# Economics of desalination concentrate disposal methods in inland regions: deep-well injection, evaporation ponds, and salinity gradient solar ponds

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# Abstract

Desalination of brackish water is a promising technology available to provide "new" water to the arid Southwest. However, as inland groundwater desalination technology develops, a need for more efficient disposal methods arises. Some options for inland brine disposal include deep-well injection and storage in evaporation ponds. Another concentrate disposal method centers on the use of salinity gradient solar ponds (SGSPs). Solar pond technology provides an avenue for utilizing reject concentrate to power the desalination unit. The goal of this research is to explore the economic impact of various disposal schemes, with particular emphasis placed on the use of SGSPs. These costs are calculated by updating an economic model developed in 1992. To improve the accuracy of the model output, a survey of desalination facilities in the Southwest and of recent data presented in published literature for brine disposal methods was conducted. The results of the survey and calculations show that costs associated with each disposal option have gone down over time and that evaporation ponds usually present the lowest cost alternative.

# 1. Introduction

Water scarcity is one of the most significant economic factors in the southwestern United States. Availability of water of sufficient quality, quantity, and reliability can determine the rate of growth in this region. For instance, access to water may be an important factor on whether a business opens in or moves to the Southwest. Desalination of brackish water is a promising technology available to provide additional water to the arid Southwest.

Since research began in the 1950s, desalination technology (also known as desalting and desalinization) has advanced to a level where it may be an economically viable option. Currently, hundreds of commercial and municipal desalination plants operate all over the globe (*1*). Of these, a majority are located near an ocean that provides an abundant source of saline water and a relatively safe waste disposal reservoir. Because desalination technology developed in coastal regions, it is often taken for granted that the ocean will be both the source of feedwater and the sink for wastewater.

However, as inland groundwater desalination technology develops - and a need for alternative water sources in these regions increases - a need for more efficient disposal methods arises. Mickley et al. (*2*) state many factors that affect the method of disposal for desalination wastewater (also known as concentrate, brine blow down, reject brine, and residual solids). These include the volume of waste, the location of the desalination plant, the availability of the receiving site, governmental regulations, the ability to expand, as well as capital and operating costs. The Southwest has favorable conditions for many types of concentrate disposal as well as abundant land available for convenient plant location and expansion. However, currently, costs associated with inland brine disposal are typically prohibitive. These costs have constrained the economic viability of desalination in the arid Southwest.

## 1.1 Disposal options for inland desalination facilities

Although discharge into an open ocean is a common way to dispose of desalination wastewater, it is typically not cost-effective to transport the concentrate from inland regions to an ocean for disposal. Brine is corrosive, so pipelines or tanker trucks must be fitted with special protective liners. Because of these requirements and the cost of transportation, ocean disposal becomes more expensive with increasing distance between the source of the waste and its final destination at the ocean.

In addition to its corrosive properties, concentrated brine may contain significant amounts of environmentally harmful or toxic substances. For this reason, they cannot be released into inland surface waters or onto the soil surface except under special circumstances. Many desalination plants in the US add reject concentrate to their local municipal sewage systems. This practice lowers the biological oxygen demand (BOD) of the treated wastewater, which may be beneficial under some circumstances. However, adding brine to the wastewater also increases the total dissolved solids (TDS) of the treated water. High TDS can make this water unsuitable for use in irrigation. Large-scale desalination facilities may not have the option of disposal into municipal sewers because the large volumes of waste brine could overwhelm the system.

Some alternative options exist for inland brine disposal. These include deep-well injection, storage in evaporation ponds, landfilling, and irrigation/cultivation of halophilic species. A relatively new focus of concentrate disposal research centers on "zero-discharge" systems.

### *1.1.1 Zero-discharge systems*

One concept of zero-discharge desalination emphasizes increased water recovery, so that the total volume of concentrate is minimized. Another kind of zero-discharge system operates as a circuit of reuse, in which a desalination unit is powered by thermal or electrical energy, which is generated using a salinity-gradient solar pond (SGSP). Maintaining the salinity gradient by adding concentrate from the desalination unit completes the circuit (see section 2.2 for a more detailed discussion of SGSPs and sections 2.3 and 2.4 for a description of SGSP-coupled desalination systems). Although these solar pond systems operate on the assumption that concentrate is a resource instead of a waste product, they may still be considered waste disposal options.

### *1.1.2 Deep well injection*

Deep well injection of reject brine is widely used in desalination and in the oil industry. The method has also been employed for moving saline groundwater that must be relocated to protect fresh water aquifers. Deep well injection can provide a safe means of permanent brine disposal because the brine is sequestered far from underground aquifers. However, some desalination facilities, as well as oil and gas companies, have rejected the deep well disposal method because these wells are "difficult to permit, costly, and impossible to use or limited in capacity to accept fluids" (*3*). Since reject brine is corrosive, many safeguards must be added to the well (*4*). The costs associated with implementing these safety measures can make the deep well disposal option prohibitively expensive.

### *1.1.3 Evaporation ponds*

An evaporation pond is merely an excavated depression in the ground which serves as a reservoir for desalination wastewater. Often, evaporation ponds are the final destination of concentrate. In these situations, once the water evaporates, the residual solids may be landfilled in situ or collected and disposed of elsewhere.

Some money-making opportunities exist in conjunction with evaporation ponds. Saline groundwater contains more elements and compounds in greater variety than seawater (*5*). Some of the elements and compounds found in both feedwater and reject brine from groundwater include sodium chloride, halite, sodium carbonate, soda ash, trona, sodium sulfate, magnesium, bromine, iodine, lithium, boron, potassium, and potash (*6*). Each of the compounds listed above have economic value, which may contribute to the overall benefit of using evaporation ponds if the compounds can be efficiently purified. Another promising use for evaporation ponds is aquaculture. Researchers at the Bedford Groundwater Interception project in Australia (*7*) have successfully raised bream, barramundi, snapper, brine shrimp, and *Dunaliella* (cyanobacteria that produce economically significant amounts of beta-carotene). However, researchers R. Tanner and colleagues at the University of Arizona (*8*) raise concerns about the safety of evaporation ponds due to the potential bioaccumulation of toxic substances in brine shrimp, which may be ingested by migratory birds. They cite several incidences when birds have died in or near evaporation ponds.

## 1.2 Research Question

The concentrate disposal problem is an important factor that keeps desalination from becoming economically viable in the southwestern US. Government restrictions and permitting processes, as well as capital and operating costs, can significantly affect the method of disposal chosen for specific sites. Concentrate is industrial waste, as opposed to household waste, and requires special permits for disposal. Moreover, because some groundwater may contain toxic compounds such as arsenic, the concentrate from these sources may even be classified as hazardous waste (*5*). A hazardous waste classification further increases the state and federal disposal regulations and, proportionately, the cost of disposal. For these reasons restrictions on brine disposal options in inland regions reduce the economic feasibility of desalination.

Solar pond technology provides an avenue for utilizing reject concentrate and bypassing some of the costly disposal restrictions. Moreover, as mentioned above, the primary benefit of solar pond-powered desalination is that it utilizes reject concentrate to power the desalination unit. Therefore, by reducing the desalination plant's dependence on an outside power source, which may result in additional annual savings, solar ponds may provide a viable means to pursue desalination technology in the arid Southwest. The goal of this research will be to explore the economic impact of various disposal schemes, with particular emphasis placed on the use of SGSPs. This thesis proposes to calculate the cost to produce water in a mathematically modeled desalination facility utilizing (1) an evaporation pond, (2) deep-well injection, and (3) salinity gradient solar ponds.

To measure the economic impact of these disposal options, I will update data presented by University of Texas at El Paso (UTEP) Masters Thesis candidate P. M.

Esquivel in her 1992 thesis, "Economic feasibility of utilizing solar pond technology to produce industrial process heat, base load electricity, and desalted brackish water" (*9*). After inputting present-day values into Esquivel's model, not only will we see how the economics of desalination wastewater disposal have changed in the past decade, we will also be able to make assumptions regarding the future economic viability of these disposal methods. To improve the accuracy of the model output, I will conduct a survey of desalination facilities in the Southwest and of recent data presented in published literature for brine disposal methods. The completed model, ideally, will show which disposal method is preferable to make inland desalination facilities economically viable.

The following chapter (Section 2) describes the history and current status of desalination technology and waste disposal strategies. Section 3 presents a detailed description and analysis of Esquivel's economic model. Sections 4 and 5 provide an explanation of the methods used to update the existing economic data, a discussion of the results of this update, and areas of further interest.

## 2. Background

### 2.1 Desalination methods

Desalting water is a practice that has been employed, in large part by ocean navigators, since before the rise of ancient Greece (*10*). The earliest desalination was performed by distillation: evaporating and condensing fresh water and leaving behind solid salts. Since then, a number of desalination methods have been developed that are based on the principles of distillation. These include multi-effect evaporators, multi-stage flash evaporators, mechanical vapor compression, and thermal vapor compression.

In a multi-effect (ME) evaporator, latent heat released by condensing water is used to evaporate water at a lower pressure in another vessel (called an “effect”). Multi-stage flash (MSF) evaporation occurs by superheating water under pressure, then releasing this pressure. The pressure release causes water to evaporate spontaneously until it cools to the boiling point (*10*, *11*). The heated water is passed through a succession of chambers (called “stages”) at lower pressures. Addition of many effects or stages reduces the energy consumption of these processes, hence the names “multi-effect” and “multi-stage flash” distillation. In thermal distillation, one ton of steam can produce approximately eight tons of potable water (*10*). Mechanical vapor compression (MVC) uses a pump to create a partial vacuum over the saline water, which causes the water to evaporate. The vapor is then condensed by reapplying pressure. Thermal vapor compression (TVC) operates on the same principle as MVC. However, in this case, a steam-jet aspirator replaces the mechanical pump.

Other methods of desalination are based on the use of membranes. There are two basic types of membrane desalination: reverse osmosis (RO) and electrodialysis (ED). In RO systems, pressure is applied to overcome the natural osmotic tendency of water to flow from areas of high concentration to low concentration. The pressure forces water molecules to flow against the osmotic gradient through a series of membranes that are permeable to water, but trap salts. ED systems exploit the ionic nature of dissolved salts. Saline water is sandwiched between cation- and anion-selective membranes. A positive charge is applied to one side and a negative charge to the other side of the apparatus. This electrical charge draws anions through the anion-selective membrane toward the positive charge and the cations through the cation-selective membrane toward the negative charge. Fresh water is left behind and is thus desalinized (*10*, *11*).

The desalination technologies discussed above are all currently exploited for commercial and municipal water production. The 1998 International Desalination Association (IDA) Worldwide Desalting Plants Inventory shows that, globally, desalination plants have a combined capacity of 22.7 million $m^3$/d (*1*). Table 1 shows the distribution of desalination methods employed as a percentage of the total amount of desalinated water produced globally each year, based on the 1998 IDA inventory. Buros (*10*) calls this relationship the installed desalination capacity.

Table 1: Installed desalination capacity

| **Desalination method** | **Abbreviation** | **Installed desalination capacity** | **Typical parameters** |
|---|---|---|---|
| Multi-stage flash | MSF | 44% | 4,000 to 60,000 $m^3$/d production, operate at top brine temperature of 90-110 ºC |
| Reverse osmosis | RO | 42% | 70 to 90% recovery |
| Electrodialysis | ED | 6% | 70 to 90% recovery |
| Multi-effect distillation | MED | 4% | 2,000 to 20,000 $m^3$/d, operate at lower temperatures than MSF, as low as 70 ºC |
| Vapor compression | VC | 4% | 500 to 20,000 $m^3$/d, operate at a temperatures as low as 50 ºC |

Adapted from Buros (*10*)

Table 1 shows that, of the 100% of desalted water produced around the globe annually, RO (42%) and MSF (44%) are the most widely used technologies. In the US, the primary desalination method currently utilized is RO, while a majority of the large seawater desalination facilities in the Middle East utilize MSF and other distillation technologies.

Mesa et al. (*12*) claim that desalinating groundwater at 2,000 to 3,000 ppm TDS by reverse osmosis requires between 1.4 and 1.7 kWh for every cubic meter of product water

(5 to 6 kWh/1000 gal), which is significantly lower than the energy required to treat seawater (5.6 kWh/$m^3$ for 30,000-40,000 ppm TDS). Distillation processes, on the other hand, utilize little electricity relative to their heat energy intake. Distillation requires 1.3 kWh/$m^3$ electricity (5 kWh/1000 gal) and 48.5 kWh/$m^3$ heat (0.66 GJ/1000 gal) independent of feedwater salinity. Thus, we see that distillation is more energy intensive than RO. Petersen (*6*) states that the energy requirements for both RO and distillation are proportional to the volume of product water.

## 2.2 Solar ponds

Salinity gradient solar ponds are a type of heat collector as well as a means of heat storage. Hot brine from a solar pond can be used as industrial process heat (e.g. as a heat source for vaporizing feedwater in MSF or MED desalination), for space/water heating, to dry grain, and in electricity generation, among other uses.

Solar ponds are able to store heat due to their unique chemically stratified nature. There are three layers in a solar pond: (1) the upper or surface layer, called the upper convection zone (UCZ), (2) the middle layer, which is the non-convection zone (NCZ) or salinity gradient zone, and (3) the lower layer, called the storage zone or lower convection zone (LCZ). Salinity increases with depth from near pure water at the surface to the bottom where salts are at or near saturation. Salinity is relatively constant in the UCZ and LCZ, and increases with depth in the NCZ. Saline water is more dense than fresh water; therefore, the water at the bottom of the pond is more dense (has a higher specific gravity) than water at the surface (See Figure 1).

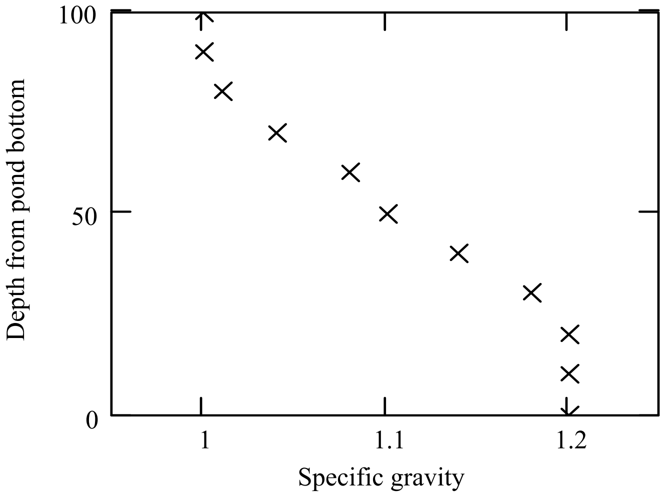

Figure 1: Typical specific gravity profile in a solar pond. Adapted from Kovac et al. (*13*)

The solar pond system is able to store heat because circulation is suppressed by the salinity-related density differences in the stratified water. Convection of hot water to the surface is repressed by the salinity (density) gradient of the NCZ. Thus, although solar energy can penetrate the entire depth of the pond, it cannot escape the storage zone.

Figure 2 shows a typical temperature profile of a solar pond. The temperature of the UCZ will be equal to or near the ambient temperature. As the Figure illustrates, temperatures in the LCZ can reach (and sometimes exceed) 90 ºC. The LCZ is heated at a rate proportional to that of incoming solar radiation and inversely proportional to its thickness (*14*).

The temperature of the storage zone depends upon several factors, including the intensity and duration of solar insolation, the thickness of the NCZ, the ambient temperature, and the stability of the salinity gradient. Figures 1 and 2 are representative, generalized pond profiles. Actual pond performance and dimensions will vary.

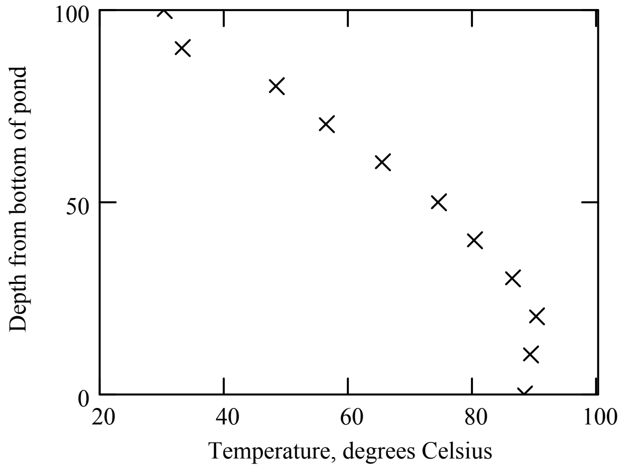

Figure 2: Typical temperature profile of a solar pond. Adapted from Kovac et al. (*13*)

Pond surface areas range from 100 to 1,000,000 $m^2$ and depths range from two to four meters. The LCZ occupies approximately the lower third of the pond. Usually, a wave suppression device will be floated on the pond surface. In some cases, the surface is completely covered in order to prevent heat loss and pond water contamination. Other design considerations include the need for a thick and sturdy liner to prevent groundwater contamination and salt for initial construction of the salinity gradient.

