Title

Solar powered desalination system

Author

Mateo, Tiffany Alisa

Publication Date

2011

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Solar Powered Desalination System

A Thesis submitted in partial satisfaction of the requirements
for the degree Master of Science

in

Chemical Engineering

by

Tiffany Alisa Mateo

Committee in charge:

Professor Deli Wang, Chair
Professor Donald Sirbuly, Co-Chair
Professor Richard Herz

2011

The Thesis of Tiffany Alisa Mateo is approved and it is acceptable in quality and form for publication on microfilm and electronically.

Co-Chair

Chair

Univerisy of California, San Diego

2011

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF GRAPHS

ACKNOWLEDGMENTS

I would like to acknowledge Professor Deli Wang for his support as the chair of my committee. His dedication to this project was evident in the countless meetings discussing ideas and information gathering. I am grateful for his guidance and support.

I would also like to acknowledge Ke Sun, Doctoral student in the Wang Research Group at UCSD. His dedication and suggestions helped me immeasurably. I would not have been able to achieve as much as I did in this project without his support.

ABSTRACT OF THESIS

Solar Powered Desalination System

by

Tiffany Alisa Mateo
Master of Science in Chemical Engineering
University of California, San Diego, 2011
Professor Deli Wang, Chair
Professor Donald Sirbuly, Co-Chair

With the increasing need for fresh water sources, especially in California with its "Water Crisis," coupled with the global "Energy Crisis," there is rising desire for fresh water production through renewable means. A study was conducted to evaluate the most efficient design for a solar powered desalination system. Two basic design types were considered. The first design type is using photoelectrochemical (PEC) cells to produce hydrogen, which would then be used to produce thermal energy to desalinate by distillation. The second design type is using photovoltaics (PV) to produce electrical energy to desalinate by membrane.

The study concluded that a PV-reverse osmosis (RO) system would be the most energy and space efficient. An RO system was assembled and tested to show feasibility. Future work includes powering the RO system using PV and calculating the system efficiency. Focusing on emergency drinking water applications, a single element design was proposed. This single element design is meant for a compact, portable solar powered desalination system.

Chapter 1: Desalination Study

1.1 Water

Water is arguably the most important chemical on Earth; what made life possible. Its simple yet unique chemical properties allow for the cycle and balance of life. Plants, animals, and humans require water for survival. The diversity and proliferation of life on Earth depends on water. Though water covers about 70% of the Earth's surface area, only about 2.5% is fresh water with 80% of this amount frozen in the icecaps or combined as soil moisture.[1] Table 1.1 outlines the distribution of water resources across the globe.

Table 1.1: Distribution of water resources across the globe[1]

Resource	Volume [km^3]	Percentage of total water	Percent of Fresh Water
Atmospheric Water	12,900	0.001	0.01
Glaciers	24,064,000	1.72	68.7
Ground Ice	300,000	0.021	0.86
Rivers	2,120	0.0002	0.006
Lakes	176,400	0.013	0.26
Marshes	11,470	0.0008	0.03
Soil Moisture	16,500	0.0012	0.05
Aquifers	10,530,000	0.75	30.1
Lithosphere	23,400,000	1.68	
Oceans	1,338,000,000	95.81	
Total	1,396,513,390		

Sources of water used by humans throughout history are almost exclusively rivers, lakes, and in more resent human history, aquifers, where ground water can be extracted. These sources combine to less than 1% of all the water on Earth, yet it's been enough to supply the human population for centuries, as well as the vast array of flora and fauna.

Not only is water essential to life as a nutritional requirement, it also serves purposes of agriculture, sanitation, and industrial processes. Types of water can be classified based on the purpose for which it is used. The first grade is set for safe drinking, household purposes, and a number of industrial applications and has a salinity range of 5-1,000 ppm.[1] Water falling under this range has low salinity and can be found in rivers and lakes, or can be generated by desalination processes. On the industrial scale, the most stringent water quality, limited to a maximum salinity of 5ppm, is set by the makeup water for boilers and applications related to the electronic industry and pharmaceuticals.[1] Other industrial applications call for less stringent water quality and include chemical reactions, dairy and food, washing and cleaning, and cooling.[1]

The second water category has a salinity range of 1,000-3,000ppm and is suitable for irrigation purposes and industrial cooling.[1] Water with salinity above 10,000ppm is termed as high salinity water; seawater salinity ranges from 30,000ppm to 50,000ppm and has an average salinity of 34,000ppm, which varies depending on local conditions affected by ambient and topographical condiciotns.[1] Table 1.2 shows the typical composition of seawater as dissolved ions. Seawater includes other suspended materials like sand, clay, microorganisms, viruses, and colloidal matter. The size of these compounds vary over a range of $5x10^{-2}$ to 0.15µm.[1] It is the salinity and the combination of suspended compounds in seawater that makes it not only “undrinkable,” but also not useful for agricultural and industrial purposes.

Table 1.2: Typical composition of seawater with salinity of 36,000ppm[1]

Compound	Composition	Mass Percent	ppm
Chloride	Cl^-	55.03	19,810.8
Sodium	Na^+	30.61	11,019.6

Table 1.2: Continued

Compound	Composition	Mass Percent	ppm
Sulfate	$(SO_4)^{- -}$	7.68	2,764.8
Magnesium	$Mg^{+ +}$	3.69	1,328.4
Calcium	$Ca^{+ +}$	1.16	417.6
Potassium	K^{+}	1.16	417.6
Carbonic Acid	$(CO_3)^{- -}$	0.41	147.6
Bromine	Br^{-}	0.19	68.4
Boric Acid	$H_3BO_3^{-}$	0.07	25.2
Strontium	$Sr^{+ +}$	0.04	14.4
Total		100	36,000

