | |
| Coal | 3 | 5 | | |

Notes:
*Capital costs will come down with technical progress, but many technologies already mature may be offset by rising fuel costs.

***Figure 17***: *Cost of RES compared to fossil fuels and nuclear power.*[43]

Taking into account that stand-alone REDS are often operated far away from grid interconnectivity, or are powered by municipal diesel generator plants that have risk exposure to oil price fluctuations, as well as high transport costs, wind power offers an overall attractive economic package for REDSs.

# Coupling RES with Desalination

Historically RES-desalination system (REDSs) match-ups were designed to operate under constant energy inputs, coupled to the grid or powered by backup diesel powered generators in remote location to supply power during low RES production. Off-grid, stand-alone, or autonomous REDSs pose the problem of renewable energy input variability, or stochastic energy production. Unpredictable and stochastic energy inputs force the desalination plant to operate in non-optimal conditions and may cause operational and technical problems. Today's RES lack the vital large-scale energy storage capacity (i.e. large battery or fuel cell banks) that could levelize electric energy production and enable an even and predictable power supply. High capacity electricity

[43] Derived by JF Thye from data presented in RES, 2005

storage is under development, but is still many years away from being an economically competitive solution.

Commonly today the grid acts as a buffer and battery for commercial wind and solar electricity production, and a number of commercial RO plants around the globe use this solution as a component of power purchase agreements with large scale wind farms, such as the 140,000 m^3/day Australian Perth Seawater RO plant.[44] The Perth RO plant is actually connected to the grid and uses grid electricity, which is provided by the wind farm and other traditional power plant sources. On low-wind days, the RO plant is not forced to scale back production, as grid thermal power plants can scale up electricity production and meet the RO plant energy needs beyond the power available from the wind farm. Similarly, on high-windy days, wind farm electricity production may exceed the RO plant needs, causing overflow wind-generated electricity to be absorbed and sold into grid. This net metering-type energy sharing arrangement is estimated to break even over time, allowing wind-generated electricity to match the annual RO plant electricity input requirements.

A stand-alone REDS has two choices to manage its energy flow:

1. **To store excess power** availability, as power production levels vary with time due to wind speed or solar irradiance changes. If power is not consumed immediately, and can not be stored due to inadequate storage capacity, it must be shed via a resistor bank and will be lost. Currently, this large scale energy storage option is the less optimal choice due to a lack of economically viable technological solutions.
2. **To optimize desalination mechanics through power matching** by scaling desalination system electricity demand and production capacity in relation to electricity load availability, while also considering power requirements for the desalination system startup and shutdown sequences, which are essential to maintaining most desalination systems' integrity and longevity (except for vapor compression desalination). A small energy storage system, such as gravity water storage, a hydrogen fuel cell, a battery bank, a small natural gas or diesel generator, or thermal bank (for solar thermal energy) may be used to power system management controls and provide the temporary energy needed to enable system startup and shutdown cycles. Though this solution adds to total system cost, which will be discussed in greater detail in the case study section below, it is currently the more viable economic alternative for REDSs. This solution, in essence, allows the water storage facility that is fed by the desalination plant to become a battery, which is charged by excess production and used in low energy and low output cycles.

## REDS Technology Matching

RESs that are generally considered as energy sources for desalination are wind, solar thermal, photovoltaic and geothermal. The matching of renewable energy sources to desalination processes is a technical and economic challenge with problems caused primarily by RES stochastic power

[44] http://www.water-technology.net/projects/perth/

outputs and the RES significant up-front capital costs, which is generally larger per kilowatt compared to traditional thermal plants. However, once constructed, RESs require no fuel inputs. It is therefore important to compare total levelized RES costs with those of their thermal counterparts, which must include fuel inputs.

As concluded above, the principal of power matching is of paramount importance in designing an autonomous REDS. Power supplied by the RES must equate to that being consumed by the desalination process. The central challenge is to create a system architecture and control mechanism that will achieve this balance.

The following three power matching strategies are currently implemented to optimize RES and desalination technology combinations:[45]

1. **Power side management** provides the desalination plant with power on demand. Therefore the power supply is designed to produce a fixed output independent of prevailing energy conditions. For this a hybrid power package with numerous power sources is required (e.g. RES combined with batteries, flywheels, or non-renewable power units). Power side management implies redundancy in the power plant.
2. **Load side management** dissipates excess power. In this architecture power is produced by a stand-alone RES and load matching is achieved by 1) switching desalination modules bundled in clusters on and off or 2) adjusting and over designing the desalination plant to deviate from its optimal operating levels (i.e. head difference and/or flow rate) without breaking. Load side management implies redundancy in the desalination plant.
3. **Integrated management** minimizes dependance on non-RESs by determining long-term averages for RES power inputs and then controlling the system to limit power delivery to these lower levels for which the desalination plant is optimized.

The relative capital costs between all three options determines how applicable a match is. The figure below summarizes feasible RES and desalination technology combinations. Geothermal technologies are not discussed in this paper.[46] This decision tree technology chart summarizes technology match limitations and will be used as a guide for later discussions on wind, PV, and solar thermal REDS matches. For example, wind-electric RESs can be matched with RO, ED, and MVC. Wind-shaft RESs (a non-electrical purely mechanical link between the systems) can only

[45] Al-Alawi, 2004

[46] Geothermal electric power plants produce constant and non-stochastic thermal loads and electricity, similar to that of fossil fuel power plants and grid electricity. They therefore do not pose the stochastic power match challenge and are typically matched with traditional desalination technologies. Geothermal power production drawbacks is its high cost of capital and geographic constraints. Of note is that geothermal RESs my supply power in the form of heat and electricity, as well as allow for a co-generative waste heat capability. A geothermal energy source would therefore be ideal for a standard electric RO or low grade thermal energy connection, such as a MED or VC desalination technology.

function with RO and MVC, as ED requires electricity for the separation of salts from water, while RO and MVC are mechanical processes whose pumps can be powered by either an electric input or a mechanical drive shaft.