Solar ponds can be constructed in almost any location; however, certain characteristics can make a site more or less suitable. University of Texas at El Paso (UTEP) Master's degree candidate J.A. Sandoval (*15*) performed an extensive survey of potential SGSP locations in West Texas and Eastern New Mexico. Sandoval determined a number of criteria that affect the favorability of any proposed SGSP site. These criteria are presented in Table 2. Sandoval assigned a weighting factor to each criterion in order to emphasize, in a computer model, those factors with greatest impact.

Because the salinity gradient must be physically constructed using solid salts and relatively fresh water, access to and cost of salt and water for initial pond construction are

Table 2: Favorability criteria for solar pond siting

| | **Favorability criteria** | **Weighting factor** |
|---|---|---|
| Site factors | Access to salt/brine | 10 |
| | Access to water | 10 |
| | Solar insolation | 7 |
| | Liner requirements | 7 |
| | Berm requirements | 7 |
| | Land access | 5 |
| | Access to utilities | 5 |
| | Soil with low permeability | 5 |
| | Soil with good adhesion for walls | 4 |
| | Low wind speed | 3 |
| | Absence of wind-borne debris | 2 |
| | Area for salt management | 2 |
| | Ratio of evaporation to rainfall | 2 |
| | Flat land | 1 |
| | High numbers of life forms | -2 |
| | Close proximity to agriculture | -2 |
| | Potential Clean Water Act violation | -2 |
| | Desiccation cracks | -2 |
| | Earth fissures | -5 |
| | Heat dissipation by groundwater | -5 |
| Value and economic criteria | Energy cost per BTU | 7 |
| | Environmental factors | 7 |
| | Total energy utilization | 5 |
| Cost criteria | Distance to application | 10 |
| | Cost of salt | 10 |
| | Berm costs | 10 |
| | Liner costs | 10 |
| | Temperature load | 7 |
| | Land cost | 5 |
| | Pond size | 5 |

Adapted from Sandoval (*15*)

the most critical factors to consider when siting a SGSP and receive weighting factors of ten in Sandoval's analysis. Another expensive, yet necessary, pond constituent is the liner. In most cases, the bottom and sides of the pond must be lined to prevent groundwater contamination. Only ponds constructed on soil with low permeability (clay-textured soils) have the option of not using a bottom liner; however, almost all ponds require that berms (the side walls) be lined to prevent slope erosion. Liner costs and salt costs are the most significant factors affecting the overall cost of solar pond construction.

The intensity and duration of solar insolation affects the temperature of the active zone and thus the operating temperature of any distillation unit coupled to the pond. Other environmental factors that affect SGSP siting include wind speed, wind-borne debris, the ratio of evaporation to rainfall, and land slope. High wind speeds can cause turbulence in the UCZ. However, this is not a significant problem because the UCZ is merely insulation for the NCZ; the UCZ protects the salinity gradient from erosion due to environmental factors. If high wind speeds are predicted, the thickness of the UCZ can be increased to ensure that the NCZ remains unaffected. Solar ponds are usually protected from wind by baffle systems or, in some cases, by covering the entire surface with transparent plastic. This plastic covering can help keep the pond free of debris during periods of high wind speed. Dust and sand that blow into the pond decrease the clarity of the water and negatively affects the amount of solar radiation that reaches the LCZ. Finally, although SGSPs can be excavated from or even sited on a sloping surface, flat land allows for more uniform LCZ characteristics. Sandoval assigns a weighting factor of one (the lowest positive value) to the land slope criterion.

The factors to which Sandoval assigns negative values are those that negatively affect the favorability of a proposed pond site. The parameters that receive a value of negative two (-2) are a) the presence of high numbers of life forms, such as algae, which can decrease pond clarity; b) nearness to agricultural sites; c) potential for violations of the Clean Water Act, which may occur if the pond is sited too close to a surface water source, for example, and d) the appearance of desiccation cracks in the soil. When this occurs the soil's permeability is increased and a liner may be required even for clay-textured soils. More important than the above factors are the possible presence of earth fissures, which are cracks that may penetrate deep underground, potentially into aquifers. The final important parameter to consider when siting a solar pond is heat dissipation by groundwater. Heat may be conducted to flowing groundwater below the pond and carried away, thus, it is necessary to ensure that the pond is far from groundwater sources.

Once a pond is properly sited and constructed, a number of factors must be considered regarding the pond's thermal efficiency. Water clarity, pond dimensions (primarily area and thickness of the LCZ), and temperature difference ($\Delta T$) between the LCZ and the UCZ all affect the pond's thermal efficiency (*13*). If the water is relatively clear, more sunlight (and thus more heat) will reach the bottom of the pond. Smaller systems are less efficient than larger systems because a greater proportion of heat is lost due to edge effects in small ponds (*16*). Temperature fluctuation in a solar pond is inversely proportional to the thickness of the LCZ. Finally, thermal efficiency is inversely proportional to $\Delta T$ due to an increased rate of heat loss from the pond at high temperatures (*14*).

Although MSF and MED can produce concentrate at a near slurry consistency, 20 to 70% of feedwater that enters an RO unit can be released with the waste stream. In some cases (i.e. when using RO) wastewater from the desalination unit must be further concentrated before it is injected into the solar pond. This additional concentration is necessary because brine in the LCZ should be at or near salt saturation for maximum heat storage capacity. Researchers at the California Department of Water Resources' Demonstration Desalination Facility in Los Baños (*13*) show that a modified vertical tube evaporator (VTE) provides adequate waste concentration while desalting additional water for use as surface water in the solar pond. At the El Paso Solar Pond Project (*14*) MSF has proved effective for brine concentration by using RO concentrate as feedwater for the MSF unit. Desalination concentrate may also be dried or further concentrated using an evaporation pond.

### 2.3 Desalination and solar ponds

A considerable number of solar pond-powered desalination facilities have been proposed and/or tested (*13-20*). The consensus among solar pond researchers is this application of solar pond technology is effective for thermal distillation applications (see section 2.1 for a description of various desalination methods). This preference exists because ME, MSF, and TVC can all operate efficiently at temperatures provided by the solar pond (50 to 90 ºC).

Figure 3 shows how a typical MSF unit operates using solar pond brine as a heat source. The hot concentrate (shown in yellow) is pumped from the active zone of the pond and into the brine heater. Feedwater (shown in gray) enters at the end of a series of *n* stages (effects). The feedwater serves as coolant fluid for the water vapor held in each effect. Water vapor in the effect condenses outside the feedwater carrying pipe. By the time the feedwater reaches the brine heater, it is pre-warmed due to its contact with the condensing vapor. In the brine heater, the feedwater is warmed to the top brine temperature (the same temperature of the solar pond brine in the brine heater). Next, the feedwater flows into the first effect where the pressure is lowered to cause the evaporation of a fraction of the feedwater. This vapor rises up the effect, where it encounters the colder feedwater carrying pipe and condenses. The condensate is the final product (shown in blue), which is pumped into storage or distributed.

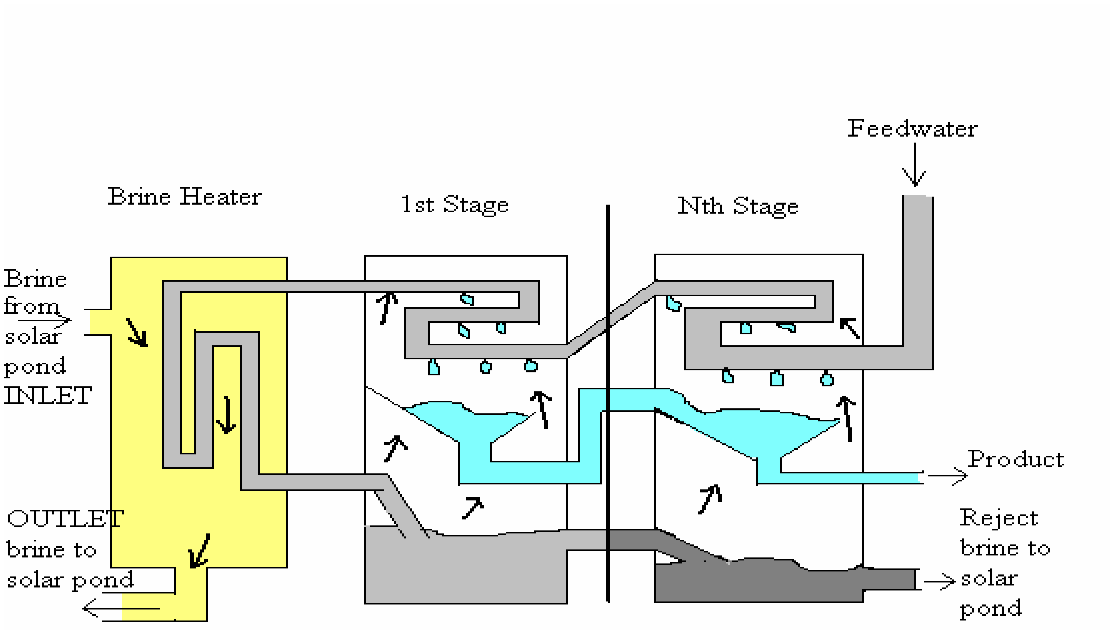

Figure 3: MSF unit using solar pond for process heat. Adapted from Buros (*10*)

As the feedwater passes into the second effect, the pressure is again lowered to cause evaporation, and so on throughout the *n* effects. Excess vapor that does not condense in the final effect is run through a condenser in order to remove the maximum amount of product. Reject brine is pumped out of the final stage and into the solar pond, or into a secondary evaporation pond, as described in Section 2.2. Computer models developed and verified by Lu et al. at the El Paso Solar Pond Project (*14*) show that, for a solar pond powered MSF unit, flash range (the difference in temperature between the first stage and the last stage), reject brine concentration level, and rate of circulation in the first effect are the only variables that significantly affect production rate.

Figure 4 illustrates how solar ponds can be incorporated into hybrid desalination systems. Hybrid systems combine the use of two or more types of desalination units. Combining RO with MSF or MED in a hybrid system provides the additional concentration

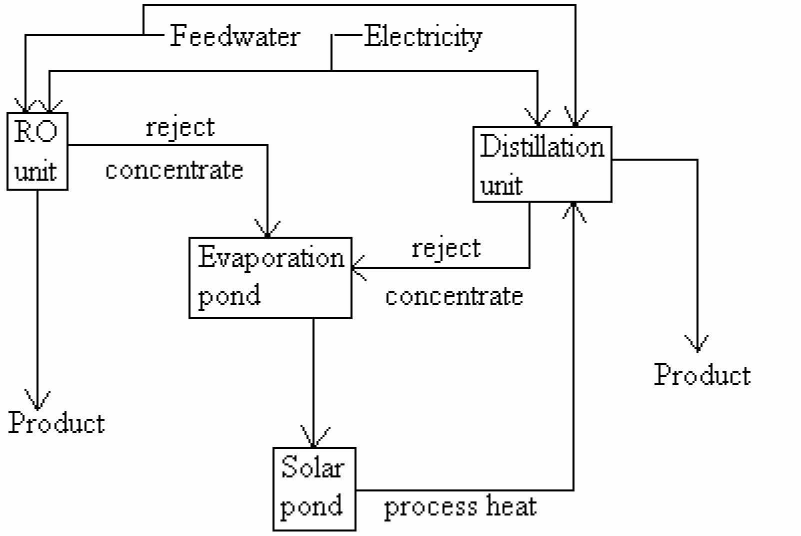

Figure 4: Example of a hybrid desalination system using solar pond process heat. From Esquivel (*9*)

needed before RO wastewater can be efficiently used for a solar pond.

## 2.4 Cogeneration

Cogeneration, in the desalination field, means the simultaneous production of both potable water and electricity. Power (defined as both heat and electricity) represents one of the major desalination operating costs. Mesa et al. (*12*) claim that the cost of energy is between 50 and 75% of operating costs, "regardless of the technology used." The authors claim that cogeneration is the only method for optimizing energy consumption of desalination. Although cogeneration facilities are more expensive than an individual power station or desalination plant, cogeneration of both power and desalted water may result in lower costs for each product than that incurred when generated separately. Petersen (*6*) claims that cogeneration costs can be 20-40% less than single-purpose desalination plants. Thus, cogeneration is an important option to consider when designing a desalination plant.

Currently, many large desalination facilities are coupled with electricity generation. This practice is especially common in arid, coastal areas of the Middle East and Northern Africa.

Lu et al. state that solar ponds are not suited for electricity generation because of the relatively low temperature of storage zone brine (*14*). However, advances in power generation technology require continuing research into this suitability. Heat engine technology, the conversion of thermal energy to mechanical energy (and sometimes to electrical energy), has become more desirable due to its ability to produce work without combustion of petroleum or coal. Specifically, a Rankine Cycle Engine (RCE) can be used in conjunction with solar ponds to produce electricity.

In an RCE, hot concentrate from a solar pond can be used to evaporate a liquid with a low boiling temperature. As the vapor expands it turns a turbine or fires a piston. If the turbine or piston is connected to a generator, electricity can be produced. Figure 5 shows a desalination system used at the El Paso solar ponds (*9*) in conjunction with an Organic Rankine Cycle Engine (ORCE) – the term "organic" refers to any organic compound with a low boiling point (such as methane or an HCFC) which acts as the working fluid by evaporating when exposed to heat from the solar pond brine. In the system diagramed in Figure 5, concentrate from both an RO unit and an MSF unit is used to maintain a salinity gradient in a solar pond, which provides thermal energy to the MSF unit and the ORCE. The ORCE produces electricity that is used to run the pumps required by both desalination units. UTEP Master's thesis candidate P. M. Esquivel reports that this system is not competitive with an identical system run using conventional energy sources. However, Esquivel's data does not take into consideration the environmental benefits of this kind of electrical production.

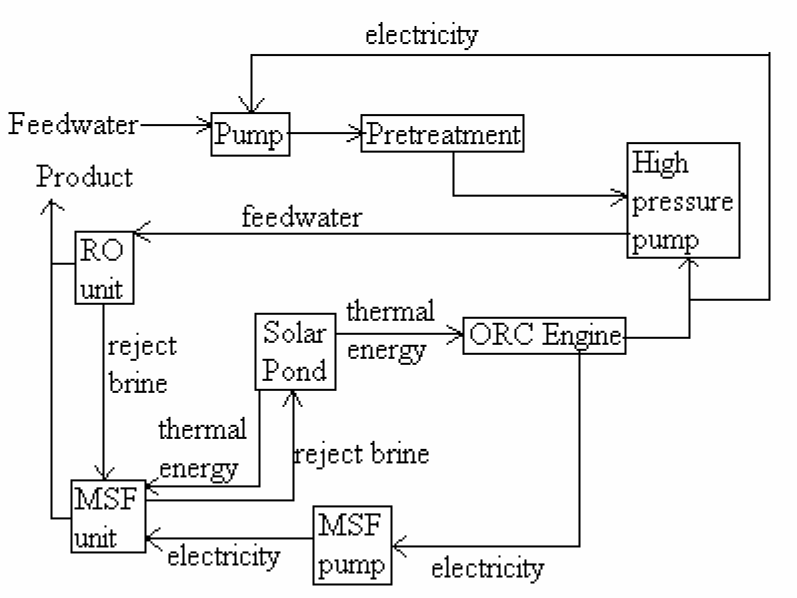

Figure 5: Cogeneration system using solar pond for process heat. Adapted from Esquivel (*9*)

It is possible that, if environmental factors are taken into account, ORCEs using process heat from solar ponds may be more competitive or that, in the future, rising costs for non-renewable energy sources will make this technology more feasible.

## 3. Existing economic data

In a report published by the International Desalination Association in 2000, Buros (*10*) states that total cost of production for brackish water desalination ranges from $0.96 to $2.31 per 1000 gallons (kgal) for capacities of one to ten million gallons per day (MGD). Seawater desalination, by comparison, costs approximately $2.88 to $11.54/kgal (dollars are US 1999). The savings for desalting brackish water are due to the reduced quantity of salts and suspended materials that must be removed compared to quantities in seawater (*5*).

The following tables (Tables 3 to 7) show economic data calculated by UTEP Master's candidate P.M. Esquivel (*9*). In her thesis, Esquivel presents the costs of a RO/MSF hybrid desalination system (see section 2.3 for a discussion on this type of facility), which is run on power generated using a solar pond and an ORCE. Additionally, Esquivel calculates costs for an RO facility using an evaporation pond and for an RO facility using deep well injection.

### 3.1 RO base system costs

To begin the economic analysis, Esquivel developed a hypothetical base system that employs RO to desalt brackish groundwater (See Table 3). Esquivel assumes that the feedwater is brackish, with salinities ranging from 1500 to 3000 ppm. Next, she assigns a recovery rate of 70% to the RO unit. This value represents the low end of possible RO recovery rates, which can vary from 70% to approximately 85%. The actual recovery rate (*RR*) is determined by:

$$RR = \frac{f_p}{f_f} \times 100\% \qquad [1]$$

where,

$f_p$ = the product water flow rate in gallons per day (GPD) and

$f_f$ = the feed water flow rate (GPD).