The average per capita consumption of the low salinity drinking water (150ppm) is limited to 2 liters/day while higher salinity water of up to 1,000ppm has a per capita consumption rate of 200-400 liters/day, which is used for cooking, washing, cleaning, gardening, and other purposes.[1] The Agricultural Research and Cooperative Extension at Penn State University determined that household water use is about 70 gallons per person, per day.[3] Table 1.3 breaks down this water use. It's clear that while water is essential for consumption, most water used by people is used for purposes other than purely drinking water. Table 1.4 shows a similar break down of household water use by the America Water Works Association Research Foundation. In addition to residential/domestic use, water is used in other sectors including industrial, commercial, and irrigation. Table 1.5 shows water withdrawals and consumptive water use. Though the specific breakdown and values vary by region, it is shown that many millions of gallons of water are used daily. Water is used to make beverages as well as in beverages. It's used in the production of many goods, the growing of crops, maintaining livestock, and in industrial processes. Table 1.6 shows how much water is required in the processing of common items. Again, it is clear that most of the water we use is not used for consumption.

Table 1.3: Average domestic water use in the United States[3]

Plumbing fixture of appliance	**Use (gal per person per day)**
Toilet	18.5
Clothes washer	15.0
Shower	11.6
Faucets	10.9
Leaks	9.5
Other	1.6
Bath	1.2
Dishwater	1.0
Total	**69.3**

Table 1.4: Mean daily per capita water use, 12 study sites[4]

Fixture/End Use	**Avg. gallons per capita per day**	**Avg. liters per capita per day**	**Indoor use percent**	**Total use percent**
Toilet	18.5	70.0	30.9%	10.8%
Clothes washer	15	56.8	25.1%	8.7%
Shower	11.6	43.9	19.4%	6.8%
Faucet	10.9	41.3	18.2%	6.3%
Other domestic	1.6	6.1	2.7%	0.9%
Bath	1.2	4.5	2.0%	0.7%
Dishwater	1	3.8	1.7%	0.6%
Indoor Total	***59.8***	***226.3***	***100.0%***	***34.8%***
Leak	9.5	36.0	NA	5.5%
Unknown	1.7	6.4	NA	1.0%
Outdoor	100.8	381.5	NA	58.7%
TOTAL	**171.8**	**650.3**	**NA**	**100.0%**

Table 1.5: Total water withdrawals and consumptive water use in Pennsylvania in 1995[3]

Purpose	**Water Use (MGD)**	**Consumptive Use (MGD)**
Thermoelectric	5,930	239
Industrial	1,870	158
Domestic	740	74
Commercial	247	11.5
Mining	182	14
Livestock	55.3	41
Irrigation	15.9	15.9

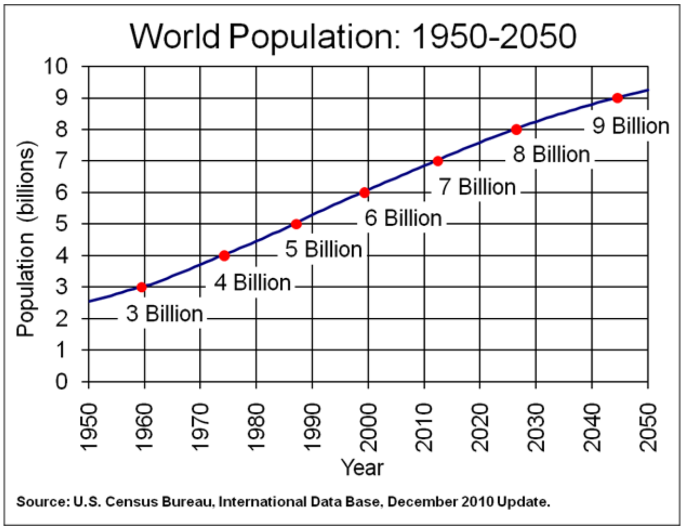
Table 1.6: Water Content of Things[5]

	Liters water
Beverages (per liter)	
Glass of beer	300
Malt beverages (processing)	50
Glass of water	~1
Bottled Water	3-4
Milk	1,000
Milk (processing)	7
Cup of coffee	1,120
Cup of tea	120
Glass of wine	960
Glass of apple juice	950
Glass of orange juice	850
Assorted Produced Goods (per kilogram)	
Roasted coffee	21,000
Tea	9,200
Bread	1,300
Cheese	5,000
Cotton textile finished	11,000
Sheet paper	125
Potato chips	925
Hamburger	16,000
Leather shoes	16,600
Microchip	16,000
Assorted Crops (per kilogram)	
Barley	1,300
Coconut	2,500
Corn	900
Sugar	1,500
Apple	700
Potato	500-1,500
Wheat	900-2,000
Alfalfa	900-2,000
Sorghum	1,100-1,800
Corn/maize	1,000-1,800
Rice	1,900-5,000
Soybeans	1,100-2,000
Assorted Animals (per kilogram of meat)	
Sheep	6,100
Goat	4,000
Beef	15,000-70,000

Table 1.6: Continued

Assorted Animals (per kilogram of meat)	**Liters Water**
Chicken	3,500-5,700
Eggs	3,300
Assorted Industrial Products (per kilogram)	
Steel	260
Primary copper	440
Primary aluminum	410
Phosphatic fertilizer	150
Nitrogenous fertilizer	120
Synthetic rubber	460
Inorganic pigments	410

With growing human population, the need for fresh water increases. The amount of fresh water resources is nearly constant since the start of life on Earth. On the other hand, the world population has increased more rapidly over a period of less than 200 years.[1] Figure 1.1 illustrates the world population growth from 1950 to the projected population in 2050. With such a rapid increase in population while the capacity of fresh water resources remains the same, there is a concern for continued ability for these sources to be enough.



Source: U.S. Census Bureau, International Data Base, December 2010 Update.