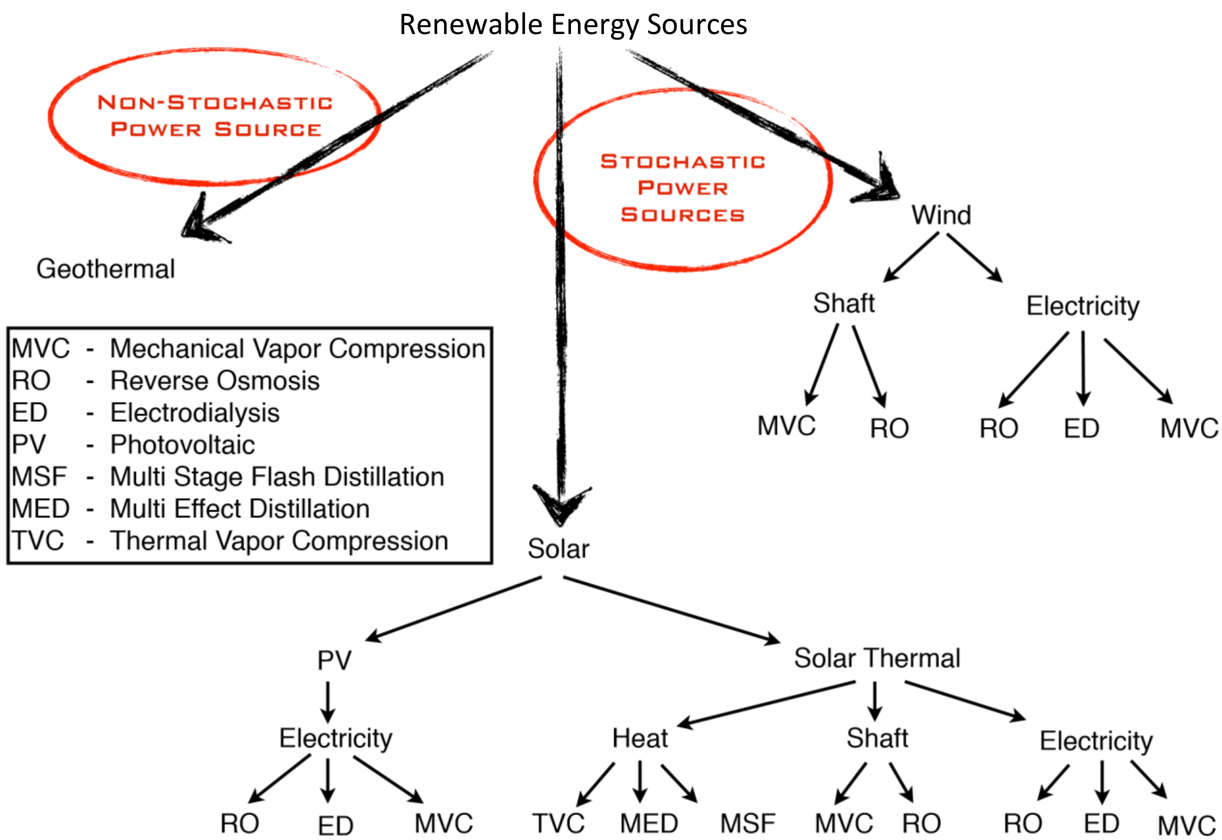
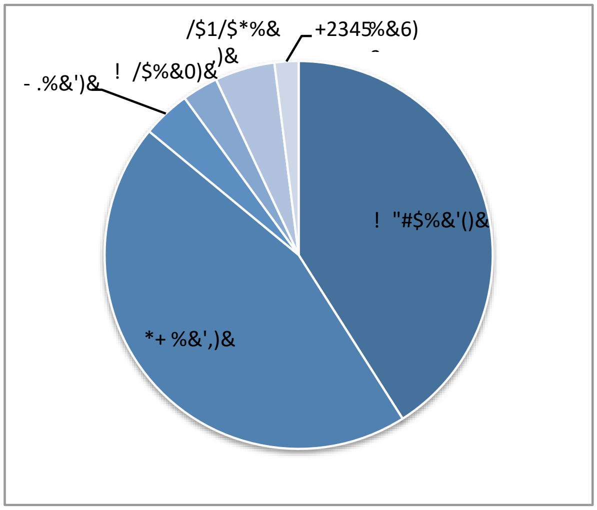



***Figure 18****: Technology chart for renewable energy system desalination combinations*[47]

## REDS Technology Implementation

For large scale wind and solar RESs (renewable energy systems) the most suitable desalination combinations are MED and MSF for solar RESs, and RO, ED, MVC for wind RESs.[48] Figure 19 shows the global installed desalination capacity by technology, irrespective of the connected power plant. Clearly RO and MSF are currently the most popular desalination options, with both together taking 86% of the market. In comparison, Figure 20 breaks out the global installed desalination capacity powered by RESs. Tzen and Morris do not discriminate in Figure 20 on how much of a desalination plant's energy is derived from RESs, but rather lump projects into RES categories if any energy is supplied by these.

[47] Eltawil et. al.
[48] Delyannis, 1996



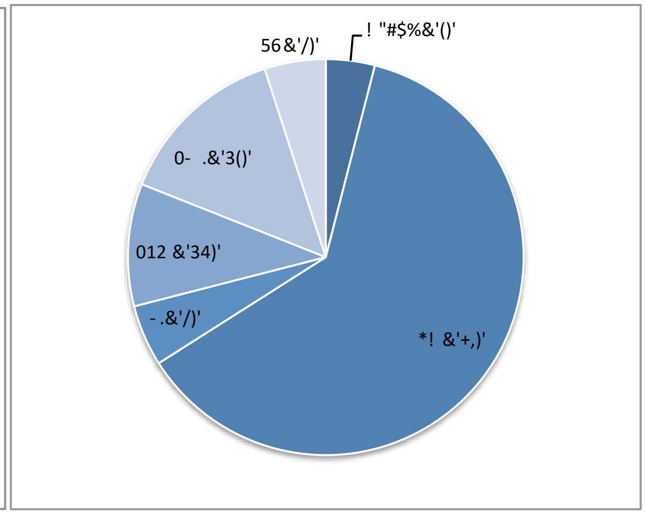


***Figure 19** (left): Global installed desalination capacity by technology (irrespective of power source).*[49]

***Figure 20** (right): Global RES-powered installed desalination capacity.*[50]

At 62% market share, clearly RO is the primary user of renewable energy, as depicted in Figure 20 above. In 2005 32% of renewable energy supplied is PV for RO and 19% is wind for RO, as shown in Figure 21 below. This means that 63% of RO (32%/51% by Figure 21) renewable energy was from PV and 37% from wind. Figure 21 shows that the third most popular REDS match is solar and MED, at 13%.

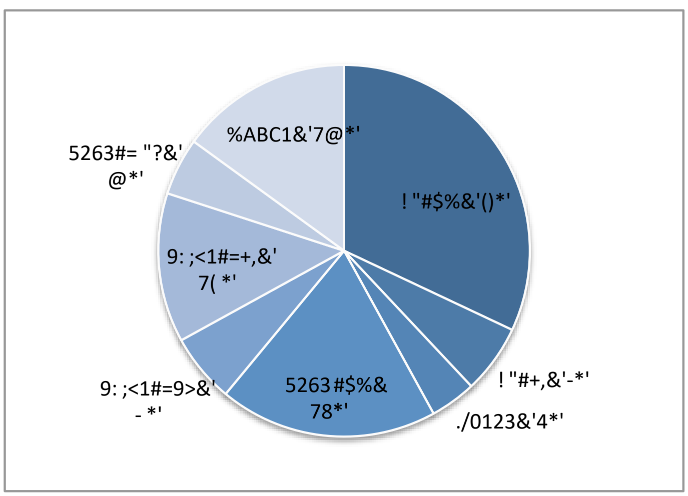


***Figure 21**: Distribution of renewable energy powered desalination technologies, percent is installed capacity.*[51]

[49] IDA, 2002

[50] Tzen and Morris, 2003

[51] Tzen, 2005

MSF plants (6% of RES with solar-MSF), due to their better efficiencies and reduced costs, pushed out MED systems (13% of RES with solar-MED) in the 1960s, and only small size MED plants were built since then. However, in the late 1990s, interest in MED increased again and currently MED processes are said to compete technically and economically with MSF technologies for solar powered RES matches. Recent advances in MED low temperature processes and increased technology robustness have spurred this comeback, allowing MED plants to perform at 94% to 96% capacity due to decreased corrosion and scaling susceptibility.[52]

## RES Technology Matching Pros and Cons

The viability of any of the above outlined combinations depends on:

- RES site capacity and the useful energy available after conversion from renewable sources (photo, thermal, mechanical, electrical energy forms)
- Water demand and system capacity determine the size of the energy collection system and desalination energy input requirements.
- Maintenance personnel availability and experience for on-site plant operation.
- Total REDS cost.