"Plant load factor" is a term that describes the operation efficiency of Esquivel's hypothetical RO unit. The actual plant load factor (*PLF*) is calculated by:

$$PLF = \frac{P_a}{DPC} \times 100\% \qquad [2]$$

where,

$P_a$ = actual production in million gallons per day (MGD) and

$DPC$ = the design production capacity.

Table 3: RO base system*

| | | |
|---|---|---|
| Water source: | Brackish | |
| Feedwater salinity: | 1500 to 3000 ppm | |
| Recovery rate: | 70% | |
| Plant load factor: | 90% | |
| Energy requirements: | 8 kWh/1000 gal | |
| Life, years: | 30 | |
| Interest rate: | 6% | |
| Feed stream volume | 1.3 MGD | 12.9 MGD |
| Plant capacity | 1 MGD | 10 MGD |
| Actual production | 0.9 MGD | 9 MGD |
| **Capital costs:** | | |
| RO equipment | $1,200,000 | $8,000,000 |
| Pretreatment equipment | $420,000 | $2,800,000 |
| Total capital: | $1,620,000 | $10,800,000 |
| **O&M costs:** | | |
| Purchased power | $163,289 | $1,632,887 |
| RO equipment | $398,800 | $3,112,000 |
| Pretreatment equipment | $147,000 | $980,000 |
| Total O&M: | $709,089 | $5,724,887 |
| **Water cost:** | | |
| Amortized capital | $117,690 | $784,599 |
| O&M yearly | $709,089 | $5,724,887 |
| 1000 gal produced annually | 329,000 | 3,290,000 |
| **Cost ($/1000 gal)** | **2.51** | **1.98** |

From Esquivel (*9*)
*All costs in this section (Section 3) are $US 1992.

Esquivel uses two design production capacities in the economic analysis, one (1) MGD and ten (10) MGD.

To determine the volume of feedwater required per day, Esquivel applies the following equation:

$$MGD_{feed} = \frac{DPC \times PLF}{RR} \qquad [3]$$

Thus, a ten MGD plant with an assumed PLF of 90% and a RR of 70% uses approximately 12.9 MGD of feedwater. Assigning the 70% RR to 12.9 $\text{MGD}_{feed}$ gives a product water flow of 9 MGD as shown in Table 3 above.

Esquivel estimates two capital costs for the RO base system: the RO equipment and the necessary pretreatment equipment. This cost data was acquired from reported costs in the Technical Assessment Guide of the Electrical Power Research Institute (*21*) and a study performed by the Bureau of Reclamation (*22*). For her thesis, Esquivel assumes that the pretreatment equipment costs 35% of the RO equipment.

Expenses related to operation and maintainance (O&M) of the RO base unit include the power that must be purchased to run pumps as well as the costs involved with operation and maintainance of the RO and pretreatment equipment. The annual purchased power requirement is calculated by applying the electricity charge ($/kW) to predicted fuel cost escalation rates over the life of the RO plant. Esquivel attained data on the cost of O&M for the RO equipment from the Electrical Power Research Institute (*21*) and again assumes that the cost of O&M for the pretreatment equipment is 35% of the O&M cost of the RO equipment.

To determine the cost of product water from the RO base unit, the amortized capital cost (*ACC*) is first calculated using the following equation:

$$ACC = \frac{TCC}{(A/P, i\%, N)} \qquad [4]$$

where,

*TCC* = total capital costs (cost of the RO and pretreatment equipment) and

(*A/P, i%, N*) = the uniform payment series present worth factor; *i%* represents the interest rate, and *N* is the plant life. This value is called the amortization factor and is calculated using the equation:

$$(A/P,i,N)=\frac{i(1+i)^{n}}{(1+i)^{n}-1} \quad [5]$$

The amortization factor is applied to the total capital cost to determine the annual payments over the life of the facility that will be required pay for the equipment. Finally, the cost to produce RO desalted water is calculated by:

$$C_{p}=\frac{ACC+O\&M_{a}}{P_{a}} \quad [6]$$

where,

$O\&M_a$ = annual operation and maintainance costs ($) and

$P_a$ = annual production (1000 gallons).

According to the data presented by Esquivel, a 1 MGD RO plant, run on power purchased from the local grid, can produce 329 million gallons per year (MGY) at a cost of $2.51/kgal. A 10 MGD plant will produce 3290 MGY at a lower cost, $1.98/kgal due to economies of scale.

The RO base system described in this section does not take into account costs associated with concentrate disposal. The following sections, however, will show how Esquivel adapts the base system for various disposal strategies.

### 3.2 RO base system with evaporation pond for waste disposal

The Bureau of Reclamation study cited above (*22*) states cost data for construction of an evaporation pond. Table 4 shows how Esquivel adapted this data to the RO base system. To achieve the minimum cost, a hypothetical evaporation pond is constructed in a natural depression with an existing clay layer.

Table 4: Cost for RO base system with evaporation pond

| Plant capacity | 1 MGD | 10 MGD |
|---|---|---|
| **Capital costs:** | | |
| RO equipment | $1,200,000 | $8,000,000 |
| Pretreatment equipment | $420,000 | $2,800,000 |
| Total capital: | $1,620,000 | $10,800,000 |
| **O&M costs:** | | |
| Purchased power | $163,289 | $1,632,887 |
| RO equipment | $398,800 | $3,112,000 |
| Pretreatment equipment | $147,000 | $980,000 |
| Total O&M: | $709,089 | $5,724,887 |
| **Water cost:** | | |
| Amortized capital | $117,690 | $784,599 |
| O&M yearly | $709,089 | $5,724,887 |
| 1000 gal produced annually | 329,000 | 3,290,000 |
| **Cost ($/1000 gal)** | 2.51 | 1.98 |
| **Brine disposal ($/1000 gal)** | $0.38 | $0.38 |
| **Total cost ($/1000 gal)** | **$2.90** | **$2.36** |

From Esquivel (*9*)

The reported cost for disposal into an evaporation pond is low because the costs for excavation and the liner are minimized by the pond's hypothetical location. As Table 4 illustrates, adding the expenses associated with an evaporation pond raises the cost to produce fresh water to $2.90/kgal and $2.36/kgal for the 1 MGD and 10 MGD plants, respectively.

### 3.3 RO base system with deep well injection for waste disposal

To calculate the costs associated with employing deep well injection to dispose of waste brine from the RO base system, Esquivel uses data reported by the Englewood Water District in Florida (*23*). Esquivel's results are shown in Table 5. This report states that costs of well design and construction can range from $0.5 million to $3 million. These systems also require monitoring wells, the cost of which is estimated to be 15% of the cost of constructing the disposal well. The O&M costs are estimated to be 10% of the capital costs of constructing and engineering the well.

Table 5: Cost of RO base unit using deep well injection

| Plant capacity | 1 MGD | 10 MGD |
|---|---|---|
| **Capital costs:** | | |
| RO equipment | $1,200,000 | $8,000,000 |
| Pretreatment equipment | $420,000 | $2,800,000 |
| Deep well injection: | | |
| Construction | $400,000 | $1,600,000 |
| Engineering, Testing | $100,000 | $400,000 |
| Monitoring well | $60,000 | $240,000 |
| Total capital: | $2,180,000 | $13,040,000 |
| **O&M costs:** | | |
| Purchased power | $163,289 | $1,632,887 |
| Deep well injection | $50,000 | $200,000 |
| RO equipment | $398,800 | $3,112,000 |
| Pretreatment equipment | $147,000 | $980,000 |
| Total O&M: | $759,089 | $5,924,887 |
| **Water cost:** | | |
| Amortized capital | $158,373 | $947,330 |
| O&M yearly | $759,089 | $5,924,887 |
| 1000 gal produced annually | 329,000 | 3,290,000 |
| **Cost ($/1000 gal)** | **2.79** | **2.09** |

From Esquivel (*9*)

Table 5, above, shows that the cost of product water is \$2.79/kgal for the 1 MGD plant and \$2.09/kgal for the 10 MGD plant. These costs are greater than that for the evaporation pond system.

### 3.4 Base system hybridized with an MSF unit, using a solar pond for process heat

To incorporate the use of salinity gradient solar ponds into the RO base system, Esquivel adds an MSF unit. The MSF unit uses the RO unit's waste brine as feedwater. Reject brine from the MSF unit is then utilized to construct solar ponds. As discussed in Section 2.3, the MSF unit supplies the necessary concentration of RO waste brine so that it may be employed in a solar pond. Esquivel claims that the annual amount of reject brine from the MSF unit and the 1 MGD RO unit allows one 10,000 $m^2$ solar pond to be constructed each year. She further states that the relationship between the RO unit design capacity and the potential annual pond construction area is linear, thus, a 10 MGD plant can provide brine for 100,000 $m^2$ of solar ponds annually.

In Esquivel's hypothetical RO/MSF hybrid system, solar ponds will be constructed each year until they are able to provide all the necessary thermal and electric power. Under this design, it will take 19 to 21 years to develop enough solar pond area to provide the required power. Over time, a decreasing amount of power will be purchased and power available from the solar ponds/ORC will increase. See Tables 6 and 7 for economic data on this system design.

Esquivel claims the pond liner is the primary cost element in solar pond construction; therefore, she calculates two separate solar pond capital cost values for both the 1 MGD plant and the 10 MGD plant. The low liner cost is reported as \$4/$m^2$, while the

Table 6: RO/MSF hybrid with pond liner cost = $4/m2

| | | |
|---|---|---|
| **RO plant capacity** | 1 MGD | 10 MGD |
| Feed stream volume | 1.3 MGD | 12.9 MGD |
| Actual production | 0.9 MGD | 9 MGD |
| | | |
| **MSF plant capacity** | 0.4 MGD | 3.9 MGD |
| Feed stream volume | 0.4 MGD | 3.9 MGD |
| Recovery rate | 90% | 90% |
| Plant load factor | 90% | 90% |
| Actual production | 0.36 MGD | 3.51 MGD |
| | | |
| **Total production** | 1.26 MGD | 12.51 MGD |
| Solar pond size | 210,000 $m^2$ | 1,900,000 $m^2$ |
| | | |
| **Capital costs:** | | |
| RO equipment | $1,200,000 | $8,000,000 |
| Pretreatment equipment | $420,000 | $2,800,000 |
| Solar pond | $2,374,159 | $15,876,715 |
| ORC engine | $485,168 | $2,859,058 |
| MSF equipment | $242,360 | $2,363,010 |
| Total capital: | $4,721,687 | $31,898,783 |
| | | |
| **O&M costs:** | | |
| RO equipment | $398,800 | $3,112,000 |
| Pretreatment equipment | $147,000 | $980,000 |
| MSF equipment | $36,354 | $354,452 |
| Purchased electrical power | $105,192 | $1,057,436 |
| Purchased thermal power | $60,875 | $582,505 |
| Solar pond | $166,191 | $317,534 |
| ORC engine | $19,081 | $190,374 |
| Total O&M: | $933,493 | $6,594,301 |
| | | |
| **Water cost:** | | |
| Amortized capital | $343,021 | $2,317,383 |
| O&M yearly | $933,493 | $6,594,301 |
| 1000 gal produced annually | 460,000 | 4,570,000 |
| | | |
| **Cost ($/1000 gal)** | **2.78** | **1.95** |

From Esquivel (*9*)

high cost is given as $15/m$^2$. As the data in Tables 6 and 7 shows, the liner cost has a significant impact upon the cost of product water for this system design. When the pond liner cost is low ($4/m$^2$) the solar pond-based system produces water at a cost of $1.95 to $2.78/kgal.

Table 7: RO/MSF hybrid with pond liner cost = $15/m2

| | | |
|---|---|---|
| **RO plant capacity** | 1 MGD | 10 MGD |
| Feed stream volume | 1.3 MGD | 12.9 MGD |
| Actual production | 0.9 MGD | 9 MGD |
| | | |
| **MSF plant capacity** | 0.4 MGD | 3.9 MGD |
| Feed stream volume | 0.4 MGD | 3.9 MGD |
| Recovery rate | 90% | 90% |
| Plant load factor | 90% | 90% |
| Actual production | 0.36 MGD | 3.51 MGD |
| | | |
| **Total production** | 1.26 MGD | 12.51 MGD |
| Solar pond size | 210,000 $m^2$ | 1,900,000 $m^2$ |
| | | |
| **Capital costs:** | | |
| RO equipment | $1,200,000 | $8,000,000 |
| Pretreatment equipment | $420,000 | $2,800,000 |
| Solar pond | $4,990,147 | $39,600,921 |
| ORC engine | $485,168 | $2,859,058 |
| MSF equipment | $242,360 | $2,363,010 |
| Total capital: | $7,337,675 | $55,622,989 |
| | | |
| **O&M costs:** | | |
| RO equipment | $398,800 | $3,112,000 |
| Pretreatment equipment | $147,000 | $980,000 |
| MSF equipment | $36,354 | $354,452 |
| Purchased electrical power | $105,192 | $1,057,436 |
| Purchased thermal power | $60,875 | $582,505 |
| Solar pond | $166,191 | $317,534 |
| ORC engine | $19,081 | $190,374 |
| Total O&M: | $933,493 | $6,594,301 |
| | | |
| **Water cost:** | | |
| Amortized capital | $533,068 | $4,040,900 |
| O&M yearly | $933,493 | $6,594,301 |
| 1000 gal produced annually | 460,000 | 4,570,000 |
| | | |
| **Cost ($/1000 gal)** | **3.19** | **2.33** |

From Esquivel (*9*)

However, when the liner cost is high ($15/$m^2$), the product water costs from $2.33 to $3.19/kgal.

The costs calculated by Esquivel are consistent with those stated by Buros (*10*) and mentioned above. More importantly, Esquivel's data illustrates that salinity gradient solar ponds can be economically competitive with evaporation ponds and deep well disposal. Buros states, "as long as conventional energy costs are relatively low and the market for the units small…it is not expected that (solar desalination units) will be developed to any great extent except to fill a small niche market" (*10*). The market for SGSP systems is limited to those areas for which other desalination methods and/or wastewater disposal means are unavailable or uneconomical as well as regions with sufficient environmental conditions such that an SGSP can operate efficiently. However, SGSPs may still represent the only opportunity to pursue desalination technology in inland, arid regions of the world when other options are unacceptable.

In areas such as the Southwest, with scant fresh water and plenty of solar radiation, Lu et al. (*14*) claim, "solar-powered desalination can and should play an important role to help solve the water problems in this region." The true potential of solar pond powered desalination remains to be seen; however, some of the critical benefits of SGSP-coupled desalination ensure that the technology must continue to develop. These benefits are associated with the low environmental impact of SGSP desalination. Solar ponds do not require non-renewable fuel input because desalination units that operate using process heat from SGSPs use little or no non-renewable fuels. Compared with units run on coal or natural gas, SGSP-coupled desalination represents a significant means of reducing air pollutant emissions. As the costs for petroleum-based fuels and coal increase over time, the value of SGSP systems should be recognized.

The following section shows how Esquivel's 1992 data is updated to reflect changes in capital costs and O&M costs of RO units, MSF units, and the concentrate disposal methods discussed above. These data will show how the economic viability of SGSP systems, deep well injection, and evaporation ponds has changed in the years since Esquivel's thesis was completed and how these costs may change in the future.

## 4. Methods

The cost data presented by Esquivel (*9*) and discussed in Section 3 of this thesis is the most comprehensive economic analysis of solar ponds versus evaporation ponds and deep well injection currently available in my thesis research. As such, it is foundation upon which I have built my own economic analysis.

The first step toward my analysis was to develop a model of Esquivel's data. This process was completed within a series of Excel spreadsheets. Essentially, I re-created Tables 4 through 7 from Section 3 along with their supporting data. After the appropriate equations were developed within the model, I proceeded by determining the current costs of the variables listed in Table 8. Variables relating to solar pond size and performance were not changed in order to ensure that my thesis will describe only those economic changes resulting from increased or decreased capital and O&M costs relating to concentrate disposal and to changes in the cost of RO and MSF desalination units in the years since the original data was gathered. Table 8 also lists the variables that remain constant between Esquivel's work and this thesis.

Table 8: Economic model variables

| Variables to be updated | Variables to remain constant |
|---|---|
| RO/MSF recovery rates | Plant load factor |
| Electrical/thermal energy requirements | Plant life |
| RO/pretreatment equipment costs | Interest rate |
| RO/pretreatment equipment O&M costs | Plant capacity |
| MSF equipment costs | |
| MSF equipment O&M costs | |
| Purchased power amount/cost | |
| Evaporation pond capital/O&M costs | |
| Deep well injection capital/O&M costs | |
| Solar pond capital/O&M costs | |
| ORCE capital/O&M costs | |
| Fuel escalation rates (electrical and thermal) | |

I obtained current cost data through direct contact with manufacturers as well as through contact with regional desalination facilities and engineering firms associated with the technology and from published literature. Once these costs were determined, I compared the spreadsheet model of current economic data with Esquivel's original results. This comparison allows me to gauge trends in the economics of desalination wastewater disposal methods and enables me to predict future changes in the economic feasibility of these methods. Moreover, the model and comparison show what conditions must exist to make SGSP-coupled desalination facilities economically viable.