Figure 1.1: World Population Growth[2]

Recently, about 40% of the world's population is suffering from serious water shortages, and expected to increase to 60% by the year 2025.[1] Not only is this due to the increase in population, it can be attributed to changes in life-style, increase economic activities, and pollution that limits the use of fresh water sources. Also, aquifers, lakes and rivers are being used as a fresh water source in increasing rates that are proving to be unsustainable and will not be able to support rapidly increasing populations. Not only is water shortage a problem, but the use of unhealthy water in developing countries causes 80-90% of all diseases and 30% of all deaths. Fresh water supply problems are not only due to population increase. In addition to pollution, other environmental factors, such as global warming contribute to fresh water availability. Increase atmospheric temperature can increase ice cap melting, which is a source of water during the summer season. Glacial melting will cause sea level rise and can lead to salt water intrusion on fresh water sources.

The state of California is familiar with the water crisis. The effects of global warming on California's water systems became clearer and increasingly challenging. Not only is California known for its high population and economic activity, it is a largely agricultural state, and water plays a key role in its operations and survival. An eight-year drought on the Colorado River watershed complicated the state's plans for living within its actual allotments from tat over-allocated source. The ecosystem of the Sacramento-San Joaquin Delta has come close to collapse, triggering a large court-ordered reduction in pumping that impacted State Water Project and Central Valley Project customers.[6]

Water impacts may be the greatest of many challenges California will experience from global warming. The Sierra Nevada snowpack could be 40% smaller by the year

2050, with more precipitation arriving as rain, creating new challenges because reservoirs have been traditionally operated to accommodate heavy spring runoff from the melting snowpack, but they will instead have to deal with rapid runoff from winter rains.[6] This could lead to further problems such as flooding. Such problems cause contrasting effects, too much water in some areas, and not enough in others. There is water, but not where it's needed; there will be decreased ability to control the sources of water. The Colorado River's two largest reservoirs are Lake Mead and Lake Powell. Human demands for water from the reservoir system, along with predicted runoff declines and evaporation increases due to global warming, would, as researchers with Scripps Institute predicted in 2008, produce a 50% chance that functional storage levels in the two reservoirs would be gone by 2021.[6]

Other problems caused by water problems have to do with energy supply. In Lake Mead and Lake Powell, there was a 50% chance that the minimum levels for hydro-electric power generation would be reached in both lakes in 2017.[6] Falling water levels not only corresponds to reduced water supply, but reduced ability to utilize water to produce electricity, a widely used and practiced method.

Water, especially fresh water, can be taken for granted. Today, the overall demand exceeds the supply of developed water in California. Desalination of water continues to attract interest, since the ocean is a dependable source of water in an era when traditional sources have become less reliable.[6]

Ocean water makes up over 95% of the water on Earth. Because of the limited natural resources of fresh water, the industrial desalination of seawater becomes a major contender for providing sustainable sources of fresh water.[1] Not only is the ocean a potentially vast source of water, more than 70% of the world population live within 70km of seas or oceans.[1] The combination of these facts makes desalination an attractive alternative to diminishing fresh water sources.

During the second half of the twentieth century, desalination of seawater proved to be the most practical and in many cases, the only possible solution for many countries, such as the Gulf States, Mediterranean and Caribbean Islands. At the turn of the century, desalination is being considered by a large number of countries as the most viable and economical solution for providing fresh water.[1] Desalination systems are currently used around the world as large scale fresh water production. In a rough evaluation of whether there is enough energy to use desalination to meet the world's future fresh water needs, the conclusion is that there are no fundamental showstoppers to desalination on a massive scale.[7] It would of course require a lot of energy and high costs, but desalination is a viable way to extend fresh water resources.[7]

1.2 Desalination

Up to the 1800's, desalination was practiced on ship boards. The process involved using single sage stills operated in the batch mode and energy is supplied from cock stoves or furnaces without recovering the heat of condensation.[1] This method separated the salts from ocean water by distillation thermally. The sugar industry established in the early 1800's resulted in considerable progress of evaporation processes and involved developing more efficient and larger scale stills for producing syrup and sugar.[1] Today, distillation processes are widely used as an effective method for separating solutes from solution.

In 1912, a six effect desalination plant with a capacity of 75 m^3/day was installed in Egypt. The total production capacity of the desalination increased between 1929-1937, due to the start of the oil industry and exponential growth occurred between 1935-1960 at an annual rate of 17%.[1] There are various sources, methods, and purposes for desalination. These depend on geological region. Forty-eight percent of the global desalination production takes place in the Middle East, mainly the Gulf countries, 19% is produced in the Americas, 14% in Asia, 14% in Europe and 6% in Africa.[8] The source for desalination is primarily seawater, but can include brackish water and waste water. Sixty-one percent of the global seawater desalination capacity is located in the six GCC (Gulf Cooperation Council) states: Saudi Arabia, United Arab Emirates, Kuwait, Bahrain, Qatar, and Oman; the three enclosed sea areas of the Gulf, the Red Sea, and the Mediterranean therefore account for about three quarters of the global seawater desalination capacity.[8]

Since fresh water has many uses and purposes, the water produced through desalination serves a variety of purposes. Desalination water is mainly used for municipal and industrial purposes: 70% of the globally desalinated water is used by municipalities and 21% by industries; other end users include the power generation industry (4%), irrigation (2%), military (1%) and tourism (1%).[8] In California, a potential for 15-20 seawater desalination projects with a combined capacity of 1.7 Mm^3/day is expected for 2030, increasing the share of desalination to 6% of California’s 2000 urban water use.[8] The two largest and most advanced projects are located in the cities of Carlsbad and Huntington Beach with a proposed capacity of 200,000 m^3/day.[8]

Estimating that the daily use of water is about 70 gallons per person, such a capacity could supply water for about 700,000 people.