Figure 22, below, presents a crude rating system for RES and desalination technology matching, using stars. Ignoring the geothermal energy column, excluded in this discussion for the noted reasons above (but included in the table as a reference for its high rating due to ints consistent thermal load), both the PV and Solar Thermal column are given higher cumulative ratings by Oldach (stars added up by column) than wind energy. However, this table does not include project economics, which heavily favors wind and steers us back to favoring wind powered desalination technologies.

| **Criterion** | **PV energy** | **Solar Thermal energy** | **Wind energy** | **Geothermal energy** |
|---|---|---|---|---|
| **Suitability for powering desalination plants** | Suited for desal requiring electrical power*** | Suited for desal plants requiring thermal power*** | Suited for desal plants requiring electrical power*** | Suited for desal plants requiring thermal power.*** |
| **Site requirements and resource availability** | Good match with high need for desal.*** | Good match with high need for desal.*** | Resource is locationdependent.** | Resource is limited to certain locations.* |
| **Continuity of power output** | Output is intermittent, & energy storage is required.* | Output is intermittent, & energy storage is required.* | Output is intermittent, & energy storage is required.* | Continuous power output.*** |
| **Predictability of power output** | Output is relatively unpredictable.** | Output is relatively unpredictable.** | Output is very unpredictable with large fluctuations.* | Output is predictable.*** |

[52] http://www.idswater.com/Common/Paper/Paper_46/INNOVATIVE%20IDEAS%20TO%20REDUCE%20CURRENT%20COST.htm

*** excellent match
** good match
* poor match

***Figure 22**: Rating for RES for Desalination.*[53]

A more detailed comparison between solar thermal, PV, and wind RES follows.

## Solar Thermal

Solar Thermal RESs have REDS operational drawbacks, but produce high quality product water, making solar thermal processes particularly suitable when pure distilled water is required for industrial or agricultural uses. As solar thermal storage depends on day radiation, significant heat storage reservoirs are required to smooth operations in REDS match-ups, adding an extra layer of complexity and capital costs.[54]

Evaporators in the heat category such as TVCs, MEDs, and MSFs require accurate process controls. These systems are found to be unstable in small sizes. Therefore medium and large size evaporators (thousands m^3/day capacity) are commonly used, which require larger energy inputs than standard size RES can provide, unless massive solar fields are built. A large solar RES, in turn, requires a large ground surface for deployment, which complicates its deployment due to potential sub-optimal terrains or the high expense of large land tracts.

## Photo Voltaic

PV modules convert solar energy into direct current (DC) electricity. Small desalination systems operating directly off of electricity are most optimal. PV-REDSs have been deployed around the world as stand-alone systems, in which the ED process, which is approximately 16% of deployed PV-REDSs (6%/38% by Figure 21) is applicable only to brackish water. Due to the PV array's large land requirements, PV-RO combinations have been limited to small capacity systems, as well, though they have been deployed in high number. This is partly due to the correlation of historical water-scarcity to hot sunny regions.

## Wind

Pairing between the best matching desalination technology for wind-RESs depends on the:

- Feed water salinity quality
- Required product water salinity quality
- Wind velocity distribution
- Power distribution - grid accessibility and independent generator power systems
- Desalination system energy demands

[53] Oldach, 2001

[54] Loupasis, 2002

Power matching with wind RESs requires energy dissipation and storage devices, as well as power control systems that include load-dumps, flywheels, batteries banks, fuel cells, or combinations thereof.

Wind and PV REDSs combinations are currently considered the newest and state of the art approaches. In both technologies the cost barrier is in their large initial capital costs. Though both technologies have become dramatically more economical in recent years, wind power is currently approximately half the solar RES cost per kilowatt of energy production. Wind's economic competitiveness over solar, and PV's need for large expanses of land has made technology developers particularly interested in the wind-REDS combination.

However, wind and PV system architectures can be applied separately or in tandem. Their economic and technical compatibility with RO desalination has recently shown the most promise.[55] The figure below is a compilation of Delyannis's recommendations for REDS matching. For seawater sources and potable product water systems, he recommends that wind RESs can be used for system sizes from small to large, versus solar RES, which should be used for small systems. Interestingly, Delyannis notes that MVC systems, rather than RO and ED, should be used for large systems, a notion contradictory to Eltawil's 2009 review on REDSs. I expect that Delyannis's work is mostly theory and technology focused, rather than inclusive of the project's economic aspects. I make this conclusion because MVC requires approximately twice as much operational energy compared to RO, as per Loupasis.[56]

| Feed water quality | Product water | RE resource available | System size | | | Suitable combination |
|---|---|---|---|---|---|---|
| | | | Small (1-50 m^3/d) | Medium (50-100 m^3/d) | Large (100-200 m^3/d) | |
| Brackish water | Distillate | Solar | * | | | Solar distillation |
| | Potable | Solar | * | | | PV–RO |
| | Potable | Solar | * | | | PV–ED |
| | Potable | Wind | * | * | | Wind–RO |
| | Potable | Wind | * | * | | Wind–ED |
| Seawater | Distillate | Solar | * | | | Solar distillation |
| | Distillate | Solar | | * | * | Solar thermal–MED |
| | Distillate | Solar | | | * | Solar thermal–MED |
| | Potable | Solar | * | | | PV–RO |
| | Potable | Solar | * | | | PV–ED |
| | Potable | Wind | * | * | | Wind–RO |
| | Potable | Wind | * | * | | Wind–ED |
| | Potable | Wind | | * | * | Wind–MVC |
| | Potable | Geothermal | | * | * | Geothermal–MED |
| | Potable | Geothermal | | | * | Geothermal–MED |

***Figure 23**: Recommended RES-desalination combinations.*[57]

55 Delyannis, 2006

56 Loupais, 2002

57 Delyannis, 2006

WATEREUSE ASSOCIATION

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# Seawater Desalination Costs

## White Paper

September 2011; Revised January 2012

The WateReuse Desalination Committee's White Papers are living documents. The intent of the Committee is to enhance the content of the papers periodically as new and pertinent information on the topics becomes available. Members of the desalination stakeholder community are encouraged to submit their constructive comments to white-papers@watereuse.org and share their experience and/or case studies for consideration for inclusion in the next issuance of the white papers.

**WATEREUSE ASSOCIATION**
**DESALINATION COMMITTEE**

# Seawater Desalination Costs

**White Paper**

## I Introduction

One of the most sensitive and critical aspects of any water project is cost. For membrane desalination, decreasing costs and producing superior water quality are among a number of significant reasons why this technology continues to be the water treatment technology of choice in the United States and around the world. This white paper serves to: provide an overview of cost drivers and components of the desalination process; present costs associated with desalination compared to other water supply alternatives; discuss challenges and perceptions; and highlight recent advances in desalination technology that affect the total delivered cost of water.

Although membrane desalination was first commercialized in the United States in the late 1960's, reverse osmosis membrane technology was not widely implemented until the 1980's, largely due to the relatively high costs compared to other potable water treatment alternatives. Why have these costs decreased or appeared more reasonable and competitive over time? Although there are a number of reasons, the reduction in costs are primarily related to improvements in manufacturing methods, the changing facets of the regulatory environment in the United States, the increased market demand and competition for membranes, and the gradual depletion of more conventional groundwater sources.

Since the early 1990's, one example of the successful implementation of reverse osmosis desalination technology is its designation as a "best available technology" (BAT) by the United States Environmental Protection Agency (US EPA) for removal (and/or reduction) of numerous inorganic contaminants (e.g., antimony, arsenic, barium, fluoride, nitrate, nitrite, boron, selenium, radionuclides), endocrine disrupting compounds (e.g., synthetic and natural hormones), and several pharmaceutical compounds.

Together with a reduction in the membrane technology costs beginning in the 1980's, BAT designation became one other (albeit significant) technical component to consider in the process of developing and potentially implementing a desalination facility. Other decision factors are rooted in both technical and nontechnical components of water supply projects such as timing, available space, and other specific locallydriven concerns. However, the determination of meaningful costs associated with membrane (including seawater membrane) desalination has proven a bit more elusive when applied without consideration of site specific issues or how the costs compare with other viable, reliable, and long-term water supply alternatives in the same locale.
For many years, planners have used tools generally available in the marketplace to determine relative costs for desalination. Most costing models for desalination plants have been developed by agencies such as the US EPA and the US Department of the Interior.

Engineering consultants have contributed select project cost experience gained from their clients or from trade journals and publications; and although this information can be very helpful, the data can at times be either too generalized or too project site-specific to be particularly helpful to project planners for specific guidance or to those interested in gauging costs compared to their particular project or environment.