## 4.1 Reverse osmosis base system

In order to calculate current capital and O&M costs for RO facilities, I built an Excel worksheet which lists the data source/plant location, the capacity of each plant (MGD), the total capital costs, unit cost of power, annual power costs, total O&M costs, and annual O&M costs minus the cost of power. This worksheet is presented in Appendix 2: Survey results.

To estimate the capital cost of my model RO facility, I graphed the data from Appendix 2, then fit a trend line to the graph (see Figure 6). Using the equation of the trend line, I was able to determine the probable capital costs for a 1 MGD and a 10 MGD RO plant.

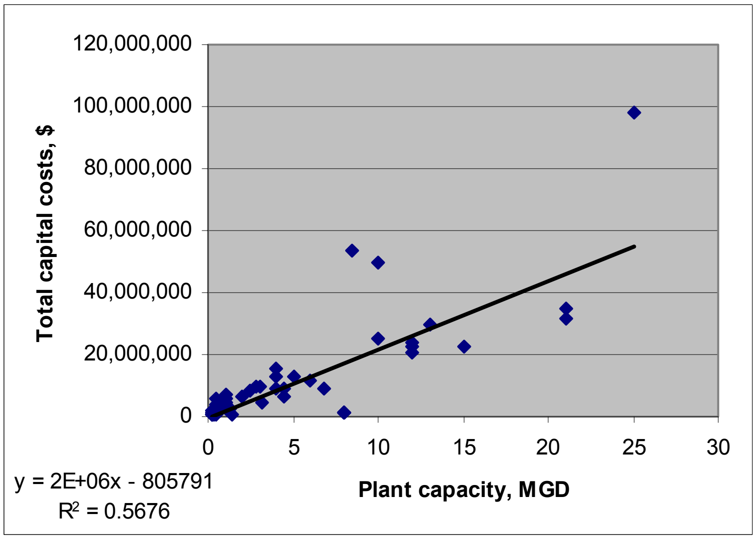

Figure 6: RO capital costs vs. plant capacity

The data in Appendix 2 and thus the calculated cost for my facility represent capital costs for both the RO equipment and the necessary pretreatment equipment.

I determined the cost of operation and maintainance (excluding costs of power) for the RO equipment and for the required pretreatment equipment as a percentage of the capital cost by subtracting the annual power charges from the annual O&M costs, then dividing the result by the values in the "Total capital costs" column. This series of calculations gives an estimate of the O&M costs as a percentage of the total capital costs.

The unit cost of electricity applied to the model is the average of the values presented in Appendix 2. The cost of electricity is adjusted annually according to the fuel escalation rate determined from data presented by the US Department of Energy (*24*).

Annual power costs for the base system were calculated by applying the unit cost of electricity ($/kWh) to the annual power requirements, 5 kWh/1000 gal of the RO base system (*12*). Next, the annual electricity cost is adjusted for present value. The present value of a future cost takes into account the idea that an investment of one dollar today is worth more than a return of one dollar 30 years from now. The present value is calculated by:

$$PV = \frac{1}{(1+i)^n} \quad [7]$$

where,

$PV$ = present value

$i$ = interest rate (%), and

$n$ = year.

The sum of the present value of the cost of electricity is then annualized by applying the amortization factor (equation 5) as discussed in Section 3.1. This series of calculations is presented in Appendix 3: Power costs for RO base system. The O&M of the desalination equipment and annual power costs represent the total operation and maintainance costs for the RO base system.

### 4.2 Evaporation pond cost calculations

In a 2001 report for the US Bureau of Reclamation (*25*), Mickley presents equations for calculating the cost of utilizing evaporation ponds for desalination concentrate disposal. These equations take into account the costs associated with purchasing land, clearing the land, excavating the pond, building dikes, lining the pond, installing fencing, and constructing an access road. The total area required for the evaporation pond includes the evaporative area (surface area of the pond) as well as the area of the dike and the perimeter of the pond. Mickley's equations for total area and total unit area capital cost are shown below:

$$A_t = (1.2A_e) \times \frac{1 + 0.155dh}{\sqrt{A_e}} \tag{8}$$

where,

$A_t$ = total area required (acres),

$A_e$ = evaporative area (acres), and

$dh$ = dike height (ft).

$$CC_u = 5406 + 465t_l + 1.07Cl + 0.931Cc + 217.5dh \tag{9}$$

where,

$CC_u$ = total unit area capital cost (\$/acre),

$t_l$ = liner thickness (mils),

$Cl$ = land cost (\$/acre), and

$Cc$ = land clearing cost (\$/acre).

The total capital cost is then calculated by multiplying $A_t$ by $CC_u$. Appendix 4: "Capital cost calculations" shows the Excel worksheet developed to utilize these equations in the model.

Evaporative areas of 15 and 150 acres were assumed based on observation of existing evaporation ponds at the Horizon City RO plant. This 1 MGD facility has two 25 acre ponds to serve as the final concentrate disposal site. Upon discussion of the size of these ponds with the plant operator, it was decided that only about a quarter of the area (one 12 acre pond) was necessary. Therefore, I assume a requirement of 15 acres for a 1 MGD facility and, linearly, 150 acres for a 10 MGD plant.

As mentioned in Section 3.2, the evaporation pond described by Esquivel's model is sited in an existing depression with a natural clay liner. The equation available to determine capital costs of an evaporation pond for this study, on the other hand, assumes the pond will be excavated and lined. This situation is more probable for desalination facilities, because it is likely that proximity to and ability to utilize a natural depression with an indigenous clay liner will be rare. I assumed a land clearing cost of $1,000/acre (which is likely for the desert Southwest) and a liner thickness of 50 mils (an average thickness). Therefore, the variables considered in this equation are the dike height and the cost of land. I assumed a range of values for each of these variables: 4, 8, and 12 foot dike heights and 0, 1000, 5000, and $10,000 land costs. This process will allow the model to show varying capital costs for different pond development circumstances.

An O&M cost of 0.5% of the capital costs for constructing the evaporation pond was assigned based on the relationship stated by Mickley (*25*). Finally, the cost per 1000 gallons of product water (assuming a recovery rate of 80%) was calculated by adding the amortized capital to the annual O&M charges and dividing by the volume of water produced (1000 gal) each year.

## 4.3 Deep well injection

Mickley's USBR report (*25*) also includes an equation for calculating the capital cost of utilizing deep-well injection as a concentrate disposal method:

$$TCC = 1000(-288 + 145.9d_t + 0.754D) \qquad [10]$$

where,

$TCC$ = total capital cost ($),

$d_t$ = tube diameter (inches), and

$D$ = well depth (feet).

The costs factored into this equation include those for drilling, testing, surveying, casing, grout, tubing and packer installation, well mobilization and demobilization, and the monitoring well.

As Mickley's equation demonstrates, the primary cost factors are the diameter of the well ("tube diameter") and the depth of the well. Mickley lists a range of tube diameters capable of supporting the recommended brine flow velocity of 10 feet per second. The minimum tube diameter required for a brine flow rate of 0.6 MGD (the daily brine production from a 1 MGD facility) is 4 inches while the maximum diameter is 24 inches. The model's 10 MGD facility will produce 2.5 MG of concentrate per day. Tube diameters required to accommodate this flow rate range from 10 to 24 inches.

In the model, Mickley's equations are developed for well depths of 2,500, 5,000, 7,500, and 10,000 feet. The worksheet developed to calculate the capital cost of an injection well for varying tube diameters and well depths is presented in Appendix 4.

O&M for deep well injection was determined to be 8% of the capital costs by Green et al (*26*). The cost per 1000 gallons of product water was calculated in the same manner as those for the evaporation pond scenario.

### 4.4 Salinity gradient solar ponds

As in the Esquivel model, I incorporated a MSF unit to further concentrate the reject from the RO unit. The recovery rate and plant load factor for the MSF unit are both assumed to be 90%. The electrical energy requirements for this unit are reported by Wade

(*27*) to be 5 kWh/1000 gal. The required thermal energy was estimated based on published data from Wade and from Mesa et al (*12*). Capital cost data for small-scale MSF equipment required by this model was not available, thus, I increased the cost data presented by Esquivel by dividing her values by 0.82695. The calculation accounts for inflation of the US dollar in the eleven years since her data was calculated. Results of the literature review show that the average annual O&M cost for MSF is 20% of the capital cost (*16*, *17*, *27* - *30*). This percentage was reduced to 15% in order to subtract the cost of energy from the annual O&M charges.

The energy requirements for both the RO and MSF units were calculated by first assuming that a 10,000 m$^2$ and 100,000 m$^2$ solar pond will provide 13,335/133,354 Giga joules (GJ) of thermal energy, respectively. Therefore, as additional ponds are constructed, an increasing amount of thermal energy will be available to operate the MSF unit. In year six, an excess of thermal energy will be available. This energy will be converted to electricity by the ORCE. The amount of electrical energy produced annually is calculated using the following equation:

$$EE_s = (GJ \times 10^9) \times \frac{1kWh}{3600 \times 10^3 J} \times eff_{conv} \qquad [11]$$

where,

$EE_s$ = electrical energy supplied by the ORCE (kWh)

$\frac{1kWh}{3600 \times 10^3 J}$ = the conversion factor from joules (J) to kilowatt-hours (kWh), and

$eff_{conv}$ = GJ to kWh conversion efficiency.

The GJ to kWh conversion efficiency is assumed, based on Esquivel's reported data, to be 7% for the 1 MGD facility and 8% for the 10 MGD facility. These calculations are presented in Appendix 5: Solar pond energy requirements.

The volume of reject from the 1 MGD RO and MSF unit is enough to construct one 10,000 $m^2$ pond per year; the 10 MGD RO plant and MSF unit are capable of supporting construction of one 100,000 $m^2$ pond per year. The energy requirements for each unit show that 15 and 13 ponds should be built for the respective desalination facilities. In order to calculate the annualized capital cost for these ponds I, like Esquivel, assumed a phased pond construction. In year one the land, fencing, and engineering costs are assigned and one 10,000 or 100,000 $m^2$ pond is built. In years 5, 10, and 15 (year 13 for the 10 MGD plant) 4, 5, and 5 (3) ponds would be built. Costs assigned during this phase of the construction are only those that apply to each individual pond: liner costs, excavation, wave control, and heat exchange equipment.

In order to predict capital costs for a range of site specific conditions, land costs were varied from \$1000 per acre to \$10,000 per acre. Total acreage required was calculated to be 45 acres for the 1MGD plant and 410 acres for the 10 MGD plant. The cost of fencing the entire property was estimated based on data from the current RS Means Catalog (*31*), which lists fencing costs to be approximately \$6.50 per foot. The perimeter of each solar pond compound was calculated to be 5,578 and 16,917 feet, respectively. The RS Means Catalog also lists an excavation estimate of \$3.24 per cubic yard. The total excavation volume for a 10,000 $m^2$ pond is 34,201 $yd^3$ and 281,708 $yd^3$ for a 100,000 $m^2$ pond (*9*). Engineering costs were assumed to be 1% of the total capital cost for solar pond construction in year one.

Costs of the pond liners were determined from communication with two manufacturing companies: Flexiliner and Engineered Textile Products, Inc. These companies both claimed an installed cost of \$1.40 per $ft^2$ or approximately \$15/$m^2$. Solar pond researcher, H. Lu of the University of Texas at El Paso, however, states that liner costs may be as low as \$4.00/$m^2$. Cost data for wave control, heat exchange equipment, and an ORCE was not available; therefore, I again adjusted Esquivel's data for inflation. Tables in Appendix 4 show the worksheets developed to calculate the capital costs for the solar ponds and for the ORCE.

Operation and maintainance costs (excluding power costs) for the solar ponds were assumed to be 7% of the capital cost, as stated by Esquivel. Annual power costs were calculated by applying the fuel rates (\$/kWh and \$/GJ) to the annual electrical and thermal energy requirements as shown in Appendix 5: Solar pond energy requirements. The cost calculations are presented in Appendix 6: Power costs for solar pond/RO/MSF system. O&M for the ORCE was assumed to be 4% and 7% of the capital cost of the engine for the 1 and 10 MGD facilities, respectively. The annual cost to produce fresh water (\$/1000 gal) using this system was calculated in the same manner as that for the evaporation pond and deep well injection strategies.

# 5. Results and Discussion

## 5.1 Model update results and comparison

The results of the updated economic model are presented in Tables 9 and 10. These tables show current estimates of the cost to produce water using evaporation ponds, deep well injection, and SGSPs.

Table 9: 1 MGD plant updated costs

| **Plant specifications** | RO plant | MSF Plant |
|---|---|---|
| Recovery rate | 80% | 90% |
| Plant load factor | 90% | 90% |
| Energy requirements, kWh/1000 gal | 5 | 5 |
| Heat requirements, GJ/1000 gal | N/A | 0.66 |
| Plant life, years | 30 | 30 |
| Interest rate | 6% | 6% |
| Feed stream volume, MGD | 1.3 | 0.26 |
| Plant capacity, MGD | **1** | **0.26** |
| Actual production, MGD | 1.0 | 0.23 |

| | **Deep-well injection** | | **Evaporation ponds** | | **Solar ponds** | |
|---|---|---|---|---|---|---|
| **Capital Costs:** | Low | High | Low | High | Low | High |
| RO/pretreatment equipment | $1,194,209 | $1,194,209 | $1,194,209 | $1,194,209 | $1,194,209 | $1,194,209 |
| MSF equipment | N/A | N/A | N/A | N/A | $293,000 | $293,000 |
| Disposal method construction | $2,180,600 | $10,753,600 | $635,988 | $1,142,969 | $1,935,364 | $4,088,281 |
| ORC engine | N/A | N/A | N/A | N/A | $506,856 | $506,856 |
| Total capital cost: | $3,374,809 | $11,947,809 | $1,830,197 | $2,337,178 | $3,422,573 | $5,575,490 |
| | | | | | | |
| **Operation and Maintainance:** | | | | | | |
| RO/pretreatment equipment | $161,218 | $161,218 | $161,218 | $161,218 | $161,218 | $161,218 |
| MSF equipment | N/A | N/A | N/A | N/A | $43,950 | $43,950 |
| Disposal method O&M | $174,448 | $860,288 | $3,180 | $5,715 | $135,475 | $286,180 |
| ORC engine | N/A | N/A | N/A | N/A | $25,343 | $25,343 |
| Purchased electrical power | $227,820 | $227,820 | $227,820 | $227,820 | $136,342 | $136,342 |
| Purchased thermal power | N/A | N/A | N/A | N/A | $14,799 | $14,799 |
| Total O&M cost: | $563,486 | $1,249,326 | $392,218 | $394,753 | $517,127 | $667,831 |
| | | | | | | |
| **Cost to Produce Water:** | | | | | | |
| Amortization factor | 0.0726 | 0.0726 | 0.0726 | 0.0726 | 0.0726 | 0.0726 |
| Amortized capital | $245,176 | $867,995 | $132,962 | $169,793 | $248,646 | $405,053 |
| | | | | | | |
| 1000 gallons produced annually | 379,600 | 379,600 | 379,600 | 379,600 | 465,010 | 465,010 |
| | | | | | | |
| **Cost ($/1000 gal):** | **$2.13** | **$5.58** | **$1.38** | **$1.49** | **$1.65** | **$2.31** |

These cost estimates demonstrate that the cost to produce water for each option has indeed changed since Esquivel's analysis was completed in 1992.

Although costs associated with each method have generally decreased since 1992, the cost of utilizing solar ponds and deep well injection did not decline as dramatically as costs for evaporation ponds.

Table 10: 10 MGD plant updated costs

**10 MGD Plant**

| **Plant specifications** | RO plant | MSF Plant |
|---|---|---|
| Recovery rate | 80% | 90% |
| Plant load factor | 90% | 90% |
| Energy requirements, kWh/1000 gal | 5 | 5 |
| Heat requirements, GJ/1000 gal | N/A | 0.66 |
| Plant life, years | 30 | 30 |
| Interest rate | 6% | 6% |
| Feed stream volume, MGD | 12.5 | 2.50 |
| Plant capacity, MGD | **10** | **2.50** |
| Actual production, MGD | 10.0 | 2.25 |

| | Deep-well injection | | Evaporation ponds | | SG solar ponds | |
|---|---|---|---|---|---|---|
| **Capital Costs:** | Low | High | Low | High | Low | High |
| RO/pretreatment equipment | $19,194,209 | $19,194,209 | $19,194,209 | $19,194,209 | $19,194,209 | $19,194,209 |
| MSF equipment | N/A | N/A | N/A | N/A | $3,458,000 | $3,458,000 |
| Disposal method construction | $3,347,800 | $10,753,600 | $6,931,056 | $10,325,173 | $17,012,390 | $34,247,220 |
| ORC engine | N/A | N/A | N/A | N/A | $2,942,880 | $2,942,880 |
| Total capital cost: | $22,542,009 | $29,947,809 | $26,125,265 | $29,519,382 | $42,607,479 | $59,842,309 |
| **Operation and Maintainance:** | | | | | | |
| RO/pretreatment equipment | $2,591,218 | $2,591,218 | $2,591,218 | $2,591,218 | $2,591,218 | $2,591,218 |
| MSF equipment | N/A | N/A | N/A | N/A | $691,600 | $691,600 |
| Disposal method O&M | $267,824 | $860,288 | $34,655 | $51,626 | $340,248 | $684,944 |
| ORC engine O&M | N/A | N/A | N/A | N/A | $147,144 | $147,144 |
| Purchased electrical power | $2,190,574 | $2,190,574 | $2,190,574 | $2,190,574 | $1,220,419 | $1,220,419 |
| Purchased thermal power | N/A | N/A | N/A | N/A | $154,727 | $154,727 |
| Total O&M cost: | $5,049,616 | $5,642,080 | $4,816,447 | $4,833,418 | $5,145,356 | $5,490,052 |
| **Cost to Produce Water:** | | | | | | |
| Amortization factor | 0.0726 | 0.0726 | 0.0726 | 0.0726 | 0.0726 | 0.0726 |
| Amortized capital | $1,637,652 | $2,175,676 | $1,897,972 | $2,144,551 | $3,095,387 | $4,347,479 |
| 1000 gallons produced annually | 3,650,000 | 3,650,000 | 3,650,000 | 3,650,000 | 4,471,250 | 4,471,250 |
| **Cost ($/1000 gal)** | **$1.83** | **$2.14** | **$1.84** | **$1.91** | **$1.84** | **$2.20** |

In the 1 MGD deep well injection option, costs on the high end actually rose by 50%. Therefore, the results of this model suggest that, for a 1 MGD facility, evaporation ponds may be the lowest-cost disposal option. Costs to produce water from the 10 MGD plant were relatively constant between disposal methods. Therefore, for facilities of this size, disposal method does not seem to be as large of an issue as it is for smaller facilities.