Though there are a variety of desalination processes, there are a few that are more widely used globally, especially for larger scale plants. Including all source water types, reverse osmosis is the prevalent desalination process accounting for 51% of the global capacity; 40% is produced by distillation plants, either multi-stage flash or multi-effect distillation plants, with relative market shares of 32% and 8%.[8] Minor desalination processes include the membrane-based nanofiltration and electrodialysis processes with about 4% market share each.[8]

The industrial desalination processes involve the separation of nearly salt-free fresh water from sea or brackish water, where the salts are concentrated in the rejected brine stream, as shown in Figure 1.2. The desalination process can be based on thermal or mechanical separation methods. The thermal separation techniques include two main categories; evaporation followed by condensation of the formed water vapor and freezing followed by melting of the formed water ice crysatls.[1] The first process is the most common and nearly at all cases it is coupled with power generation units, which may be based on steam or gas turbine systems.[1] The evaporation process may take place over a heat transfer area and is termed as boiling or within the liquid bulk and is defined as flashing.[1]

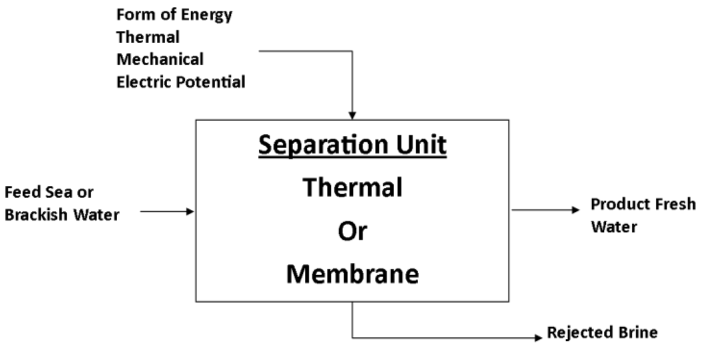


Figure 1.2: Definition of desalination process[1]

Though there are obvious advantages to water desalination, mainly having a limitless supply of source water, there are of course some environmental considerations. Desalination produces highly concentrated salt brines that may also contain other chemical pollutants and safe disposal of this effluent is a challenge.[9] The release of high salinity brine may cause impingement and entrainment of marine organisms. Subsurface and beach intake will affect the local shore environment as well as the wildlife in the nearby area. These concerns may take a backseat as the alternative is considered, depleting the natural freshwater sources, impacting those local ecosystems and leaving the population with a devastating water shortage.

1.2.1 Desalination Process Evaluation

When choosing which desalination process to use in the design, each process was evaluated primarily based on fresh water production capacity, production costs, and energy requirements. Table 1.7 shows the comparison between various desalination processes. Desalination by distillation requires large-scale evaporation that mimics the natural hydrologic cycle and generally is high in costs and energy use. Distillation can produce water with much lower salt content than membrane systems. The use of membranes to desalinate water mimics the natural biological process of osmosis and has generally lower capital costs, which increase along with the salt content of water; and requires less energy than thermal systems. Membranes can also remove microorganisms and many organic contaminants.

Table 1.7: Desalination Processes

Method/Technique		Capacity	Energy Requirements	Pros/Cons	Uses
Membranes	Reverse osmosis (RO): uses pressure on solutions with concentrations of salt to force fresh water to move through a semi-permeable membrane, leaving salts behind	- 46% global capacity - Ashkelon, largest RO plant in the world, 100 MGD	- depend directly on the concentration of salts in the water and lesser on the temperature of the feed water - major energy used for pressurizing the feed water	- needs better pretreatment of feed water to reduce the use of chemicals that end up in the brine causing disposal problems - needs improved membranes that are more durable and increase the flux of pure water - needs to reduce biofouling in membranes - needs more effective energy recovery and use - needs development of less expensive materials	- municipal purposes

Table 1.7: Continued

Method/Technique		Capacity	Energy Requirements	Pros/Cons	Uses
Membranes	Electrodialysis (ED)/Electodialysis reversal (EDR): uses electrical currents to move salt ions selectively through a membrane leaving fresh water behind	5% global capacity	- large part of costs due to energy requirements - direct current used to separate the ions in membrane stack (EDR)	- produce more product and less brine than distillation processes - can treat water with a higher level of suspended solids than RO - needs fewer pretreatment chemicals - can operate highly turbid water and are less prone to biofouling that RO (EDR) - higher water recovery than RO	- industrial and power plant cooling towers - freshwater fish farms - municipal uses: treat industrial wastes, concentrate polluted ground water for further treatment
Distillation	Multi-effect distillation (MED): takes place in a series of vesses and reduces the ambient pressure, allows seawater to undergo multiple boilings without supplying additional heat after the first effect	- 3% global capacity - plants typically build in units of 0.3-3 MGD	- energy used for thermal requirements	- MSF units with lower costs and less tendency to scale have displaced this process	- smaller towns and industrial uses