A consolidated list of representative examples includes:

1. In 1979, the US EPA published *Estimating Water Treatment Costs.* This document is still used by some industry professionals as a reference guide to compute cost estimates for pretreatment, post-treatment, and conventional treatment technologies.
2. Previous to the US EPA document, the Department of the Interior developed in 1967 and 1969 the *Guideline for Uniform Presentation of Desalting Costs Estimates* (Research and Development Progress Report No. 264), which is sometimes still referenced yet, by today's standards, appears quite dated.
3. In 1999, the Department of the Interior's Bureau of Reclamation developed the *Water Treatment Evaluation Routine* program and manual (based on the US EPA *Estimating Water Treatment Costs).*
4. In 2003 and updated in 2008, a Water Treatment Cost Estimation Program was jointly developed by I. Moch & Associates and the Bureau of Reclamation (WT Cost II©)[58] to estimate costs and is partially based on updated cost curves generated by the US EPA (*Estimating Water* Treatment *Costs*, EPA-600/2-79-162a, EPA-600/2-79-162b, EPA-600/2-79-162c, August 1979) and is an upgraded version of the WaTER (Water Treatment Estimation Routine) excel spreadsheet developed by the Bureau of Reclamation in 1999.
5. In 2009, Global Water Intelligence[59] developed a desalination cost estimation program available on their website for reference by professionals interested in capital, operations and maintenance costs associated with desalination plants.

The water treatment industry continues to work towards standardization; however, there is no single resource or programming tool to capture all of the particular nuances materially affecting Seawater Reverse Osmosis (SWRO) facility costs.

Some of the above referenced models look at the cost of the technology in a "stand-alone" fashion, while others consider the impacts associated with other ancillary factors which can be site-specific. Costing sources are one tool in the planner/designer's toolbox, and a typical planning approach could incorporate use of computer programs, established cost curves, other bid costs for comparison, and similar applications for comparison

[58] Moch, I., Querns, W, M., and Steward, D.; WT Cost II, Desalination and Water Purification Research and Development Program Report No. 130, February 2008.
[59] GWI/DesalData Cost Estimator: www.desaldata.com.

purposes. Therefore, it is important to gain a comprehensive understanding of the costs associated with desalination when utilizing these models or developing the costs for desalination projects. Additionally, common sense is necessary when using these tools insofar as a particular project may have some unique components that cannot be modeled in a computer program alone. In any given situation, water industry planners, managers, and engineers can best serve the needs of the water stakeholder community through an awareness of the design and expected operating conditions of the proposed water treatment plant, as well as the validity and accuracy of the costing sources.

## II Cost Trends

The unit costs for desalination processes have fallen considerably over the last three decades[60]. Figure 1 further exemplifies the downward trend[61].

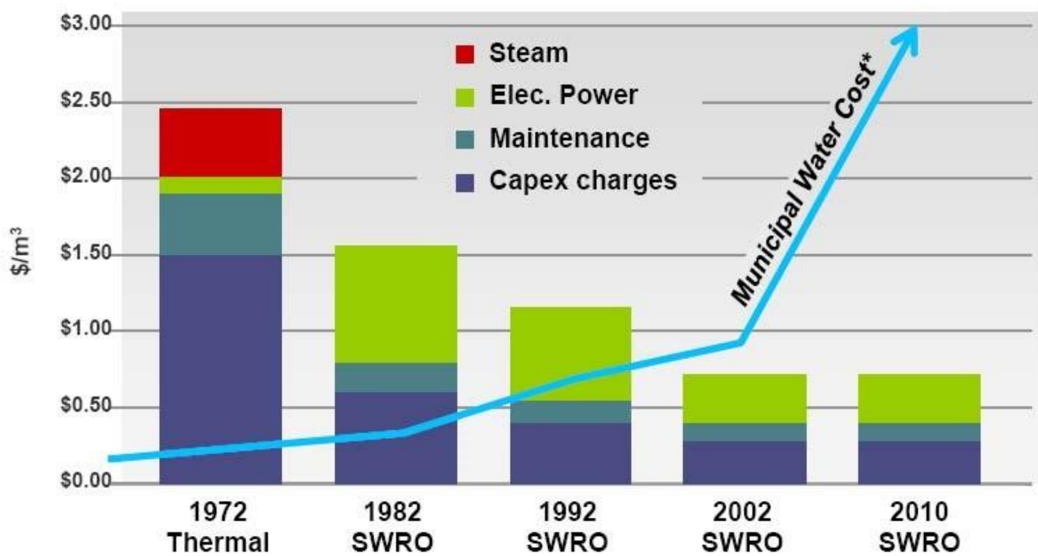


**Figure 1**
**SWRO Cost Trend**[62]
** Water costs for San Diego, Monterey, Perth, Sydney, and Barcelona*

As shown in Figure 2, there is also an economy of scale cost-benefit associated with increasing plant capacity to effectively lessen membrane desalination plant unit construction costs.

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[60] Zhou, Y., and R. S. J. Tol (2005), Evaluating the Costs of Desalination and Water Transport, *Water Resources Res.*, 41, W03003, doi:10.1029/2004WR003749.
[61] Tom Willardson, CFO: Energy Recovery Incorporated reference presentation material, February 24, 2011.
[62] Ibid.


**Figure 2**
**Unit Construction Cost vs. Capacity**[63]

The historic downward trend of the cost of desalination is generally associated with technology improvements such as improved SWRO membrane performance and significant advances in the ability to recover more energy from the desalination process. However, considering other unassociated factors, Figure 3 shows that the costs have remained flat in recent years (even in consideration of increased production capacities) and, in a few cases, trended upwards. Identification of the various key project components that make up costs, as described in Section III, explains this trend and the drivers behind facility costs and the cost to supply water to end-users.

[63] Wilf, M., Awerbuch, L., Bartels, C., Mickley, M., Pearce, G., Voutchkov, N., 2007. *The Guidebook to Membrane Desalination Technology: Reverse Osmosis, Nanofiltration and Hybrid Systems Process Design, Applications and Economics*. Balaban Publishers, Rehovot, Israel.