Table 11 shows a comparison between Esquivel's original values and the updated variables. This table illustrates how the additional cost associated with purchasing, operating, and maintaining the MSF and ORCE equipment required to utilize SGSPs

Table 11: Original and updated costs

| | | | Evaporation Ponds | Deep well Injection | Salinity Gradient Solar Ponds |
|---|---|---|---|---|---|
| Cost of desalination and pretreatment equipment | Esquivel | 1MGD | $1,620,000 | $1,620,000 | $2,347,528 |
| | Update | | $1,194,209 | $1,194,209 | $1,994,065 |
| | Esquivel | 10 MGD | $10,800,000 | $10,800,000 | $16,022,068 |
| | Update | | $19,194,209 | $19,194,209 | $25,595,089 |
| Annual power costs | Esquivel | 1MGD | $163,289 | $163,289 | $166,067 |
| | Update | | $227,820 | $227,820 | $151,141 |
| | Esquivel | 10 MGD | $1,632,887 | $1,632,887 | $1,639,941 |
| | Update | | $2,190,574 | $2,190,574 | $1,375,146 |
| Disposal method Capital costs | Esquivel: High | 1MGD | $125,020 | $560,000 | $4,990,147 |
| | Update: High | | $498,678 | $10,753,600 | $2,317,439 |
| | Esquivel: Low | | $125,020 | $560,000 | $2,374,159 |
| | Update: Low | | $131,052 | $2,180,600 | $1,307,520 |
| | Esquivel: High | 10 MGD | $1,250,200 | $2,240,000 | $39,600,921 |
| | Update: High | | $4,504,882 | $10,753,600 | $19,133,912 |
| | Esquivel: Low | | $1,250,200 | $2,240,000 | $15,876,715 |
| | Update: Low | | $1,428,220 | $3,347,800 | $10,726,278 |
| Disposal method O&M costs | Esquivel | 1MGD | $0 | $50,000 | $166,191 |
| | Update: High | | $2,493 | $860,288 | $162,221 |
| | Update: Low | | $7,141 | $363,361 | $214,526 |
| | Esquivel | 10 MGD | $0 | $200,000 | $317,534 |
| | Update: High | | $51,626 | $860,288 | $684,944 |
| | Update: Low | | $34,655 | $267,824 | $340,248 |

increases the annual production cost of a desalination facility which, in some circumstances, may make the option unacceptable. However, additional capital and O&M costs associated with the MSF and ORCE units required to utilize SGSPs may be offset by savings resulting from increased water production.

The following figures (Figures 7 through 16) are intended to help the reader visualize the economic differences between the three disposal options and the changes in cost between Esquivel's data and the update results.

Figures 7 through 10 show the change in cost to produce water ($/1000 gal) from Esquivel's data to this update. These figures illustrate that the updated cost to produce

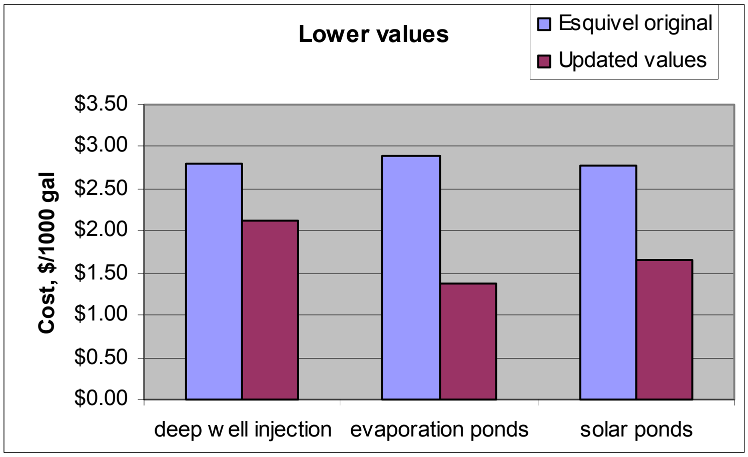

Figure 7: Cost comparison, 1 MGD (low values)

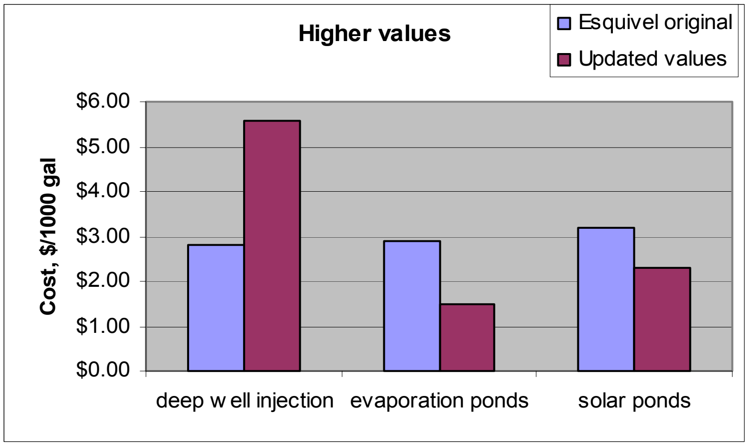

Figure 8: Cost comparison, 1 MGD (high values)

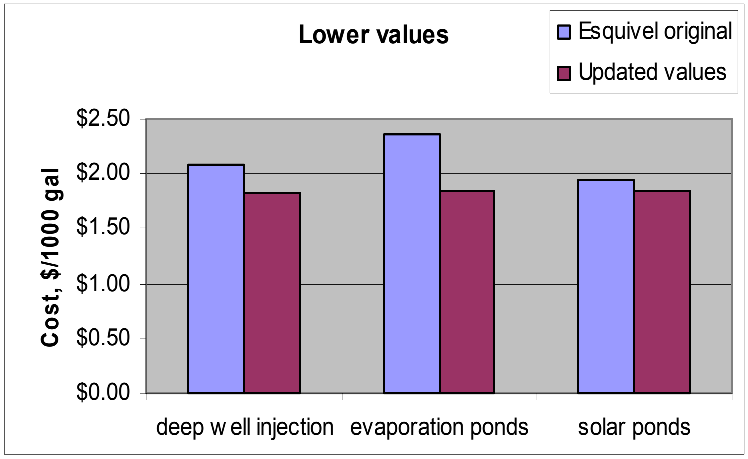

Figure 9: Cost comparison, 10 MGD (low values)

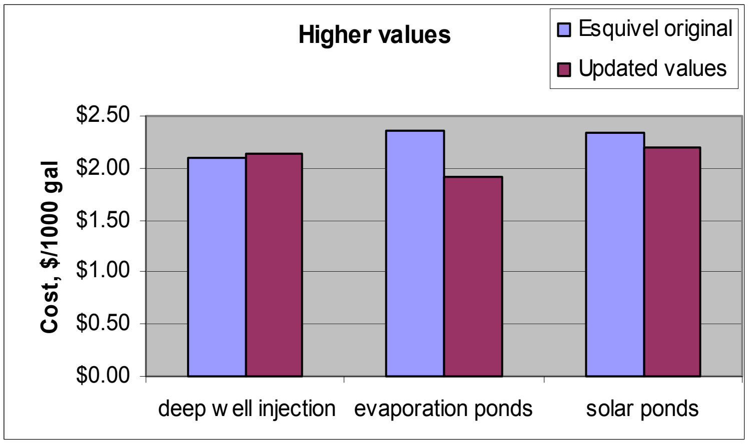

Figure 10: Cost comparison, 10 MGD (high values)

desalted water is lower than Esquivel's estimates in all but the high-cost deep well injection options.

Figures 11 and 12 show the cost of desalination and pretreatment equipment, including the MSF unit costs and ORCE costs associated with the solar pond option.

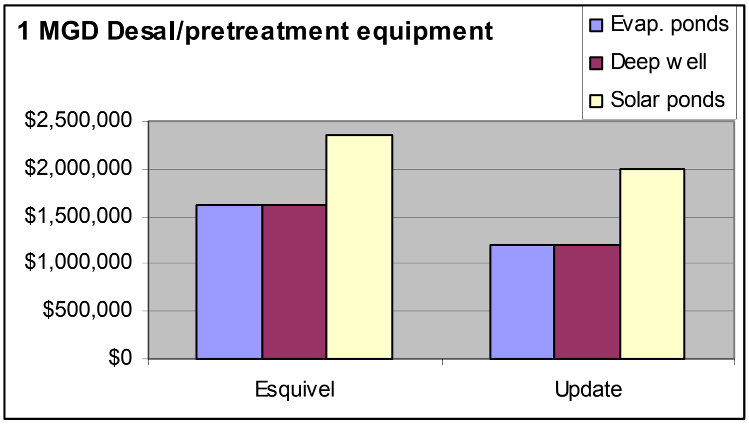

Figure 11: Desalination equipment cost comparison, 1 MGD

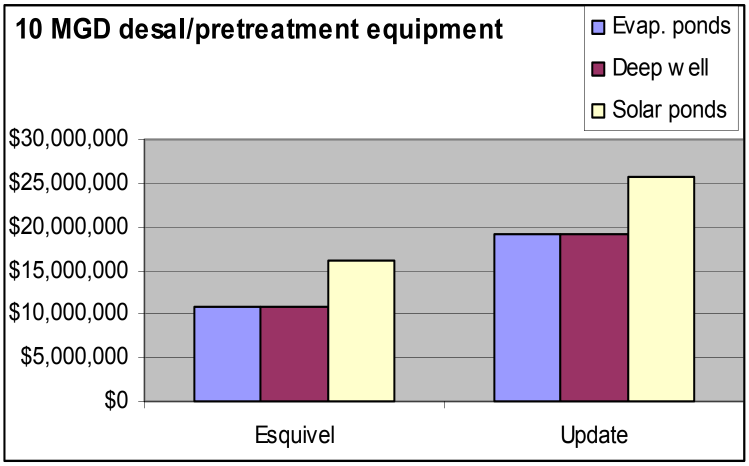

Figure 12: Desalination equipment cost comparison, 10 MGD

Figures 11 and 12 show that the capital costs, including costs of the MSF and ORCE equipment, have gone down for the 1 MGD facility and up for the 10 MGD facility.

Figures 13 and 14 demonstrate that the updated annual power costs are higher for facilities using evaporation ponds and deep well injection than the annual power costs for plants using SGSPs. This situation differs from Esquivel, where the SGSP-run facility requires slightly more power than the conventional facilities.

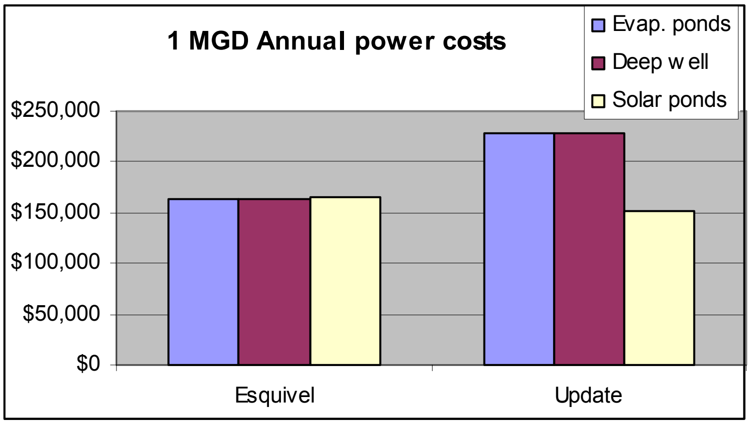

Figure 13: Annual power cost comparisons, 1 MGD

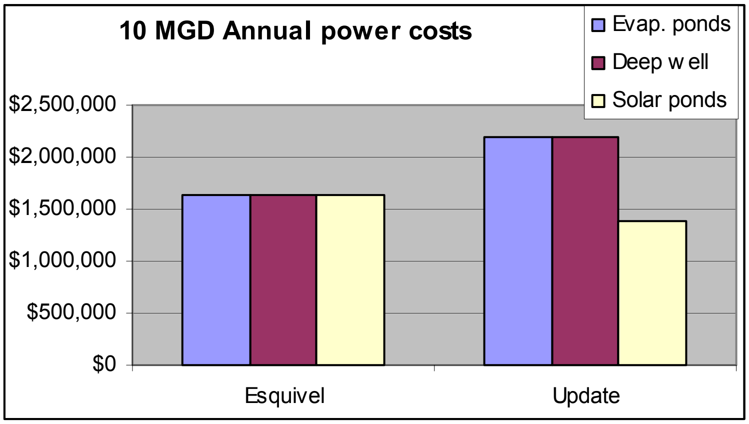

Figure 14: Annual power cost comparisons, 10 MGD

Annual power costs for the SGSP-run facility were lower than Esquivel's costs, even though the unit cost of power ($/kWh) is almost twice as much in the update calculations. As Figures 13 and 14 show, using SGSPs can result in an overall energy cost savings.

The specific construction costs associated with each disposal method are presented in figures 15 and 16. The dramatically high cost of deep injection well construction for the 1 MGD plant (Figure 15) indicates that this concentrate disposal method may not be the most favorable choice for smaller-sized facilities.

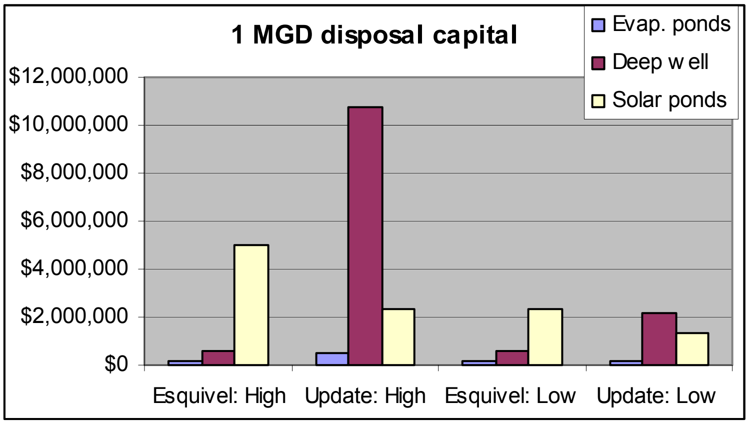

Figure 15: Disposal construction cost comparison, 1 MGD

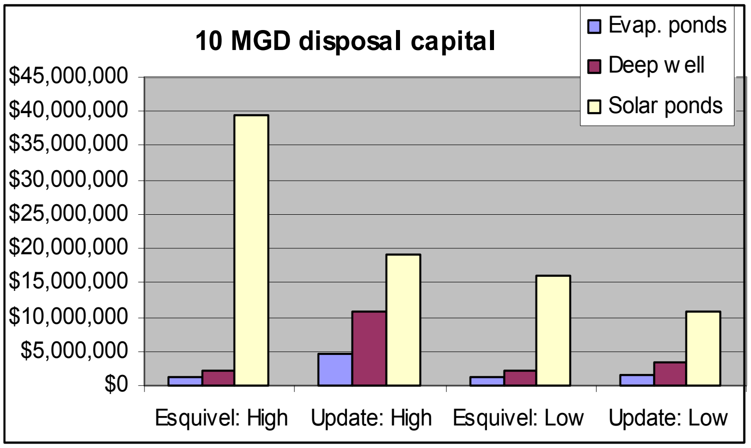

Figure 16: Disposal construction cost comparison, 10 MGD

Figure 16 shows the exceptionally high constructions costs of salinity-gradient solar ponds. Although the overall cost to produce water for the 10 MGD plant is virtually the same for all disposal options, the initial capital outlay required to utilize solar ponds may likely be prohibitive.