Table 1.7: Continued

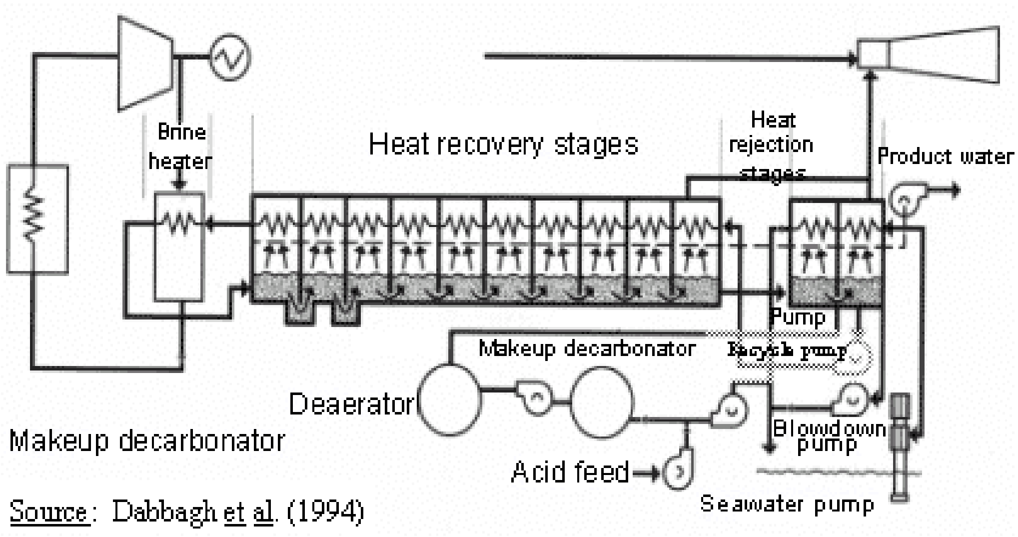
Method/Technique		Capacity	Energy Requirements	Pros/Cons	Uses
Distillation	Multi-stage flash (MSF): evaporation “flashing” occurs from the bulk liquid	- 36% global capacity - Shuweihat, largest MSF plant (2005) 120 MGD	- energy needed for evaporation	- can produce high-quality fresh water with very low salt concentrations from water with high salt concentrations - minimizes scale	- municipal purposes
	Vapor compression (VC): takes advantage of reducing the boiling point temperature by reducing ambient pressure, but the heat for evaporating the water comes from the compression of vapor rather than the direct exchange of hear from steam produced in a boiler	- 5% global capacity - units usually built in the 0.066-0.5 MGD range			- small and medium-scale seawater desalting units - tourist resorts - small industries - remote sites
Other	Ion-exchange: use resins to remove undesirable ions in water	5% global capacity	- economically unattractive compared with RO and ED	- the greater the concentration of dissolved solids, the more often the expensive resins have to be replaced - effective at lower concentrations and for small scale systems	- homes - municipal water treatment plants to remove calcium and magnesium ions in “hard” water

Table 1.7: Continued

Method/Technique		Capacity	Energy Requirements	Pros/Cons	Uses
Other	Freezing: when ice crystals form, dissolved salts are naturally excluded	- 5% global capacity - units usually built in the 0.066-0.5 MGD range	- lower minimum energy requirement	- minimal potential for corrosion - little scaling or precipitation - difficulty of handling and processing ice and water mixtures - not proven commercially feasible	- small number of demonstration plants for treatment of some industrial wastes
	Membrane distillation: combines use of thermal distillation and membranes; primarily uses thermal evaporation and uses membranes to pass vapor, which is condensed to produce fresh water	5% global capacity	- requires more pumping energy per unit of fresh water produced - requires more money than other approaches	- requires more space - simple and only small temperature differential needed to operate	- best suited for desalting saline water where inexpensive low-grade thermal energy is available, such a from industries or solar collectors

1.2.2 Multi-stage Flash Distillation

Multi-stage flash distillation (MSF) is the desalination process that distills sea water by flashing a portion of the water into steam in multiple stages of what are basically countercurrent heat exchangers. Figure 1.3 shows a schematic of a multistage flash distillation system. The MSF process is an innovative concept, where vapor formation takes place within the liquid bulk instead of the surface of hot tubes.[1] This is a major advantage over the original and simple concept of thermal evaporation where submerged tubes of heating steam are used to perform fresh water evaporation.[1]



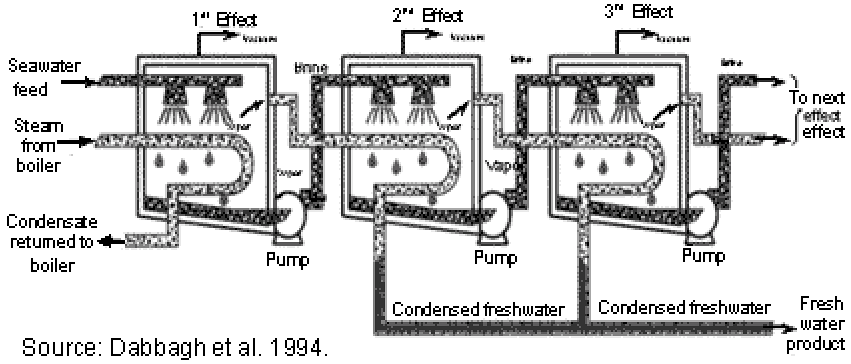
Source: Dabbagh et al. (1994)

Figure 1.3: Schematic of a multistage flash distillation system

The energy requirement for a MSF system is in two stages, electrical energy for pumping the water, and steam energy for heating the brine; the total energy requirement is in the order of 17 kWh/m^3 of water produced.[10] MSF distillation plants, especially large ones are often paired with power plants in a cogeneration configuration where waste heat from the power plant is used to heat the seawater, proving cooling for the power plant at the same time.[10] This reduces the energy needed by one-half or two-thirds. Located on the Umm Al Nar island, 12 miles to the east of Abu Dhabi city, the existing gas-fired plant has an installed power generation capacity of 850MW and uses five 57,000 m^3/day MSF units for desalination. Low grade steam from the adjacent power plant heats the tubes within the distiller units' brine heaters, which in turn heat the seawater intake.[11]

1.2.3 Multi-effect Distillation

A multi-effect distillation (MED) system is an evaporator consisting of several consecutive cells, or effects, maintained at decreasing levels of pressure and temperature from the first (hot) cell to the last (cold) cell. The vapor reuse in the multiple effect system allows reduction of the brine and the temperature due to low values and prevent rejection of large amount of energy to the surrounding.[1] A schematic of a MED system is shown in Figure 1.4. Each cell mainly consists of a horizontal tubes bundle, the top of the bundle is sprayed with the sea water make-up that then flows down from tube to tube by gravity.[12] Less electrical consumption is required for MED systems compared to other thermal processes such as MSF.