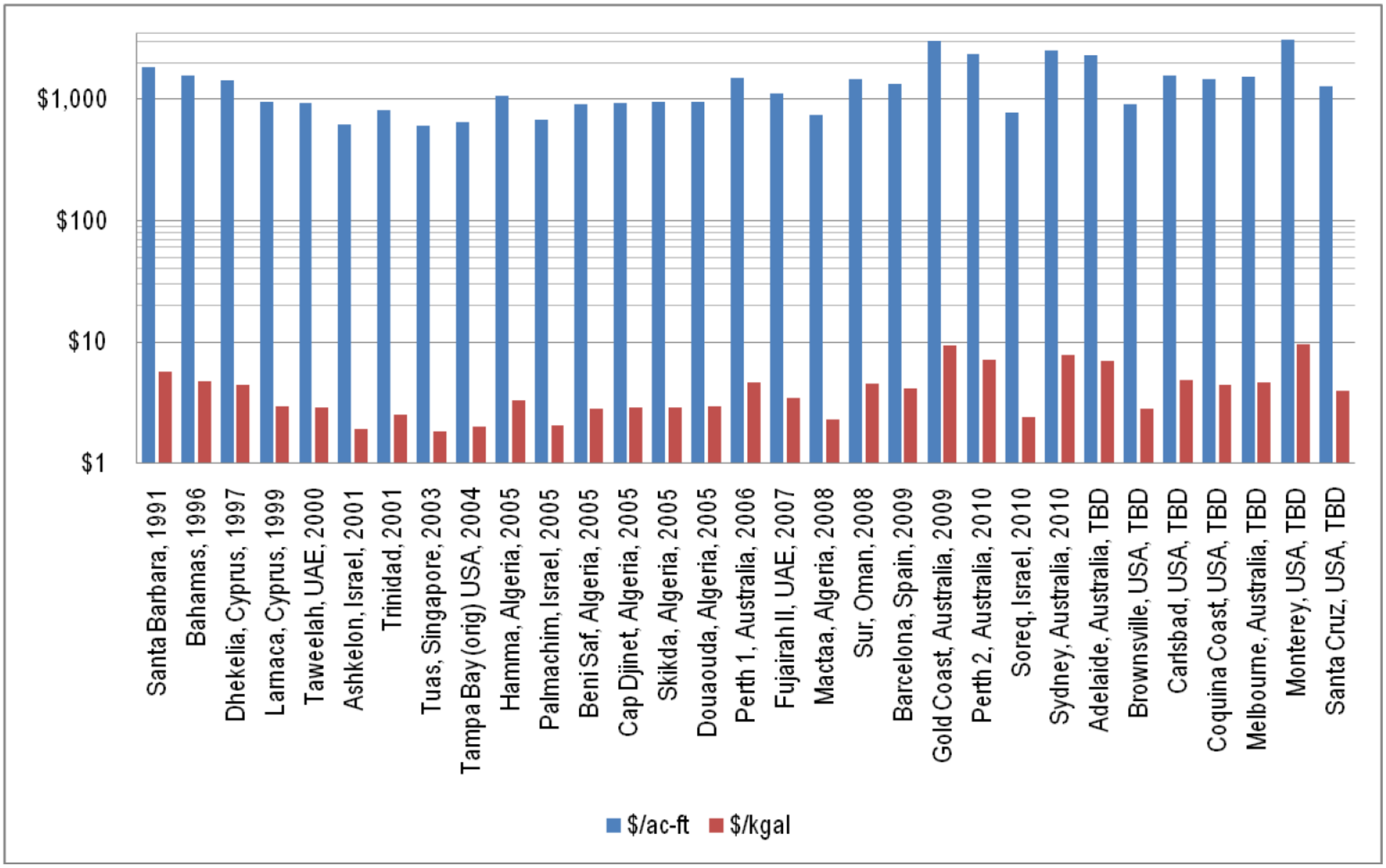


**Figure 3**
**SWRO Cost Trends, Annualized**[64]

## III Project Capital Cost Drivers

What drives the overall cost of a desalination facility? The individual, categorical factors causing and contributing to the overall cost of a project are largely the same regardless of the project. However, the magnitude of these factors can vary significantly amongst differing projects and, therefore, result in cost differences. Figure 4 shows the cost categories associated with a SWRO desalination project.

[64] Courtesy of Water Desalination Report; Presented at the Texas Innovative Water Workshop, San Antonio, Texas, October 11, 2010.

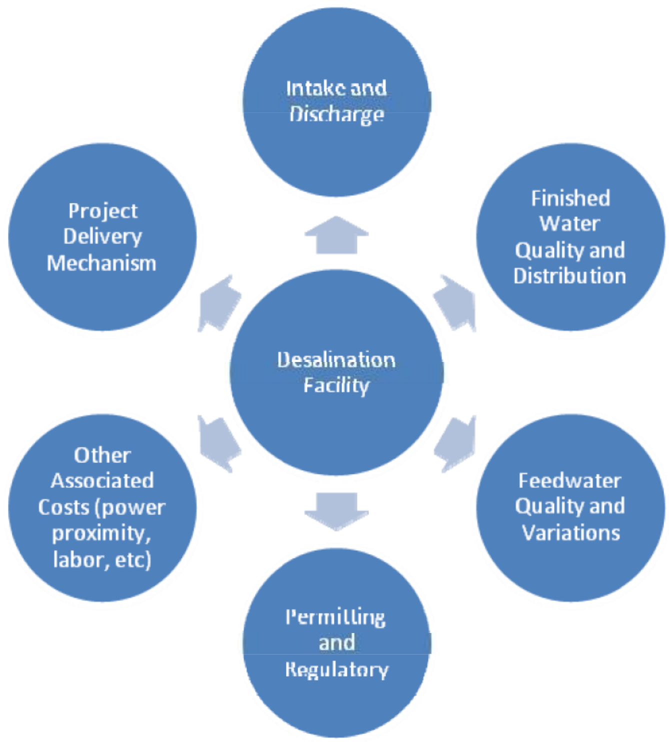


**Figure 4**
**Cost Categories Contributing to SWRO Projects**[65]

The level of accuracy desired with cost estimates is dependent on the end purpose of using the estimate and the degree of effort invested. The AACE categorizes the level of effort in five estimate classes[66].

Using an AAC-defined assumption that the conceptual screening process has been completed (Class 5; 20% to -50% low to +30% to +100 high), the potential impact that each cost category in Figure 4 should be assessed in order to gain a reasonable understanding of the associated, overall capital and operating costs.

A. Selection of Intake and Concentrate Discharge

Feed water intake configuration directly affects capital and operational costs of the treatment process. For example, open intake costs will represent approximately US$ 0.5 – 1.5MM per MGD and up to US$ 3.0MM per MGD for complex tunnel and offshore intake systems. Without consideration for the cost of land associated with each option, beach well intakes are usually less costly on an equipment basis. However, once land acquisition and easements are factored into the process, this intake type is typically 40 to 50% more costly than an open intake of similar capacity. Horizontal and slant wells are comparable to open intake (yet more costly than co-located open intakes using existing

[65] Dietrich Consulting Group, LLC.

[66] AACE International Recommended Practice No. 18R-97. Cost estimate classification system-as applied in engineering, procurement, and construction for the process industries.

infrastructure), and infiltration galleries typically cost more than open intakes. Of all the intake options, only open intakes have the longest-running installation history and reliability necessary to support the full-scale development of a large desalination facility at a new site. As a result, there is a significant depth of understanding related to the costs associated with constructing open intakes as well as the associated discharge pipeline.

The intake and feed water source selection cost impact is demonstrated in Figure 3. In Australia, for example, costs for newly constructed intake/outfall structures can approach a third of the total project cost (based on distance to the facility and related infrastructure costs) and are much more expensive than the proposed 50 MGD Carlsbad, California seawater desalination project, largely due to this project's access to the adjacent power plant intake and discharge infrastructure. Alternatively, for the proposed 50 – 150 MGD Camp Pendleton project, which is currently in the development phase with the San Diego County Water Authority (SDCWA), cost estimates approach US$ 1.3B to US$ 1.9B (2009 constant dollars) for Phase 1 that incorporates dedicated intake and outfall structures approximately 2-miles offshore, and 13 miles of conveyance pipeline. This is more than two times the construction cost of the Carlsbad facility[67].

Few SWRO facilities exist employing an intake type differing from the conventional open-intake. This lack of available installations for use as a qualitative benchmark for costing same-site alternatives is important for planners and engineers focused on process considerations and/or cost comparisons. However, published information is limited and can be site-specific. Generalized guidance is contained in Table 1. Source types range from beach wells to open-ocean intakes.

[67] Lopez, Cesar (SDCWA): "Camp Pendleton SWRO Feasibility Study", AMTA Annual Conference and Exposition, San Diego, CA, July 12, 2010.

**Table 1**
**Comparative Water Quality, Cost, and Reliability from Various Intake Types**

| Intake Type | Relative Cost (for equal capacity) | Relative Intake Space Requirements | Relative Pretreatment Space Requirements | Reliability |
|---|---|---|---|---|
| Beach Wells | Low | High | Theoretically Less | Variable based on subsurface lithology |
| Horizontal Directional-Drilled Wells | Medium | High | Theoretically Less | Unknown |
| Radial Wells | Medium | High | Theoretically Less | Unknown |
| Constructed Seabed / infiltration Gallery | High | Medium | Theoretically Less | Unknown |
| Submerged Open Intake | Medium-Low | Low | More | High |
| Surface – Open Intake | Low | Low | More | High |
| Co-located Intake | Low | Low | More | High |

By definition, the reverse osmosis desalination process creates two flow streams at a ratio of approximately 50:50. The "concentrate" stream is about twice as salty as the feed water.