The results of this update indicate that, although water produced in a facility utilizing SGSPs is comparable in cost to facilities using other disposal options, SGSPs are not likely to be the disposal method of choice. This outcome is expected because 1) a 1 MGD facility will be most likely to select evaporation ponds due to their comparatively low capital and O&M costs and 2) a 10 MGD facility would not choose to use salinity gradient solar ponds because of the very high initial capital costs associated with this method.

### 5.2 Future trends

The results of this study indicate that the cost impact of all three disposal methods will continue to decline. However, increases in the capital and O&M cost of desalination equipment as well as the cost of power may have a significant impact on the disposal method chosen for a desalination facility. As equipment costs rise, the most inexpensive disposal strategy must be chosen.

Salinity gradient solar ponds, although not dramatically cheaper than other disposal methods, may still be a viable option especially in circumstances where the unit cost of power is very high or where access to a power grid is limited. Moreover, the actual cost of utilizing SGSPs may be lower than reported above when other factors are taken into account, such as savings incurred by bypassing the waste disposal permitting process, the environmental savings associated with using a renewable fuel, or tax breaks that may be developed for facilities that use renewable fuels.

## 6. Limitations

This thesis relies heavily on data presented by UTEP Master's candidate P. M. Esquivel (*9*). I must assume that Esquivel's data is accurate and complete. However, I am confident in this assumption because her results appear reasonable when compared to other, published, economic data. Additionally, because Esquivel's model is based on climatological data for the El Paso, TX region, economic data should be accurate for inland desalination facilities in the desert southwest but may not apply to facilities in other regions.

## 7. Significance

By analyzing present-day costs of desalination wastewater disposal methods in contrast with an economic model developed in 1992, not only can we see how the economics of desalination wastewater disposal have changed in the past decade, we can also make assumptions regarding the future economic viability of these disposal methods.

This economic model can be manipulated for a variety of site-specific characteristics. Therefore, it may be useful in determining estimated annual costs for any proposed facility in the arid Southwest and may help planners decide which disposal technology will be best suited to their situation.

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## Appendix 1: List of abbreviations

$/GJ – dollars per Giga joule

$/kW – dollars per kilowatt

(A/P, i%, N) – uniform payment series present worth factor

$ACC$ – amortized capital cost

$A_e$ – evaporative area of an evaporation pond (acres)

$A_t$ – total area required for evaporation pond (acres)

BOD – biological oxygen demand

$C_c$ – land clearing cost ($/acre)

$CC_u$ – unit area capital cost ($/acre)

CFR – Code of Federal Regulations

$C_l$ – land cost ($/acre)

$D$ – well depth (feet)

$dh$ – dike height (feet)

$DPC$ – design production capacity (MGD)

ED – electrodialysis

$EE_s$ – electrical energy supplied by ORCE (kWh)

$eff_{conv}$ – GJ to kWh conversion efficiency (%)

EPA – Environmental Protection Agency

$f_f$ – feed water flow rate (GPD)

$f_p$ – product water flow rate (GPD)

gal – gallon

GJ – Giga joules

i% - interest rate

IDA – International Desalination Association

J – joules

kgal – 1000 gallons

kWh – kilowatt-hours

LCZ – lower convection zone (a.k.a. storage layer)

m$^2$ – square meters

m$^3$/d – cubic meters per day

ME – multi-effect evaporator

MGD – million gallons per day

MGY – million gallons per year

MSF – multi-stage flash

MVC – mechanical vapor compression

n – Plant life, years

NCZ – non-convection zone of a solar pond (a.k.a. middle layer)

O&M – operation and maintainance

$O\&M_a$ – annual operation and maintainance costs

ORCE – organic Rankine cycle engine

$P_a$ – actual production (MGD)

*PLF* – plant load factor

RCRA – Resource Conservation and Recovery Act

RO – reverse osmosis

*RR* – recovery ratio

SGSP – salinity gradient solar pond

*TCC* – total capital costs

TDS – total dissolved solids

$t_l$ – liner thickness (mils)

TVC – thermal vapor compression

UCZ – upper convection zone of a solar pond (also known as the surface layer)

UTEP – University of Texas at El Paso

VTE – vertical tube evaporator

$\Delta \mathrm{T}$ – temperature difference between the LCZ and the UCZ

## Appendix 2: RO cost survey results

The values in rows 1 (Hastings, FL) to row 32 (Cape Coral, FL) represent data gathered by Leitner and Associates, Inc. in a 1997 survey (*32*). This data was adjusted to represent 2003 dollars by multiplying each value by 0.9527 to account for inflation.

| **Plant** | **Capacity, MGD** | **Total capital costs** | **Cost of power, $/kWh** | **Annual power costs** | **Total annual O&M** | **O&M - power** |
|---|---|---|---|---|---|---|
| Hastings, FL | 0.221 | 952,690 | | 13,396 | 20,476 | 7080 |
| Osprey, FL | 0.225 | 2,083,627 | 0.0619 | 43,795 | 216,120 | 172325 |
| Lutz, FL | 0.238 | 952,646 | 0.0619 | 20,007 | 62,878 | 42871 |
| Kennedy, TX | 0.2592 | 1,031,962 | 0.0667 | 67,413 | 123,603 | 56190 |
| Manson, IA | 0.2664 | 692,892 | 0.5926 | 37,288 | 69,914 | 32626 |
| Toluca, IL | 0.375 | 681,173 | 0.0715 | | | |
| Stuart, FL | 0.4 | 1,574,796 | | 52,398 | | |
| Ocracoke, NC | 0.43 | 1,678,904 | 0.7812 | 50,135 | 312,267 | 262132 |
| Fairfield, NC | 0.5 | 3,810,758 | 0.1286 | 57,162 | | |
| Tustin, CA | 0.5 | 855,838 | | 60,629 | 318,201 | 257573 |
| Ewa Beach, HI | 0.5 | 6,083,875 | | | | |
| Venice, FL (1) | 0.5 | 1,452,851 | | | | |
| Gasparilla Is., FL | 0.75 | 2,141,960 | 0.0695 | 62,752 | 197,893 | 135140 |
| Dare Co., NC (1) | 1 | 4,628,315 | 0.1048 | | | |
| Nevada, MO | 1 | 6,834,594 | | 143,186 | 418,801 | 275616 |
| Wabasso, FL | 1 | 2,438,664 | 0.0629 | 68,852 | 202,229 | 133378 |
| Wauchula, FL | 1.31 | 2,761,371 | 0.0743 | | | |
| Jasper, FL | 1.4 | 762,152 | | | | |
| Englewood, FL (2) | 2.5 | 8,254,315 | 0.0715 | 138,141 | 331,158 | 193017 |
| Vero Beach, FL | 2 | 6,764,095 | 0.0743 | 142,766 | | |
| Chandler, AZ | 2.84 | 9,443,425 | 0.0705 | | 1,524,318 | 1524318 |
| Dare Co., NC (2) | 3 | 9,950,800 | 0.0362 | 124,977 | 760,901 | 635924 |
| Barien, IL | 3.2 | 4,763,448 | 0.0715 | 221,884 | 863,051 | 641166 |
| Riverside, CA | 4 | 13,194,750 | 0.0857 | 476,349 | 1,148,002 | 671652 |
| Santa Ana (2) | 4.5 | 6,296,325 | 0.0715 | 352,498 | 701,186 | 348688 |
| Venice, FL (2) | 4 | 8,755,217 | 0.0524 | 424,806 | 823,122 | 398316 |
| Marco Is., FL | 4 | 15,243,032 | | 488,734 | 1,238,508 | 749774 |
| Sarasota, FL | 4.5 | 8,736,163 | 0.0500 | 504,930 | 1,778,081 | 1273151 |
| Melbourne, FL (2) | 5 | 13,128,061 | | | | |
| Jupiter, FL | 6 | 11,512,300 | 0.0562 | 234,006 | 1,138,809 | 904803 |
| Mt. Pleasant, SC | 6.85 | 8,764,743 | 0.0476 | 504,930 | 1,710,540 | 1205609 |
| Cape Coral, FL | 15 | 22,864,548 | 0.0476 | 5,430,381 | 1,794,490 | |
| Horizon city, TX | 1 | 6,000,000 | | | | |
| Scottsdale, AZ | 13 | 30,000,000 | | | | |
| Ettouney et al. | 0.2642 | 924,000 | | 1,710,000 | | |
| Ettouney et al. | 8.4544 | 53,300,000 | | 6,261,000 | | |
| Ettouney et al. | 10 | 49,700,000 | | 4,300,000 | | |
| Ettouney et al. (*28*) | 25 | 98,000,000 | | | | |
| Hydrotec estimate | 1 | 2,500,000 | | | | |

| **Plant** | **Capacity, MGD** | **Total capital** | **Cost of power, $/kWh** | **Annual power costs** | **Total annual O&M** | **O&M - power** |
|---|---|---|---|---|---|---|
| Hydrotec estimate | 10 | 25,000,000 | | | | |
| Bick, Oron | 8 | 1,191,178 | | | | |
| Bick, Oron | 8 | 1,202,310 | | | | |
| Bick, Oron | 8 | 1,180,045 | | | | |
| Bick, Oron | 8 | 1,202,310 | | | | |
| Bick, Oron | 8 | 1,291,370 | | | | |
| Bick, Oron | 8 | 1,335,900 | | | | |
| Bick, Oron | 8 | 1,124,383 | | | | |
| Bick, Oron (*33*) | 8 | 1,191,178 | | | | |
| Schoeman, Steyn | 21 | 31,800,000 | | | | |
| Schoeman, Steyn | 21 | 35,000,000 | | | | |
| Schoeman, Steyn | 12 | 20,400,000 | | | | 7062750 |
| Schoeman, Steyn | 12 | 22,700,000 | | | | 11628900 |
| Schoeman, Steyn (*34*) | 12 | 24,000,000 | | | | 14470425 |

I personally visited Horizon City, where I collected data and toured the facility. Data for Scottsdale, AZ and "Hydrotec estimate" were collected through telephone and e-mail correspondence. The remaining data in this section was taken from published literature.

# Appendix 3: Power costs for RO base system

## Electricity costs for 1 MGD RO base system

| | | | |
|---|---|---|---|
| RO plant size, MGD | 1 | Annual production, 1000 gallons | 379,600 |
| Base rate, $/kWh | 0.12 | Required energy, kWh/1000 gal | 5 |
| Interest | 6% | | |

| Year | Fuel esc. Rate | Adj Fuel rate | Annual kWh | Cost | Adj for PV | Adj Cost |
|---|---|---|---|---|---|---|
| 1 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.9434 | $214,868 |
| 2 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.8900 | $202,706 |
| 3 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.8396 | $191,232 |
| 4 | 0.9773 | 0.1173 | 1,898,000 | $222,590 | 0.7921 | $176,312 |
| 5 | 0.9773 | 0.1173 | 1,898,000 | $222,590 | 0.7473 | $166,332 |
| 6 | 0.9773 | 0.1173 | 1,898,000 | $222,590 | 0.7050 | $156,917 |
| 7 | 0.9773 | 0.1173 | 1,898,000 | $222,590 | 0.6651 | $148,035 |
| 8 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.6274 | $142,899 |
| 9 | 0.9773 | 0.1173 | 1,898,000 | $222,590 | 0.5919 | $131,751 |
| 10 | 0.9773 | 0.1173 | 1,898,000 | $222,590 | 0.5584 | $124,293 |
| 11 | 0.9773 | 0.1173 | 1,898,000 | $222,590 | 0.5268 | $117,258 |
| 12 | 0.9773 | 0.1173 | 1,898,000 | $222,590 | 0.4970 | $110,620 |
| 13 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.4688 | $106,783 |
| 14 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.4423 | $100,738 |
| 15 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.4173 | $95,036 |
| 16 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.3936 | $89,657 |
| 17 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.3714 | $84,582 |
| 18 | 1.0000 | 0.1200 | 1,898,000 | $227,760 | 0.3503 | $79,794 |
| 19 | 1.0227 | 0.1227 | 1,898,000 | $232,930 | 0.3305 | $76,986 |
| 20 | 1.0227 | 0.1227 | 1,898,000 | $232,930 | 0.3118 | $72,629 |
| 21 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.2942 | $70,045 |
| 22 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.2775 | $66,080 |
| 23 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.2618 | $62,340 |
| 24 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.2470 | $58,811 |
| 25 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.2330 | $55,482 |
| 26 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.2198 | $52,342 |
| 27 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.2074 | $49,379 |
| 28 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.1956 | $46,584 |
| 29 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.1846 | $43,947 |
| 30 | 1.0455 | 0.1255 | 1,898,000 | $238,123 | 0.1741 | $41,460 |

| | |
|---|---|
| Total PV | $3,135,899 |
| A/P,6%,30 | 0.07264891 |
| | |
| Annuity of PV | $227,820 |

**Electricity costs for 10 MGD RO base system**

| | | | |
|---|---|---|---|
| RO plant size, MGD | 10 | Annual production | |
| Base rate, $/kWh | 0.12 | 1000 gallons | 3,650,000 |
| Interest | 6% | Required energy, kWh | 5 |

| Year | Fuel esc. Rate | Adj Fuel rate | Annual kWh | Cost | Adj for PV | Adj Cost |
|---|---|---|---|---|---|---|
| 1 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.9434 | $2,066,038 |
| 2 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.8900 | $1,949,092 |
| 3 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.8396 | $1,838,766 |
| 4 | 0.9773 | 0.1173 | 18,250,000 | $2,140,287 | 0.7921 | $1,695,308 |
| 5 | 0.9773 | 0.1173 | 18,250,000 | $2,140,287 | 0.7473 | $1,599,347 |
| 6 | 0.9773 | 0.1173 | 18,250,000 | $2,140,287 | 0.7050 | $1,508,818 |
| 7 | 0.9773 | 0.1173 | 18,250,000 | $2,140,287 | 0.6651 | $1,423,413 |
| 8 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.6274 | $1,374,033 |
| 9 | 0.9773 | 0.1173 | 18,250,000 | $2,140,287 | 0.5919 | $1,266,833 |
| 10 | 0.9773 | 0.1173 | 18,250,000 | $2,140,287 | 0.5584 | $1,195,125 |
| 11 | 0.9773 | 0.1173 | 18,250,000 | $2,140,287 | 0.5268 | $1,127,476 |
| 12 | 0.9773 | 0.1173 | 18,250,000 | $2,140,287 | 0.4970 | $1,063,657 |
| 13 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.4688 | $1,026,757 |
| 14 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.4423 | $968,639 |
| 15 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.4173 | $913,810 |
| 16 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.3936 | $862,085 |
| 17 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.3714 | $813,288 |
| 18 | 1.0000 | 0.1200 | 18,250,000 | $2,190,000 | 0.3503 | $767,253 |
| 19 | 1.0227 | 0.1227 | 18,250,000 | $2,239,713 | 0.3305 | $740,254 |
| 20 | 1.0227 | 0.1227 | 18,250,000 | $2,239,713 | 0.3118 | $698,353 |
| 21 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.2942 | $673,511 |
| 22 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.2775 | $635,388 |
| 23 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.2618 | $599,423 |
| 24 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.2470 | $565,493 |
| 25 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.2330 | $533,484 |
| 26 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.2198 | $503,287 |
| 27 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.2074 | $474,799 |
| 28 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.1956 | $447,924 |
| 29 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.1846 | $422,569 |
| 30 | 1.0455 | 0.1255 | 18,250,000 | $2,289,645 | 0.1741 | $398,650 |

| | |
|---|---|
| Total PV | $30,152,876 |
| A/P,6%,30 | 0.07264891 |
| Annuity of PV | $2,190,574 |

# Appendix 4: Capital cost calculations

**Evaporation pond capital cost calculations**

**Total unit area capital cost ($/acre) = 5406 + 465 x liner thickness + 1.07 x land cost + 0.931 x land clearing cost + 217.5 x dike height**

**Total area = 1.2 x evaporative area x (1 + 0.155 x dike height/sqrt(evaporative area))**

**Total area calculations**

| | 1MGD Plant | 10 MGD Plant |
|---|---|---|
| Evaporative area, acres: | 15 | 150 |
| Dike height, ft | Total area, acres | Total area, acres |
| 4 | 21 | 228 |
| 8 | 24 | 234 |
| 12 | 27 | 241 |

**Unit area capital cost calculations**

| | |
|---|---|
| Land clearing cost, $/acre | 1000 |
| Liner thickness, mils | 50 |

**1 MGD plant**

| | Dike height, ft | | |
|---|---|---|---|
| Land cost, $/acre | 4 | 8 | 12 |
| 0 | $30,457 | $31,327 | $32,197 |
| 1000 | $31,527 | $32,397 | $33,267 |
| 5000 | $35,807 | $36,677 | $37,547 |
| 10000 | $41,157 | $42,027 | $42,897 |

**10 MGD plant**

| | Dike height, ft | | |
|---|---|---|---|
| Land cost, $/acre | 4 | 8 | 12 |
| 0 | $30,457 | $31,327 | $32,197 |
| 1000 | $31,527 | $32,397 | $33,267 |
| 5000 | $35,807 | $36,677 | $37,547 |
| 10000 | $41,157 | $42,027 | $42,897 |