Source: Dabbagh et al. 1994.

Figure 1.4: Schematic of a multi-effect distillation system

There are several large thermal seawater desalination plants on the Arabian Peninsula, using the MSF method or the MED method. Figures 1.5 and 1.6 show a comparison of investment costs and costs of water diving water costs by thermal and electrical energy among other production costs. (ME-TVC is multi-effect distillation with thermocompression.) These comparisons show that the MSF method is favorable to the MED method based on investment and production costs.[13]

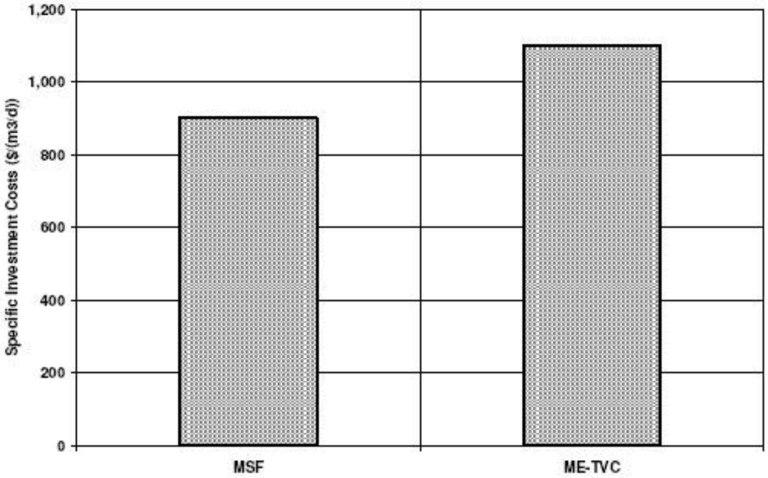


Figure 1.5: Investment costs of latest competition of very large thermal seawater desalination plants on the Arabian Peninsula [$/(m^3/d)][13]

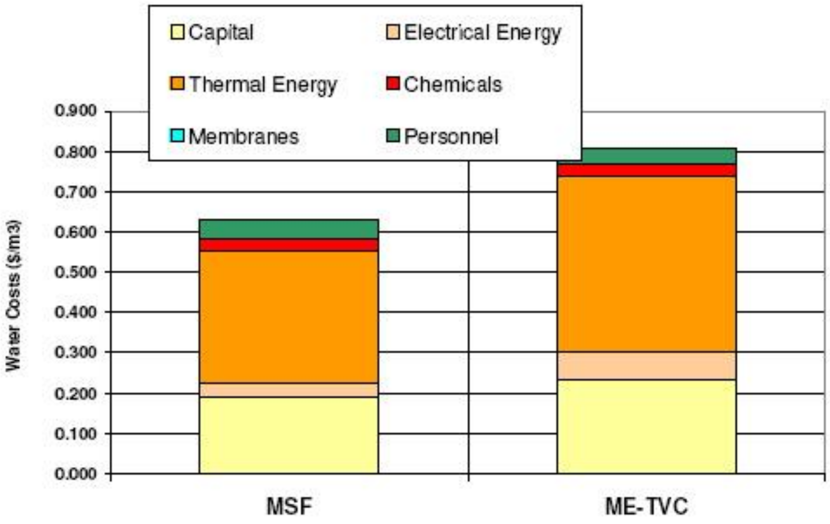


Figure 1.6: Costs of water from very large thermal desalination plants at the Arabian Peninsula [$/m^3][13]

1.2.4 Reverse Osmosis

Reverse osmosis (RO) systems use a series of filters and membranes to separate salts and other suspended solids from water. Instead of using thermal energy to distil the source water, mechanical pressure is needed to drive water across a selective membrane.

A number of membrane-based desalination processes are used on an industrial scale as shown in Table 1.8. There is an inherent difference in the separation mechanism in all filtration processes and the reverse osmosis process. In filtration, separation is made by a sieving mechanism, where the membrane passes smaller particles and retains larger ones; in osmosis or reverse osmosis processes, the membrane permeates only the solvent and retains the solute.[1] Figure 1.7 shows the relative size of common materials filtered by the different separation processes.

Table 1.8: Membrane-based desalination processes[1]

Membrane-based process	Particle size range (µm)
Microfiltration	0.15
Ultrafiltration	0.15 to $5\text{x}10^{-2}$
Nanofiltration	$5\text{x}10^{-2}$ to $5\text{x}10^{-3}$
Reverse Osmosis	$5\text{x}10^{-3}$ to 10^{-4}