Various methods are available to dispose of the concentrate stream, and the availability of alternatives will vary due to many site-specific variables. With that consideration, conveyance alternatives and a range of costs associated with each alternative are contained in Table 2. The costs do not include conveyance attributable to connecting the desalination plant to the disposal location (in the case of discharge to the ocean, this would be from the desalination plant to the shore line) because the conveyance distance, terrain, and associated costs are site-specific and highly variable, and this conveyance cost can dominate disposal costs.

**Table 2**
**Concentrate Disposal Costs**[68]

| Disposal Method | Construction Cost | |
|---|---|---|
| | (US$ MM / MGD) | (US$ MM /acre-foot/day) |
| New Outfall w/Diffusers | 2.0 – 5.5 | 0.7 - 1.8 |
| Power Plant Outfall | 0.2 – 0.6 | 0.07 - 0.20 |
| Sanitary Sewer | 0.1 – 0.4 | 0.03 - 0.13 |
| WWTP Outfall | 0.3 – 2.0 | 0.1 - 0.7 |
| Deep Well Injection | 2.5 – 6.0 | 0.8 - 2.0 |
| Evaporation Ponds | 3.0 – 9.5 | 1.0 - 3.1 |
| Zero-Liquid Discharge | 5.5 – 15.0 | 1.8 - 4.9 |

Regarding cost trends and the upward spikes observed in the most recent Australian SWRO projects in Figure 3, the plant discharges were located in the vicinity of marine habitats with high sensitivity to elevated salinity (compared to those encountered by the US projects). These designs resulted in the need to build complex concentrate discharge diffuser systems, with costs, in most cases, exceeding 30% of the total desalination project expenditures. By comparison, most of the desalination plants yielding the lowest water production costs have concentrate discharges either located in coastal areas with very intensive natural mixing or are combined with power plant outfall structures which use the buoyancy of the warm power plant cooling water to provide accelerated initial mixing and salinity plume dissipation at lower cost. The intake and discharge facility costs for these plants are usually less than 10% of the total desalination plant costs, which is much less significant compared to the US projects' cost estimates as a total percentage of costs.

B. Feed and Finished Water Quality

[68] Adapted from Wright and Missimer, 1997.

The type of pretreatment system and type of pretreatment technology selected are very dependent on the feed water quality. Because open ocean feed water (compared with well water, for example) will typically contain a greater level of suspended material and impurities that could possibly foul a reverse osmosis membrane, the capability of the pretreatment necessary to suitably pre-condition the feed water is crucial to ensure a long, sustainable membrane service life. For example, some coastal well water supplies and certain open ocean sources are generally expected to contain very low levels of foulants and particulates; therefore, a lesser-degree of pretreatment may be warranted. It is important to keep this point in context, because suspended material content (e.g., iron, sulfur, manganese) of coastal ocean locations is sitespecific and could eliminate the potential benefit of a lesser-degree of pretreatment and the associated capital and operational costs.

Typical costs associated with pretreatment will range from US$ 0.5MM to US$ 1.5MM per MGD. The lower range of costs is representative of a conventional single-stage media filtration system, which is a technology that has been in service treating public water supplies since the 1700's. Costs will increase as additional pretreatment process steps are added, such as two-stages of media filters, or media filtration followed by a micro- or ultrafiltration membrane system which approaches the higher end of the cost range.

Additionally, as with any seawater desalination project, the feed water temperature, source water
"cleanliness" (such as suspended biomass or turbidity), and ambient salinity fluctuations also affect project costs. For example, if a SWRO facility planned along the Northern California coast treats seawater that is on average 10 degrees colder than a SWRO facility located in Southern California, the necessary feed pressure would increase 10 to 15% over the warmer water to achieve the equivalent production value, thereby increasing energy consumption and associated operating costs.

Base-line costs for the desalination component of a facility usually range from US$ 1.5MM to US$ 4.0MM/MGD. The lower range of costs represents a single stage, single pass SWRO system which is capable of reliably meeting a TDS of less than 450 mg/L. Individual analyte concentration limitations such as boron or chloride (for horticultural water quality purposes) can also affect costs, because at very low concentration limits an additional membrane treatment step might be necessary. If this is the case, additional costs associated with producing a lower TDS product water will increase from 15 to 30% of the cost of the single stage, single pass system. Table 3 contains relative finished water treatment costs within the fence line of a desalination facility compared to base-line desalination system costs.

**Table 3**
**Target Finished Water Quality and Relative Cost; $MM/MGD**

| Target Finished Water Quality | Construction Costs, $MM/MGD | Operation and Maintenance Costs, $MM/MGD | Cost of Water, $MM/MGD[69] |
|---|---|---|---|
| TDS:Cl = 500[70]:250 mg/L Boron = 1 mg/L | 1.0 | 1.0 | 1.0 |
| TDS:Cl = 250:100 mg/L Boron = 0.75 mg/L | 1.15 – 1.25 | 1.05 – 1.10 | 1.10 – 1.18 |
| TDS:Cl = 100:50 mg/L Boron = 0.5 mg/L | 1.27-1.38 | 1.18-1.25 | 1.23-1.32 |
| TDS:Cl = 30:10 mg/L Boron = 0.3 mg/L | 1.40-1.55 | 1.32-1.45 | 1.36-1.50 |

C. Distribution

Throughput (or "production") capacity of a desalination facility (as with any other type of production facility) affects the size and number of the equipment needed, as well as the space necessary to locate a treatment plant. Coastal communities utilizing desalination as a source of drinking water are usually in close proximity to the treatment facility; therefore, land is usually priced at a premium. The cost of locating a facility closer to the point of use and a suitable power source should be weighed against the costs associated with additional intake and discharge pipeline easements, transmission line costs, materials used for construction, permits, labor, and maintenance associated with moving a plant farther away from an intake/discharge or distribution service area. By material cost alone, a 20-mile distribution system delivering 50 MGD could increase by 15 to 30% of total project capital costs (or more) when compared to a 2-mile pipeline based on available easements, rights of-way, and existing subsurface utilities.

The project sites in Australia are between 10 and 50 miles from the points of delivery, and, in the case of the 66 MGD Sydney SWRO facility, the cost of the product water delivery system was greater than the cost of the SWRO treatment plant (Plant cost

[69] Dietrich Consulting Group, LLC.

[70] 500 mg/L drinking water quality limitation is a United States EPA Secondary Water Quality Standard. 14 Water Desalination Report, Volume 46, Issue 29, August 2, 2010.

$7.80/kgal[14]; US$ 586MM[71] vs. US$ 490MM). The cost breakdown is also similar for the Melbourne, Australia plant.

D. Permitting and Regulatory Issues

The regulatory landscape differs vastly in the communities served by desalination facilities. These differences can have a profound impact on project delivery timelines, legal costs, and in some cases alter the design of the SWRO facility. Without question, each country has its own set of environmental criteria which must be met by any single project. And in consideration of laws in the United States, each State and region has its own set of rules, regulations, and standards, all of which conform to federal laws and guidelines while potentially being more restrictive, and usually related to site-specific nuances. For example, permitting costs for the Tampa, Florida 25 MGD SWRO project are estimated to have been
US$ 2.5MM – US$ 5MM while permitting costs for 10 – 50 MGD projects in California can exceed US$ 10MM –20MM. Permitting costs can also be bracketed by project complexity. For low-complexity projects, the permitting cost is 0.5 to 3.5% of the total capital cost of SWRO projects. For high-complexity projects, permitting is estimated at 4.5 to 5.0% of the total project capital costs. Finally, actual permitting costs will also depend on degree of membrane piloting or demonstration work (if necessary), extent of local/state permit hearings, and Federal CWA Section 401/404 offshore permitting, as applicable[16].