**Total capital cost calculations**

**1 MGD plant**

| Land cost, $/acre | Dike height, ft<br>4 | 8 | 12 |
|---|---|---|---|
| 0 | $635,988 | $744,423 | $857,873 |
| 1000 | $658,331 | $769,850 | $886,383 |
| 5000 | $747,704 | $871,556 | $1,000,421 |
| 10000 | $859,420 | $998,688 | $1,142,969 |

**10 MGD plant**

| Land cost, $/acre | Dike height, ft<br>4 | 8 | 12 |
|---|---|---|---|
| 0 | $6,931,056 | $7,334,676 | $7,749,716 |
| 1000 | $7,174,555 | $7,585,198 | $8,007,262 |
| 5000 | $8,148,548 | $8,587,286 | $9,037,445 |
| 10000 | $9,366,040 | $9,839,896 | $10,325,173 |

**Deep well injection cost calculations**

**Total capital cost ($) = (-288 + 145.9 x well diameter + 0.754 x well depth) x 1000**

| Plant capacity | Reject flow rate, MGD | Possible well diameters, in |
|---|---|---|
| 1 MGD | 0.26 | 4 |
| | | 6 |
| | | 10 |
| | | 12 |
| | | 16 |
| | | 20 |
| | | 24 |
| 10 MGD | 2.5 | 10 |
| | | 12 |
| | | 16 |
| | | 20 |
| | | 24 |

**1 MGD plant capital costs**

| Well diameter, in | Well depth, ft<br>2,500 | 5,000 | 7,500 | 10,000 |
|---|---|---|---|---|
| 4 | $2,180,600 | $4,065,600 | $5,950,600 | $7,835,600 |
| 6 | $2,472,400 | $4,357,400 | $6,242,400 | $8,127,400 |
| 10 | $3,056,000 | $4,941,000 | $6,826,000 | $8,711,000 |
| 12 | $3,347,800 | $5,232,800 | $7,117,800 | $9,002,800 |
| 16 | $3,931,400 | $5,816,400 | $7,701,400 | $9,586,400 |
| 20 | $4,515,000 | $6,400,000 | $8,285,000 | $10,170,000 |
| 24 | $5,098,600 | $6,983,600 | $8,868,600 | $10,753,600 |

**10 MGD plant capital costs**

| | Well depth, ft | | | |
|---|---|---|---|---|
| Well diameter, in | 2,500 | 5,000 | 7,500 | 10000 |
| 12 | $3,347,800 | $5,232,800 | $7,117,800 | $9,002,800 |
| 16 | $3,931,400 | $5,816,400 | $7,701,400 | $9,586,400 |
| 20 | $4,515,000 | $6,400,000 | $8,285,000 | $10,170,000 |
| 24 | $5,098,600 | $6,983,600 | $8,868,600 | $10,753,600 |

**Solar pond capital costs for 1 MGD RO/.4 MGD MSF**

**Start-up costs, $**

Total area per pond, m2: 10,000

| | Land cost (for 45 acres) | | | | | |
|---|---|---|---|---|---|---|
| | $45,000 | | $225,000 | | $450,000 | |
| Liner cost ($/m2): | $4.00 | $15.00 | $4.00 | $15.00 | $4.00 | $15.00 |
| Liner, $/pond | $73,008 | $273,780 | $73,008 | $273,780 | $73,008 | $273,780 |
| Excavation, $/pond | $107,487 | $107,487 | $107,487 | $107,487 | $107,487 | $107,487 |
| Wave control, $/pond | $12,100 | $12,100 | $12,100 | $12,100 | $12,100 | $12,100 |
| HX equipment, $/pond | $18,100 | $18,100 | $18,100 | $18,100 | $18,100 | $18,100 |
| Fencing, $ total | $36,257 | $36,257 | $36,257 | $36,257 | $36,257 | $36,257 |
| Engineering, $ total | $2,470 | $4,477 | $2,470 | $4,477 | $2,470 | $4,477 |

**Phased pond construction**

**Capital costs, liner cost = $4.00**

| Land cost: | $45,000 | | $225,000 | | $450,000 | |
|---|---|---|---|---|---|---|
| | Capital cost | Present value of capital | Capital cost | Present value of capital | Capital cost | Present value of capital |
| Year | | | | | | |
| 1 | $294,422 | $277,756 | $474,422 | $447,567 | $699,422 | $659,832 |
| 5 | $842,780 | $629,774 | $842,780 | $629,774 | $842,780 | $629,774 |
| 10 | $1,053,475 | $588,255 | $1,053,475 | $588,255 | $1,053,475 | $588,255 |
| 15 | $1,053,475 | $439,578 | $1,053,475 | $439,578 | $1,053,475 | $439,578 |
| **Total capital cost:** | | **$1,935,364** | | **$2,105,175** | | **$2,317,439** |

**Capital costs, liner cost = $15.00**

| Land cost: | $45,000 | | $225,000 | | $450,000 | |
|---|---|---|---|---|---|---|
| | Capital cost | Present value of capital | Capital cost | Present value of capital | Capital cost | Present value of capital |
| Year | | | | | | |
| 1 | $497,201 | $469,058 | $677,201 | $638,869 | $902,201 | $851,133 |
| 5 | $1,645,868 | $1,229,888 | $1,645,868 | $1,229,888 | $1,645,868 | $1,229,888 |
| 10 | $2,057,335 | $1,148,805 | $2,057,335 | $1,148,805 | $2,057,335 | $1,148,805 |
| 15 | $2,057,335 | $858,454 | $2,057,335 | $858,454 | $2,057,335 | $858,454 |
| **Total capital cost:** | | **$3,706,205** | | **$3,876,017** | | **$4,088,281** |

**Solar pond capital costs for 10 MGD RO/3.9 MGD MSF**

**Start-up costs, $**

Total area per pond, m2: 100,000

| | Land cost (for 410 acres) | | | | | |
|---|---|---|---|---|---|---|
| | $0 | | $2,050,000 | | $4,100,000 | |
| Liner cost ($/m2): | $4.00 | $15.00 | $4.00 | $15.00 | $4.00 | $15.00 |
| Liner, $/pond | $675,124 | $2,531,715 | $675,124 | $2,531,715 | $675,124 | $2,531,715 |
| Excavation, $/pond | $885,352 | $885,352 | $885,352 | $885,352 | $885,352 | $885,352 |
| Wave control, $/pond | $121,000 | $121,000 | $121,000 | $121,000 | $121,000 | $121,000 |
| HX equipment, $/pond | $181,000 | $181,000 | $181,000 | $181,000 | $181,000 | $181,000 |
| Fencing, $ total | $109,961 | $109,961 | $109,961 | $109,961 | $109,961 | $109,961 |
| Engineering, $ total | $19,724 | $38,290 | $19,724 | $38,290 | $19,724 | $38,290 |

**Phased pond construction**

**Capital costs, liner cost = $4.00**

| Land cost: | $0 | | $2,050,000 | | $4,100,000 | |
|---|---|---|---|---|---|---|
| | Capital cost | Present value of capital | Capital cost | Present value of capital | Capital cost | Present value of capital |
| Year | | | | | | |
| 1 | $1,992,161 | $1,879,397 | $4,042,161 | $3,813,359 | $6,092,161 | $5,747,322 |
| 5 | $7,449,904 | $5,567,002 | $7,449,904 | $5,567,002 | $7,449,904 | $5,567,002 |
| 10 | $9,312,380 | $5,199,984 | $9,312,380 | $5,199,984 | $9,312,380 | $5,199,984 |
| 13 | $9,312,380 | $4,366,007 | $9,312,380 | $4,366,007 | $9,312,380 | $4,366,007 |
| **Total capital cost:** | | **$17,012,390** | | **$18,946,352** | | **$20,880,315** |

**Capital costs, liner cost = $15.00**

| Land cost: | $0 | | $2,050,000 | | $4,100,000 | |
|---|---|---|---|---|---|---|
| | Capital cost | Present value of capital | Capital cost | Present value of capital | Capital cost | Present value of capital |
| Year | | | | | | |
| 1 | $3,867,318 | $3,648,413 | $5,917,318 | $5,582,375 | $7,967,318 | $7,516,338 |
| 5 | $14,876,268 | $11,116,413 | $14,876,268 | $11,116,413 | $14,876,268 | $11,116,413 |
| 10 | $18,595,335 | $10,383,538 | $18,595,335 | $10,383,538 | $18,595,335 | $10,383,538 |
| 13 | $11,157,201 | $5,230,931 | $11,157,201 | $5,230,931 | $11,157,201 | $5,230,931 |
| **Total capital cost:** | | **$30,379,295** | | **$32,313,257** | | **$34,247,220** |

**ORCE acquisition, 1 MGD plant**

Annual kWh required: 2,325,050

Total kW installed: 295

| Year | kW purchased | $/kW | Capital required | Present Value of Capital |
|---|---|---|---|---|
| 5 | 295 | $2,300 | $678,287 | $506,856 |

Total engine capital: **$506,856**

**ORCE acquisition, 10 MGD plant**

Annual kWh required: 22,356,250

Total kW installed: 2,836

| Year | kW purchased | $/kW | Capital required | Present Value of Capital |
|---|---|---|---|---|
| 5 | 1000 | $1,700 | $1,700,000 | $1,270,339 |
| 9 | 1000 | $1,700 | $1,700,000 | $1,006,227 |
| 13 | 836 | $1,700 | $1,421,200 | $666,314 |

Total engine capital: **$2,942,880**

# Appendix 5: Solar pond energy requirements

| **Energy Requirements for 1 MGD RO/.4 MGD MSF** | | annual RO production: | 379,600 | kgal |
|---|---|---|---|---|
| | | annual MSF production: | 85,410 | kgal |
| (assuming 3,000 ppm feedwater) | | | | |
| RO energy requirements, kWh/1000 gal: | 5 | | | |
| MSF energy requirements, kWh/1000 gal: | 5 | GJ/1000 gal: | 0.66 | |
| GJ to kWh conversion efficiency: | 7% | | | |

| | | Thermal energy (GJ) | | | GJ available | Electrical energy (kWh) | | |
|---|---|---|---|---|---|---|---|---|
| Year | Pond size, $m^2$ | Supplied | Required | Purchased | for electricity | Supplied | Required | Purchased |
| 1 | 10,000 | 0 | 56,371 | 56,371 | 0 | 0 | 2,325,050 | 2,325,050 |
| 2 | 20,000 | 13,335 | 56,371 | 43,036 | 0 | 0 | 2,325,050 | 2,325,050 |
| 3 | 30,000 | 26,670 | 56,371 | 29,701 | 0 | 0 | 2,325,050 | 2,325,050 |
| 4 | 40,000 | 40,005 | 56,371 | 16,366 | 0 | 0 | 2,325,050 | 2,325,050 |
| 5 | 50,000 | 53,340 | 56,371 | 3,031 | 0 | 0 | 2,325,050 | 2,325,050 |
| 6 | 60,000 | 66,675 | 56,371 | (10,304) | 10,304 | 200,363 | 2,325,050 | 2,124,687 |
| 7 | 70,000 | 80,010 | 56,371 | (23,639) | 23,639 | 459,655 | 2,325,050 | 1,865,395 |
| 8 | 80,000 | 93,345 | 56,371 | (36,974) | 36,974 | 718,947 | 2,325,050 | 1,606,103 |
| 9 | 90,000 | 106,680 | 56,371 | (50,309) | 50,309 | 978,238 | 2,325,050 | 1,346,812 |
| 10 | 100,000 | 120,015 | 56,371 | (63,644) | 63,644 | 1,237,530 | 2,325,050 | 1,087,520 |
| 11 | 110,000 | 133,350 | 56,371 | (76,979) | 76,979 | 1,496,822 | 2,325,050 | 828,228 |
| 12 | 120,000 | 146,685 | 56,371 | (90,314) | 90,314 | 1,756,113 | 2,325,050 | 568,937 |
| 13 | 130,000 | 160,020 | 56,371 | (103,649) | 103,649 | 2,015,405 | 2,325,050 | 309,645 |
| 14 | 140,000 | 173,355 | 56,371 | (116,984) | 116,984 | 2,274,697 | 2,325,050 | 50,353 |
| **15** | 150,000 | 186,690 | 56,371 | (130,319) | 130,319 | 2,533,988 | 2,325,050 | (208,938) |
| 16 | 160,000 | 200,025 | 56,371 | (143,654) | 143,654 | 2,793,280 | 2,325,050 | (468,230) |
| 17 | 170,000 | 213,360 | 56,371 | (156,989) | 156,989 | 3,052,572 | 2,325,050 | (727,522) |
| 18 | 180,000 | 226,695 | 56,371 | (170,324) | 170,324 | 3,311,863 | 2,325,050 | (986,813) |
| 19 | 190,000 | 240,030 | 56,371 | (183,659) | 183,659 | 3,571,155 | 2,325,050 | (1,246,105) |
| 20 | 200,000 | 253,365 | 56,371 | (196,994) | 196,994 | 3,830,447 | 2,325,050 | (1,505,397) |
| 21 | 210,000 | 266,700 | 56,371 | (210,329) | 210,329 | 4,089,738 | 2,325,050 | (1,764,688) |
| 22 | 220,000 | 280,035 | 56,371 | (223,664) | 223,664 | 4,349,030 | 2,325,050 | (2,023,980) |
| 23 | 230,000 | 293,370 | 56,371 | (236,999) | 236,999 | 4,608,322 | 2,325,050 | (2,283,272) |
| 24 | 240,000 | 306,705 | 56,371 | (250,334) | 250,334 | 4,867,613 | 2,325,050 | (2,542,563) |
| 25 | 250,000 | 320,040 | 56,371 | (263,669) | 263,669 | 5,126,905 | 2,325,050 | (2,801,855) |
| 26 | 260,000 | 333,375 | 56,371 | (277,004) | 277,004 | 5,386,197 | 2,325,050 | (3,061,147) |
| 27 | 270,000 | 346,710 | 56,371 | (290,339) | 290,339 | 5,645,488 | 2,325,050 | (3,320,438) |
| 28 | 280,000 | 360,045 | 56,371 | (303,674) | 303,674 | 5,904,780 | 2,325,050 | (3,579,730) |
| 29 | 290,000 | 373,380 | 56,371 | (317,009) | 317,009 | 6,164,072 | 2,325,050 | (3,839,022) |
| 30 | 300,000 | 386,715 | 56,371 | (330,344) | 330,344 | 6,423,363 | 2,325,050 | (4,098,313) |

**Energy Requirements for 10 MGD RO/3.9 MGD MSF**

annual RO production: 3,650,000 kgal
annual MSF production: 821,250 kgal

(assuming 3,000 ppm feedwater)
RO energy requirements, kWh/1000 gal: 5
MSF energy requirements, kWh/1000 gal: 5
GJ/1000 gal: 0.66
GJ to kWh conversion efficiency: 8%