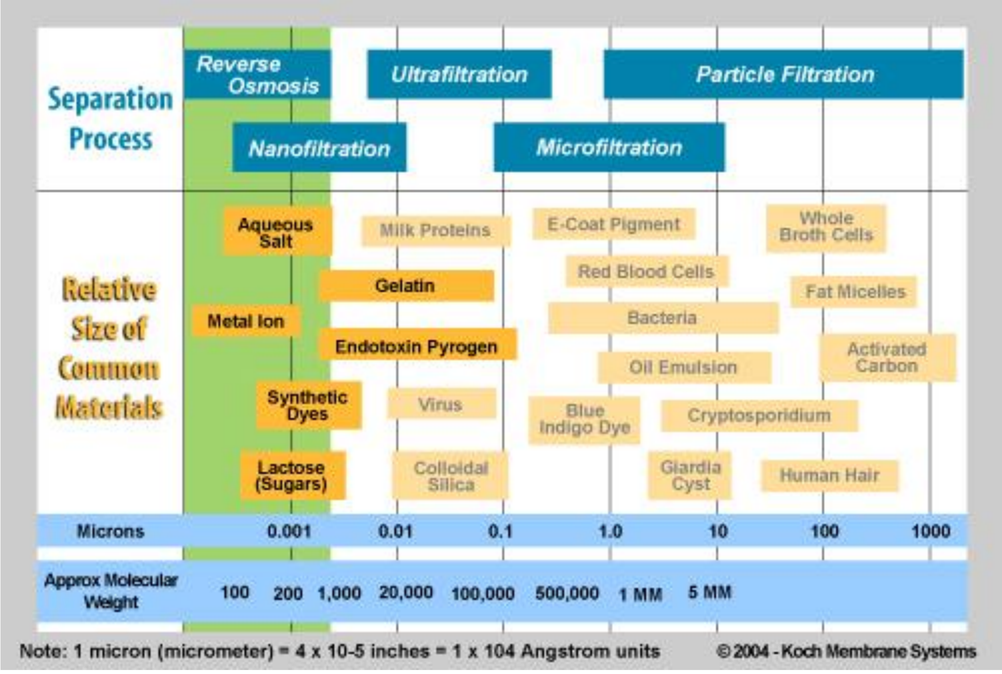


Figure 1.7: Relative size of common materials filter by process

There is a need for pretreatment processes in RO systems. The feed water may contain various amounts of suspended solids and dissolved matter. Reduction in the feed water volume during the RO process results in increase of the concentration of suspended particles and dissolved ions which results in physical masking of the membrane surface area and blockage of the membrane module.[1] This not only causes membrane damage and increased maintenance, but reduces the efficiency of the system. In addition, membrane damage can be caused by system operation at excessively low pH values, high chlorine concentration, or presence of other aggressive chemical compounds that would react and destruct the membrane material.[1] A number of pretreatment processes are used to remove particles, adjust pH, and reduce levels of free chlorine.

The majority of RO membranes are made almost exclusively from two polymers: cellulose acetate blends and aromatic polyamides.[14] Membranes are a fairly new technology for desalination compared to distillation methods. Cellulose acetate was the first polymer used for manufacturing reverse osmosis membranes, developed by Loeb and Sourirajan in the late 1950s, and is derived from cellulose, a material naturally present in plant tissue.[14] Peterson et al. introduced the second membrane material, aromatic polyamide, in the early 1980s.[14] More recently, thin film composites can be used for reverse osmosis membranes. Table 1.9 compares the three types of membranes.

Table 1.9: Comparison of Reverse Osmosis Membrane Types

Type	Description	Pros	Cons
Cellulosic Membrane	Thin surface layers that are dense	Low cost, convenient to install	Easily compacted (in high temp/press), limited pH range: 3-8 pH, degrades if temp high at 35C, vulnerable to bacteria

Table 1.9: Continued

Type	Description	Pros	Cons
Thin Film Composites (TFC)	Surface film that is dense and thin. Types: polyfurane cyanurate, aromatic polyamide, alkyl-aryl poly urea	One of the most efficient	Degrade when exposed to free chlorine, need constant monitoring of carbon prefilter
Aromatic Polyamide Membrane	Developed by Dupont	Like cellulosic membrane, but has higher resistance to biological attacks and hydrolysis, able to sustain sudden rise in temp	Constant exposure to high temp will damage

The design of RO membranes needs to provide high packing density and allows for convenient separation of feed, permeate, and concentrated streams. The two major membrane module configurations are hollow fiber and spiral wound; at present, the spiral wound configuration is most commonly used in commercial desalination systems.[14] A cutaway drawing of a spiral wound membrane element can be seen in Figure 1.8, provided by FLUIDSYSTEMS®. Commercial elements have between 20 and 40 membrane envelopes attached to the permeate tube, forming an element with a 20cm diameter and a length of 1m; such an element would contain 37-41m^2 of active membrane area.[14]

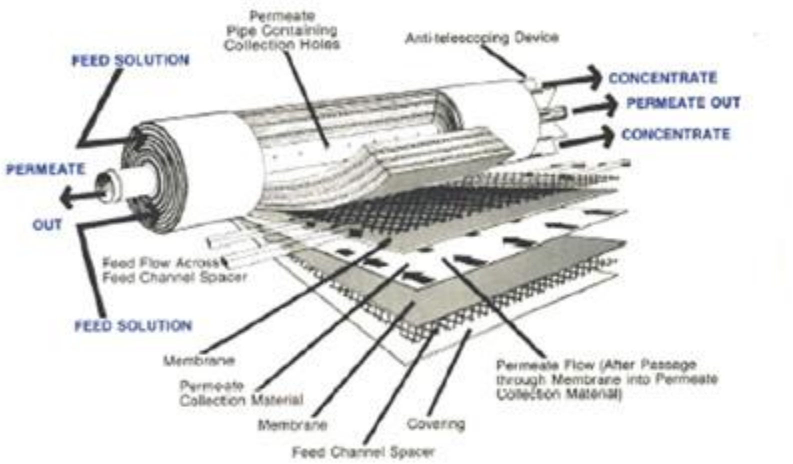


Figure 1.8: Cutaway Drawing of a Spiral Wound Membrane Element

RO systems require more electrical energy compared to distillation methods because of the high pressures needed to drive water across the membrane. Figure 1.9 shows electrical energy consumption of the MSF, MED, and RO desalination methods. While RO systems require higher electrical energy, there is no need for the high thermal energy required by the distillation methods, making the overall energy requirements for RO systems much less, as shown in Figure 1.10. Table 1.10 compares the fresh water production capacity and energy consumption of four industrial desalination processes, provided by Wangnick Consulting, 2010, which is summarized in Table 1.11. RO desalination systems have a fair production capacity as well as being on the low end of energy consumption per volume of water produced.