Whereas Australia has invested upwards of US$ 13 billion in numerous large-scale desalination projects producing 500 MGD over the last six years, the US has only been successful at bringing online one 25 MGD SWRO desalination facility in Tampa, FL at US$ 150MM. Additionally, major California projects such as Carlsbad and Huntington Beach have taken over 11 years to develop and permit, mainly due to permitting challenges and land use considerations.

E. Project Delivery Mechanism

A number of project delivery methods and financing tools have proven to be successful in the SWRO desalination industry. The size of the project, expected contract duration, location, competition, risk allocation, and project (owner) preferences all dictate by what means the project is delivered. For example, the combination of large capacity SWRO facilities, enhanced competition, and owner preferences for lowrisk have enabled the design- build- own- operate (DBOOT) project delivery community to commission SWRO projects at an exceptionally low all-inclusive cost of US$ 800 – US$ 1,000/ac-ft. in North Africa. Without exception, the lowest cost desalination projects to date have been delivered under turnkey DBOOT contracts where private sector developers or consortia share risks with the public sector based to their ability to control and mitigate the

[71] Water Desalination Report, Volume 46, Issue 16, April 26, 2010.

respective project related risks. A contributing cause to the lower costs are that the insurance and contingencies in DBOOT contracts are between 10 and 20% of the total capital cost of the project; whereas similar costs for the more traditional project design/bid/build projects can be higher.

One other delivery method, recently applied to large SWRO projects in Australia, is the Owner-EngineerContractor “Alliance” approach. The alliance model is an alternative means to further minimize and isolate the owner risks involved in procuring large-scale desalination plants. The alliance model incorporates a two-stage bidding process involving selection of qualified private sector companies and then engages the top-two companies in a competitive project development phase (which is paid for by the owner). Although the risk and reward mechanisms between the owner and engineer/contractor are negotiable, the insurance and contingency premiums are historically more than 30% of the total project costs.

16 Wilf, M., Awerbuch, L., Bartels, C., Mickley, M., Pearce, G., Voutchkov, N., 2007. *The Guidebook to Membrane Desalination Technology: Reverse Osmosis, Nanofiltration and Hybrid Systems Process Design, Applications and Economics*. Balaban Publishers, Rehovot, Israel.



F. Other Associated Costs

Other associated project costs include proximity to a power supply, the availability of skilled labor, and environmental mitigation. These cost impacts may be the result of market conditions or issues unknown during the conceptual design process. For example, the overlapping schedules of the series of large Australian SWRO projects created a temporary shortage of skilled labor, which in turn resulted in an increase in unit labor costs. Because skilled labor expenditures can consume up to 50% of the construction costs, a facilities’ construction cost can increase by 20% or more.

In several instances involving Spanish desalination projects, substantial project delays were caused by the inability of the local power company to install power substations and transmission lines; or, the receiving water authority did not adequately plan system integration and distribution pipelines for the product water, thereby substantially increasing the total project costs. This has also been a challenge in some regions of South Africa.

## IV Capital Cost Breakdown

Costs associated with a desalination plant can be annualized to provide a frame of reference to the total cost of water produced, and in some cases, delivered to the actual point of use for each particular project. These annualized costs can be quite complex and are based on a number of variables including the amount financed, interest rate, loan period, inflation, depreciation, plant utilization, and more. For a frame of reference, the typical annualized costs for seawater desalination projects vary widely from US $2.00/1,000 gallons (kgal) to $12.00/kgal. The higher end of the cost range is associated with smaller capacity plants (less than 1 MGD), because economies of scale cannot be realized, or can be attributed to site-specific intake, discharge, and conveyance. If the intake, discharge, and conveyance components are removed from the annualized cost, the range narrows from US $2.00/kgal to approximately $6.00/kgal. By comparison, the range for brackish water membrane desalinating processes (BWRO) is US $0.40/kgal to $4.00/kgal.

Because of the potentially wide-ranging cost differences between projects, unit cost contributions associated with the overall plant cost can be clarified by breaking down plant costs by contribution type. For example, as seen in Figure 5, the intake and discharge costs associated with construction are approximately 10 to 12% of the total plant costs. Please note that Figure 5 is an example of typical project plant costs, and site specific cost contributions associated with key components such as the unit cost of power, distance for distribution, and labor, for example, will alter the ratio accordingly.

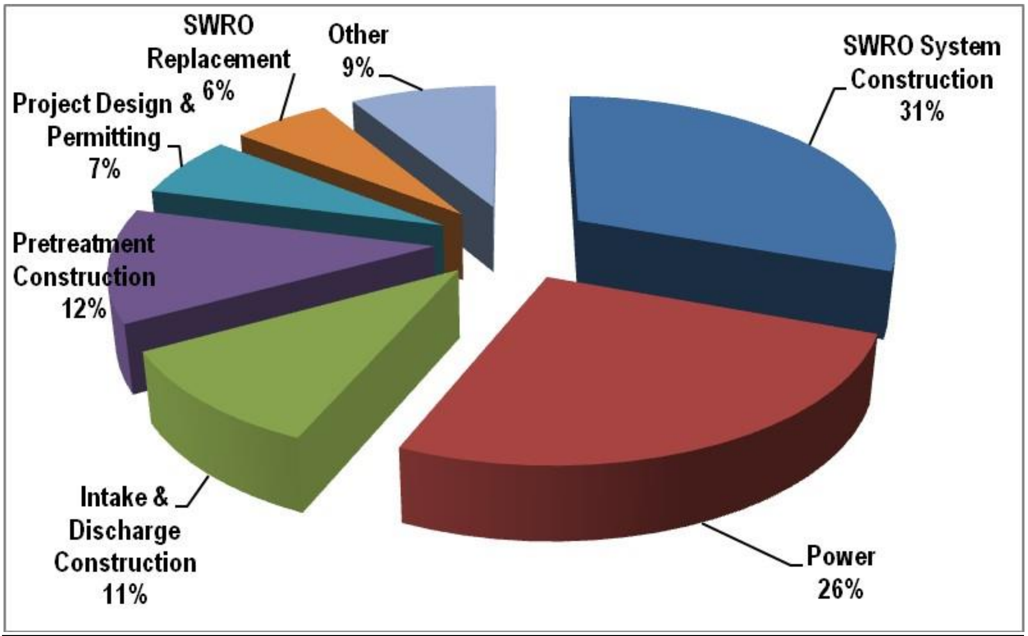


**Figure 5**[72]

**Typical SWRO Plant Construction Cost Breakdown**

## V Operation and Maintenance Cost Breakdown

All drinking water production facilities require operational attention and regular maintenance to ensure a long, productive and efficient plant. A typical design lifespan for a water production facility is 20 to 30-years, based on the size of the facility; financial terms and arrangements; and procurement method (such as BOOT, DBO, D-B, etc.). However, regardless of procurement type, the typical plant operation and maintenance costs (O&M) are associated with the parameters described in Table 4.

**Table 4**
**Operation and Maintenance Parameters for Desalination Plants (*Typical Example*)**[73]

| Cost Association | Parameter | Percentage of Total O&M Costs |
|---|---|---|
| Maintenance | Instruments<br>Pump upkeep<br>Facility upkeep including intake pipeline pigging | 6% |

[72] Dietrich Consulting Group, LLC.
[73] Dietrich Consulting Group, LLC.

| | | |
|---|---|---|
| | Minor equipment replacement<br>Video/CCTV intake/wells and associated cleaning | |
| Legal/Permitting | Environmental monitoring<br>Permit compliance | 2% |
| Operations | Labor | 6% |
| | Sludge and solids waste disposal<br>Bar rack and band screen solids waste disposal | 4% |
| | Cartridge Filters and RO Membrane Replacements | 11% |
| | Power (Energy) | 55% |
| | Chemicals | 6% |
| | Other Related | 10% |

Some examples of the sub-components contributing to the total percentage of O&M costs contained in Table 4 are affected by locale. Trends such as increasing power; solid waste disposal, or increases in chemical costs would shift the allocation. Regarding power, typical costs for labor and power associated with water treatment production are 45% (labor) and 25% (power) higher in California, compared to Florida or Texas.