| Year | Pond size, m$^2$ | Thermal energy (GJ) | | | GJ available for electricity | Electrical energy (kWh) | | |
|---|---|---|---|---|---|---|---|---|
| | | Supplied | Required | Purchased | | Supplied | Required | Purchased |
| 1 | 100,000 | 0 | 542,025 | 542,025 | 0 | 0 | 22,356,250 | 22,356,250 |
| 2 | 200,000 | 133,354 | 542,025 | 408,671 | 0 | 0 | 22,356,250 | 22,356,250 |
| 3 | 300,000 | 266,708 | 542,025 | 275,317 | 0 | 0 | 22,356,250 | 22,356,250 |
| 4 | 400,000 | 400,062 | 542,025 | 141,963 | 0 | 0 | 22,356,250 | 22,356,250 |
| 5 | 500,000 | 533,416 | 542,025 | 8,609 | 0 | 0 | 22,356,250 | 22,356,250 |
| 6 | 600,000 | 666,770 | 542,025 | (124,745) | 124,745 | 2,772,111 | 22,356,250 | 19,584,139 |
| 7 | 700,000 | 800,124 | 542,025 | (258,099) | 258,099 | 5,735,533 | 22,356,250 | 16,620,717 |
| 8 | 800,000 | 933,478 | 542,025 | (391,453) | 391,453 | 8,698,956 | 22,356,250 | 13,657,294 |
| 9 | 900,000 | 1,066,832 | 542,025 | (524,807) | 524,807 | 11,662,378 | 22,356,250 | 10,693,872 |
| 10 | 1,000,000 | 1,200,186 | 542,025 | (658,161) | 658,161 | 14,625,800 | 22,356,250 | 7,730,450 |
| 11 | 1,100,000 | 1,333,540 | 542,025 | (791,515) | 791,515 | 17,589,222 | 22,356,250 | 4,767,028 |
| 12 | 1,200,000 | 1,466,894 | 542,025 | (924,869) | 924,869 | 20,552,644 | 22,356,250 | 1,803,606 |
| **13** | 1,300,000 | 1,600,248 | 542,025 | (1,058,223) | 1,058,223 | 23,516,067 | 22,356,250 | (1,159,817) |
| 14 | 1,400,000 | 1,733,602 | 542,025 | (1,191,577) | 1,191,577 | 26,479,489 | 22,356,250 | (4,123,239) |
| 15 | 1,500,000 | 1,866,956 | 542,025 | (1,324,931) | 1,324,931 | 29,442,911 | 22,356,250 | (7,086,661) |
| 16 | 1,600,000 | 2,000,310 | 542,025 | (1,458,285) | 1,458,285 | 32,406,333 | 22,356,250 | (10,050,083) |
| 17 | 1,700,000 | 2,133,664 | 542,025 | (1,591,639) | 1,591,639 | 35,369,756 | 22,356,250 | (13,013,506) |
| 18 | 1,800,000 | 2,267,018 | 542,025 | (1,724,993) | 1,724,993 | 38,333,178 | 22,356,250 | (15,976,928) |
| 19 | 1,900,000 | 2,400,372 | 542,025 | (1,858,347) | 1,858,347 | 41,296,600 | 22,356,250 | (18,940,350) |
| 20 | 2,000,000 | 2,533,726 | 542,025 | (1,991,701) | 1,991,701 | 44,260,022 | 22,356,250 | (21,903,772) |
| 21 | 2,100,000 | 2,667,080 | 542,025 | (2,125,055) | 2,125,055 | 47,223,444 | 22,356,250 | (24,867,194) |
| 22 | 2,200,000 | 2,800,434 | 542,025 | (2,258,409) | 2,258,409 | 50,186,867 | 22,356,250 | (27,830,617) |
| 23 | 2,300,000 | 2,933,788 | 542,025 | (2,391,763) | 2,391,763 | 53,150,289 | 22,356,250 | (30,794,039) |
| 24 | 2,400,000 | 3,067,142 | 542,025 | (2,525,117) | 2,525,117 | 56,113,711 | 22,356,250 | (33,757,461) |
| 25 | 2,500,000 | 3,200,496 | 542,025 | (2,658,471) | 2,658,471 | 59,077,133 | 22,356,250 | (36,720,883) |
| 26 | 2,600,000 | 3,333,850 | 542,025 | (2,791,825) | 2,791,825 | 62,040,556 | 22,356,250 | (39,684,306) |
| 27 | 2,700,000 | 3,467,204 | 542,025 | (2,925,179) | 2,925,179 | 65,003,978 | 22,356,250 | (42,647,728) |
| 28 | 2,800,000 | 3,600,558 | 542,025 | (3,058,533) | 3,058,533 | 67,967,400 | 22,356,250 | (45,611,150) |
| 29 | 2,900,000 | 3,733,912 | 542,025 | (3,191,887) | 3,191,887 | 70,930,822 | 22,356,250 | (48,574,572) |
| 30 | 3,000,000 | 3,867,266 | 542,025 | (3,325,241) | 3,325,241 | 73,894,244 | 22,356,250 | (51,537,994) |

# Appendix 6: Power costs for solar pond/RO/MSF system

**Electrical energy costs for 1 MGD RO/.4 MGD MSF using solar ponds**

| | |
|---|---|
| RO plant size, MGD | 1 |
| Base rate, $/kWh | $0.1200 |
| Interest | 6% |

| Year | Fuel esc. Rate | Adj Fuel rate | Annual kWh | Cost | Adj for PV | Adj Cost |
|---|---|---|---|---|---|---|
| 1 | 1.0000 | 0.1200 | 2,325,050 | $279,006 | 0.9434 | $263,213 |
| 2 | 1.0000 | 0.1200 | 2,325,050 | $279,006 | 0.8900 | $248,314 |
| 3 | 1.0000 | 0.1200 | 2,325,050 | $279,006 | 0.8396 | $234,259 |
| 4 | 0.9773 | 0.1173 | 2,325,050 | $272,673 | 0.7921 | $215,982 |
| 5 | 0.9773 | 0.1173 | 2,325,050 | $272,673 | 0.7473 | $203,757 |
| 6 | 0.9773 | 0.1173 | 2,124,687 | $249,175 | 0.7050 | $175,658 |
| 7 | 0.9773 | 0.1173 | 1,865,395 | $218,766 | 0.6651 | $145,492 |
| 8 | 1.0000 | 0.1200 | 1,606,103 | $192,732 | 0.6274 | $120,923 |
| 9 | 0.9773 | 0.1173 | 1,346,812 | $157,949 | 0.5919 | $93,490 |
| 10 | 0.9773 | 0.1173 | 1,087,520 | $127,540 | 0.5584 | $71,218 |
| 11 | 0.9773 | 0.1173 | 828,228 | $97,131 | 0.5268 | $51,168 |
| 12 | 0.9773 | 0.1173 | 568,937 | $66,723 | 0.4970 | $33,159 |
| 13 | 1.0000 | 0.1200 | 309,645 | $37,157 | 0.4688 | $17,421 |
| 14 | 1.0000 | 0.1200 | 50,353 | $6,042 | 0.4423 | $2,673 |
| 15 | 1.0000 | 0.1200 | 0 | $0 | 0.4173 | $0 |
| 16 | 1.0000 | 0.1200 | 0 | $0 | 0.3936 | $0 |
| 17 | 1.0000 | 0.1200 | 0 | $0 | 0.3714 | $0 |
| 18 | 1.0000 | 0.1200 | 0 | $0 | 0.3503 | $0 |
| 19 | 1.0227 | 0.1227 | 0 | $0 | 0.3305 | $0 |
| 20 | 1.0227 | 0.1227 | 0 | $0 | 0.3118 | $0 |
| 21 | 1.0455 | 0.1255 | 0 | $0 | 0.2942 | $0 |
| 22 | 1.0455 | 0.1255 | 0 | $0 | 0.2775 | $0 |
| 23 | 1.0455 | 0.1255 | 0 | $0 | 0.2618 | $0 |
| 24 | 1.0455 | 0.1255 | 0 | $0 | 0.2470 | $0 |
| 25 | 1.0455 | 0.1255 | 0 | $0 | 0.2330 | $0 |
| 26 | 1.0455 | 0.1255 | 0 | $0 | 0.2198 | $0 |
| 27 | 1.0455 | 0.1255 | 0 | $0 | 0.2074 | $0 |
| 28 | 1.0455 | 0.1255 | 0 | $0 | 0.1956 | $0 |
| 29 | 1.0455 | 0.1255 | 0 | $0 | 0.1846 | $0 |
| 30 | 1.0455 | 0.1255 | 0 | $0 | 0.1741 | $0 |

| | |
|---|---|
| Total PV | $1,876,726 |
| A/P,6%,30 | 0.0726489 |
| Annuity of PV | $136,342 |

**Thermal energy costs for 1 MGD RO/.4 MGD MSF using solar ponds**

| | |
|---|---|
| RO plant size, MGD | 1 |
| Base rate, $/GJ | $1.50 |
| Interest | 6% |

| Year | Fuel esc. Rate | Adj Fuel rate | Annual GJ | Cost | Adj for PV | Adj Cost |
|---|---|---|---|---|---|---|
| 1 | 0.0300 | 1.5000 | 56,371 | $84,556 | 0.9434 | $79,770 |
| 2 | 0.0300 | 1.5450 | 43,036 | $66,490 | 0.8900 | $59,176 |
| 3 | 0.0300 | 1.5914 | 29,701 | $47,264 | 0.8396 | $39,684 |
| 4 | 0.0300 | 1.6391 | 16,366 | $26,825 | 0.7921 | $21,248 |
| 5 | 0.0300 | 1.6883 | 3,031 | $5,116 | 0.7473 | $3,823 |
| 6 | 0.0300 | 1.7389 | 0 | $0 | 0.7050 | $0 |
| 7 | 0.0300 | 1.7911 | 0 | $0 | 0.6651 | $0 |
| 8 | 0.0300 | 1.8448 | 0 | $0 | 0.6274 | $0 |
| 9 | 0.0300 | 1.9002 | 0 | $0 | 0.5919 | $0 |
| 10 | 0.0300 | 1.9572 | 0 | $0 | 0.5584 | $0 |
| 11 | 0.0300 | 2.0159 | 0 | $0 | 0.5268 | $0 |
| 12 | 0.0300 | 2.0764 | 0 | $0 | 0.4970 | $0 |
| 13 | 0.0300 | 2.1386 | 0 | $0 | 0.4688 | $0 |
| 14 | 0.0300 | 2.2028 | 0 | $0 | 0.4423 | $0 |
| 15 | 0.0300 | 2.2689 | 0 | $0 | 0.4173 | $0 |
| 16 | 0.0300 | 2.3370 | 0 | $0 | 0.3936 | $0 |
| 17 | 0.0300 | 2.4071 | 0 | $0 | 0.3714 | $0 |
| 18 | 0.0300 | 2.4793 | 0 | $0 | 0.3503 | $0 |
| 19 | 0.0300 | 2.5536 | 0 | $0 | 0.3305 | $0 |
| 20 | 0.0300 | 2.6303 | 0 | $0 | 0.3118 | $0 |
| 21 | 0.0300 | 2.7092 | 0 | $0 | 0.2942 | $0 |
| 22 | 0.0300 | 2.7904 | 0 | $0 | 0.2775 | $0 |
| 23 | 0.0300 | 2.8742 | 0 | $0 | 0.2618 | $0 |
| 24 | 0.0300 | 2.9604 | 0 | $0 | 0.2470 | $0 |
| 25 | 0.0300 | 3.0492 | 0 | $0 | 0.2330 | $0 |
| 26 | 0.0300 | 3.1407 | 0 | $0 | 0.2198 | $0 |
| 27 | 0.0300 | 3.2349 | 0 | $0 | 0.2074 | $0 |
| 28 | 0.0300 | 3.3319 | 0 | $0 | 0.1956 | $0 |
| 29 | 0.0300 | 3.4319 | 0 | $0 | 0.1846 | $0 |
| 30 | 0.0300 | 3.5348 | 0 | $0 | 0.1741 | $0 |
| | | | | | Total PV | $203,700 |
| | | | | | A/P,6%,30 | 0.072648911 |
| | | | | | Annuity of PV | $14,799 |

**Electrical energy costs for 10 MGD RO/3.9 MGD MSF using solar ponds**

| | |
|---|---|
| RO plant size, MGD | 10 |
| Base rate, $/kWh | $0.1200 |
| Interest | 6% |

| Year | Fuel esc. Rate | Adj Fuel rate | Annual kWh | Cost | Adj for PV | Adj Cost |
|---|---|---|---|---|---|---|
| 1 | 1.0000 | 0.1200 | 22,356,250 | $2,682,750 | 0.9434 | $2,530,896 |
| 2 | 1.0000 | 0.1200 | 22,356,250 | $2,682,750 | 0.8900 | $2,387,638 |
| 3 | 1.0000 | 0.1200 | 22,356,250 | $2,682,750 | 0.8396 | $2,252,489 |
| 4 | 0.9773 | 0.1173 | 22,356,250 | $2,621,852 | 0.7921 | $2,076,752 |
| 5 | 0.9773 | 0.1173 | 22,356,250 | $2,621,852 | 0.7473 | $1,959,200 |
| 6 | 0.9773 | 0.1173 | 19,584,139 | $2,296,749 | 0.7050 | $1,619,118 |
| 7 | 0.9773 | 0.1173 | 16,620,717 | $1,949,211 | 0.6651 | $1,296,337 |
| 8 | 1.0000 | 0.1200 | 13,657,294 | $1,638,875 | 0.6274 | $1,028,251 |
| 9 | 0.9773 | 0.1173 | 10,693,872 | $1,254,135 | 0.5919 | $742,320 |
| 10 | 0.9773 | 0.1173 | 7,730,450 | $906,596 | 0.5584 | $506,239 |
| 11 | 0.9773 | 0.1173 | 4,767,028 | $559,058 | 0.5268 | $294,505 |
| 12 | 0.9773 | 0.1173 | 1,803,606 | $211,520 | 0.4970 | $105,119 |
| 13 | 1.0000 | 0.1200 | 0 | $0 | 0.4688 | $0 |
| 14 | 1.0000 | 0.1200 | 0 | $0 | 0.4423 | $0 |
| 15 | 1.0000 | 0.1200 | 0 | $0 | 0.4173 | $0 |
| 16 | 1.0000 | 0.1200 | 0 | $0 | 0.3936 | $0 |
| 17 | 1.0000 | 0.1200 | 0 | $0 | 0.3714 | $0 |
| 18 | 1.0000 | 0.1200 | 0 | $0 | 0.3503 | $0 |
| 19 | 1.0227 | 0.1227 | 0 | $0 | 0.3305 | $0 |
| 20 | 1.0227 | 0.1227 | 0 | $0 | 0.3118 | $0 |
| 21 | 1.0455 | 0.1255 | 0 | $0 | 0.2942 | $0 |
| 22 | 1.0455 | 0.1255 | 0 | $0 | 0.2775 | $0 |
| 23 | 1.0455 | 0.1255 | 0 | $0 | 0.2618 | $0 |
| 24 | 1.0455 | 0.1255 | 0 | $0 | 0.2470 | $0 |
| 25 | 1.0455 | 0.1255 | 0 | $0 | 0.2330 | $0 |
| 26 | 1.0455 | 0.1255 | 0 | $0 | 0.2198 | $0 |
| 27 | 1.0455 | 0.1255 | 0 | $0 | 0.2074 | $0 |
| 28 | 1.0455 | 0.1255 | 0 | $0 | 0.1956 | $0 |
| 29 | 1.0455 | 0.1255 | 0 | $0 | 0.1846 | $0 |
| 30 | 1.0455 | 0.1255 | 0 | $0 | 0.1741 | $0 |

| | |
|---|---|
| Total PV | $16,798,862 |
| A/P,6%,30 | 0.07264891 |
| Annuity of PV | $1,220,419 |

**Thermal energy costs for 10 MGD RO/3.9 MGD MSF using solar ponds**

| | |
|---|---|
| RO plant size, MGD | 10 |
| Base rate, $/GJ | $1.50 |
| Interest | 0% |

| Year | Fuel esc. Rate | Adj Fuel rate | Annual GJ | Cost | Adj for PV | Adj Cost |
|---|---|---|---|---|---|---|
| 1 | 0.0300 | 1.5000 | 542,025 | $813,038 | 1.0000 | $813,038 |
| 2 | 0.0300 | 1.5450 | 408,671 | $631,397 | 1.0000 | $631,397 |
| 3 | 0.0300 | 1.5914 | 275,317 | $438,126 | 1.0000 | $438,126 |
| 4 | 0.0300 | 1.6391 | 141,963 | $232,690 | 1.0000 | $232,690 |
| 5 | 0.0300 | 1.6883 | 8,609 | $14,534 | 1.0000 | $14,534 |
| 6 | 0.0300 | 1.7389 | 0 | $0 | 1.0000 | $0 |
| 7 | 0.0300 | 1.7911 | 0 | $0 | 1.0000 | $0 |
| 8 | 0.0300 | 1.8448 | 0 | $0 | 1.0000 | $0 |
| 9 | 0.0300 | 1.9002 | 0 | $0 | 1.0000 | $0 |
| 10 | 0.0300 | 1.9572 | 0 | $0 | 1.0000 | $0 |
| 11 | 0.0300 | 2.0159 | 0 | $0 | 1.0000 | $0 |
| 12 | 0.0300 | 2.0764 | 0 | $0 | 1.0000 | $0 |
| 13 | 0.0300 | 2.1386 | 0 | $0 | 1.0000 | $0 |
| 14 | 0.0300 | 2.2028 | 0 | $0 | 1.0000 | $0 |
| 15 | 0.0300 | 2.2689 | 0 | $0 | 1.0000 | $0 |
| 16 | 0.0300 | 2.3370 | 0 | $0 | 1.0000 | $0 |
| 17 | 0.0300 | 2.4071 | 0 | $0 | 1.0000 | $0 |
| 18 | 0.0300 | 2.4793 | 0 | $0 | 1.0000 | $0 |
| 19 | 0.0300 | 2.5536 | 0 | $0 | 1.0000 | $0 |
| 20 | 0.0300 | 2.6303 | 0 | $0 | 1.0000 | $0 |
| 21 | 0.0300 | 2.7092 | 0 | $0 | 1.0000 | $0 |
| 22 | 0.0300 | 2.7904 | 0 | $0 | 1.0000 | $0 |
| 23 | 0.0300 | 2.8742 | 0 | $0 | 1.0000 | $0 |
| 24 | 0.0300 | 2.9604 | 0 | $0 | 1.0000 | $0 |
| 25 | 0.0300 | 3.0492 | 0 | $0 | 1.0000 | $0 |
| 26 | 0.0300 | 3.1407 | 0 | $0 | 1.0000 | $0 |
| 27 | 0.0300 | 3.2349 | 0 | $0 | 1.0000 | $0 |
| 28 | 0.0300 | 3.3319 | 0 | $0 | 1.0000 | $0 |
| 29 | 0.0300 | 3.4319 | 0 | $0 | 1.0000 | $0 |
| 30 | 0.0300 | 3.5348 | 0 | $0 | 1.0000 | $0 |

| | |
|---|---|
| Total PV | $2,129,784 |
| A/P,6%,30 | 0.07264891 |
| Annuity of PV | $154,727 |