## VI Cost Comparison with Other Water Supply Alternatives – a California Perspective

The cost of desalinated water has decreased significantly over the last two decades; and, all indicators are that the costs associated with the technology will continue to decrease as technology and efficiencies improve. However, similarly sized facilities do not always offer comparative costs for a number of reasons, including feed water and finished water quality goals, intake type, and distance to service area. All of these factors can have a marked effect on the overall cost of water. The importance of understanding these differences cannot be overemphasized when describing costs related to various desalination projects and treating different source waters.

Although there is only one large-scale seawater desalination facility in the United States, those that are in the planning and budgetary cost stage appear to be highest in California compared to the majority of the United States. Due to the large number of plants under consideration in California compared to the rest of the country, the cost warrants further discussion. The cost of desalination in California is relatively higher than that of traditional low-cost water sources (groundwater and river water), as well as water reclamation and reuse for irrigation and industrial use purposes. In fact, the cost of traditional local groundwater water supplies in some parts of the state is as “low” as US $0.50/1,000 gallons ($160/AF, annualized). However, the quantity of such low-cost sources is very limited (less than 30% of the water resources statewide), and water quality has become an issue in certain areas.

In California, many water agencies have embarked on exploring seawater desalination because of the diminishing capacities of fresh surface and ground water. Most of the water utilities in Southern California currently purchase imported water from the Bay Delta and Colorado River at a rate of US $2.30 to $2.45/1,000 gallons ($750 to $800/AF), and the cost of these water supplies is very likely to increase by 15% or more through 2015 due to additional expenditures needed to comply with more stringent drinking water quality regulatory requirements promulgated by the US EPA.

Based on the 2006 California Water Charge Survey published in July 2006 by Black & Veatch (http://www.bvaeservices.com/news/articles/jul06/ca_survey_businesswire.htm), the average residential monthly charge for 1500 cubic feet of drinking water was US $36.39 (US $3.24/1,000 gallons or $1,058/AF). The survey also indicates that the cost of residential water supply has increased by 16.7% since 2003.

The great majority of projects included in the California desalination initiative were at one time considered “premature.” However, water utilities and stakeholders are once again considering whether desalination product water today at a cost of US $2.91 to $3.7/1,000 gallons ($850 to $1,200/AF)[74] is too expensive. If the cost comparison of desalination versus other traditional supplies is made on a “comparable basis” suggesting that all components affecting the cost of water are accounted for, then the costs for production of desalinated seawater would be similar to the future total costs for delivery of new incremental water supplies to many parts of the state (especially to municipalities and utilities in Southern California relying on imported water supplies). For example, the commodity charge for one large California municipal water district is US $935 to $1,060/AF without a desalination component[75]. Another example is Figure 6, which contains a projection of the comparative costs associated with importing water into San Diego in the southernmost region of California in 2020[76].

[74] In 2005 dollars; based on asset life of 30 years and unit power costs of US$0.08/kWh to US$0.11/kWh.

[75] West Basin Municipal Water District FY 2010-2011 Water Rates and Charges; includes MWD RTS and Reliability Service Charge.

[76] San Diego County Water Authority, September 2010 Planning Committee.


**Figure 6**
**2020 Imported Water Supply Costs, Southern California**[77]

The argument was made at one time that desalinating seawater and brackish water is generally more expensive than the production of reclaimed water and the implementation of water conservation measures. However, with the exception of potable reuse, water conservation and recycling do not create new sources of drinking water. Also, under conditions of prolonged drought when the available water resources cannot be replenished at the rate of their use, aggressive reuse and conservation can help but may not completely alleviate the need for new water resources and water rationing. Simply put, if your backyard well is dry, you cannot solve your household water supply challenges by reusing or conserving more of the well water which you do not have.

The primary differences stem from the significant reduction of the costs for seawater and brackish water desalination since the early 2000's and the incrementally higher costs associated with achieving goals such as dramatic increases in water reuse and conservation after such measures have already been implemented.

In the early nineties, comprehensive conservation and reuse were uncommon for the majority of the municipalities in California, as the prolonged drought during this period forced many utilities to implement low-cost water reuse and conservation measures that now comprise 5 to 15% of their water portfolios. Utilities already having comprehensive water reuse and conservation programs simply cannot squeeze an additional 10 to 15% of water savings via the same low-cost reuse and conservation measures. Implementing the next tier of more sophisticated equipment and technology-intensive reuse and conservation measures to reach water-saving goals of 20 to 25% comes at a price which, in some cases, may approach that of desalination.

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[77] REGIONAL STRATEGIES: PEAK DEMAND GAP & CRITICAL PEAK PRICING, Shahid Chaudhry, California Energy Commission, August 2005. Energy Workshops for W&WW Agencies.

Without normalizing data from foreign desalination plants for the site specific conditions in California (labor, construction, equipment costs, etc.), electrical energy accounts for between 30 and 40% of the total water production costs of a typical membrane seawater desalination plant. Due to site-specific differences, the power costs for seawater desalination in California contribute closer to 20 to 30% of the total costs of water production. Therefore, fluctuations in international fuel markets will not have a dramatic effect on the viability of desalination as has been assumed previously. It should also be noted that unit energy cost increases affect all water supply alternatives, largely due to the energy intensive nature of transporting water from Northern California to Southern California.

## VII Challenges and Perceptions

During a period of prolonged drought in California in the early nineties, emergency fast-track implementation of a number of water desalination projects began, setting the stage for many potentially biased perceptions at the time concerning the relatively high cost of seawater desalination. Today, some of those perceptions about costs associated with seawater desalination remain, thus posing challenges to professionals, planners, and stakeholders alike.

The perception that seawater desalination can be a drought-proof alternative to other water supplies has enabled other utilities and water suppliers around the world to effectively incorporate seawater desalination as one alternative to dwindling (or unavailable) water supplies. In the US, for example, Tampa Bay, Florida has implemented seawater desalination as a drought-proof measure. In particular, and under consent order by the State of Florida and the Southwest Florida Water Management District, this measure was determined to be a necessity in order to alleviate wellfield over-pumping and devastation of wetlands[78]. By some arguable accounts, thousands of acres of wetlands that had virtually "dried up" over many years began to fill with water.

There is also the perception that the site-specific costs associated with intake or concentrate disposal may develop (or trend) upward, and may not outweigh the potential benefit of a drought-proof resource. This trend will be influenced by the regulatory environment (specifically regarding the intake facility) and is not associated with the cost of the desalination processes or concentrate disposal. For example, in Tampa, a comprehensive environmental study beginning in 2002[79] revealed that, to date, there is no indication that the SWRO desalination facility concentrate has had an adverse impact on Tampa Bay. Therefore, the costs associated with co-locating with a nearby power plant

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[78] Southwest Florida Water Management District (http://www.swfwmd.state.fl.us/) wetland recovery strategy.

[79] Study commissioned by Tampa Bay Water and administered by PBS&J.

and the associated mixing and dilution can be reliable when applied to other similar co-located projects.

## VIII Concluding Remarks

One of the most sensitive and critical aspects of any water project is cost. Membrane desalination has experienced an overall downward trend in overall costs, and technological advances will continue to bring costs down even further. Additionally, when investigating the costs associated with desalination compared to other supplies, comparable cost estimating practices will tend to level the playing field when all of the costs associated with delivering water are considered.

However, as with any infrastructure project, it is important to recognize that the various components supporting the overall desalination treatment facility can vary significantly and are based on site location. For membrane desalination, decreasing technological costs, the drought-proof nature of the process, and producing superior water quality are among a number of significant reasons why this application is the water treatment technology of choice in the United States and around the world.