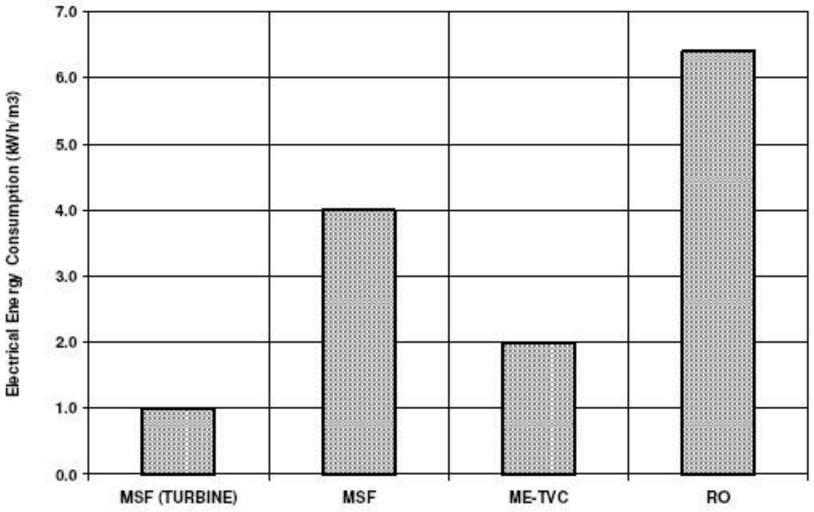


Figure 1.9: Consumption of electrical energy by desalination processes [kWh/m^3][13]

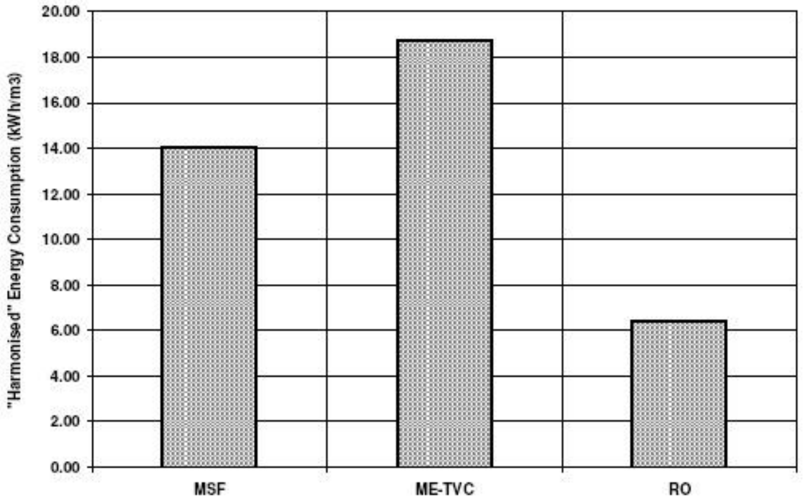


Figure 1.10: Harmonized energy consumption of desalination processes [kWh/m^3][13]

Table 1.10: Energy requirements of industrial desalination processes

	MSF	**MED-TVC**	**MED**	**MVC**	**RO**
Typical unit size m^3 d^{-1}	50,000 - 70,000	10,000 - 35,000	5,000 - 15,000	100 - 2500	24,000
Electrical Energy Consumption kWh m^{-3}	4 – 6	1.5 – 2.5	1.5 – 2.5	7 - 12	3 – 5.5

Table 1.10: Continued

	MSF	**MED-TVC**	**MED**	**MVC**	**RO**
Thermal Energy Consumption kJ kg $^{-1}$	190 (GOR =12.2) – 390 (GOR =6)	145 (GOR =16) – 390 (GOR =6) #[1]	230 (GOR =10) – 390 (GOR =6)	None	None
Electrical Equivalent #[2] for Thermal Energy kWh m^{-3}	#[3] 9.5 – 19.5	#[4] 9.5 – 25.5	#[5] 5 – 8.5	None	None
Total Equivalent Energy Consumption kWh m^{-3}	13.5 - 25.5	11 - 28	6.5 - 11	7 - 12	3 - 3.5 (Up to 7 with Boron treatment)

GOR – Gain Output Ratio

#[1] Lower Value to be applied only if heating energy is extremely expensive, e.g in combination with solar energy heating.

#[2] Electrical equivalent is that electrical energy which cannot be produced in a turbine because of extraction of the heating steam

#[3] Assuming that pressure in the condonser of a large commercial steam turbine is kept at 0.1 bara at a seawater temperature of 35 ^{0}C and steam extraction pressure is some 3.5 bara (loss is 475 kJ /kg steam)

#[4] Assuming that pressure in the condenser of a large commercial steam turbine is kept at 0.1 bara at a seawater temperature of 35 ^{0}C and steam extraction pressure is some 15 bara (loss is 737 kJ/kg steam)

#[5] Assuming that pressure in the condenser of a large commercial steam turbine is kept at 0.1 bara at a seawater temperature of 35 ^{0}C and steam extraction pressure is some 0.5 bara (loss is 258 kJ/kg steam)

Note: In this case GOR includes Steam/heat for Vacuum system

Source: WANGNICK CONSULTING (2010)

Table 1.11: Desalination Production Capacity and Energy Requirements by Process

Process	Water Production [m^3/day]	Energy Consumption [kWh/m^3]
MSF	50,000 - 70,000	13.5 - 25.5
RO	24,000	3 – 3.5 (7 w/ Boron treatment)
MED-TVC	10,000 – 35,000	11 – 28
MED	5,000 – 15,000	6.5 – 11
MVC	100 – 2500	7 – 12

1.3 Hydrogen

Focusing on MSF and MED methods for salt water desalination, the idea is to use hydrogen combustion as thermal energy required for the distillation process. A simple schematic of such a system can be seen in Figure 1.11. There is a major environmental advantage to using hydrogen as a fuel source. Compared to the combustion of fossil fuels and natural gas, hydrogen combustion produces no greenhouse gases. It is the ultimate clean fuel. Another advantage is that it stores approximately 2.6 times the energy per unit mass as gasoline. Table 1.12 shows the reaction energy for hydrogen combustion.

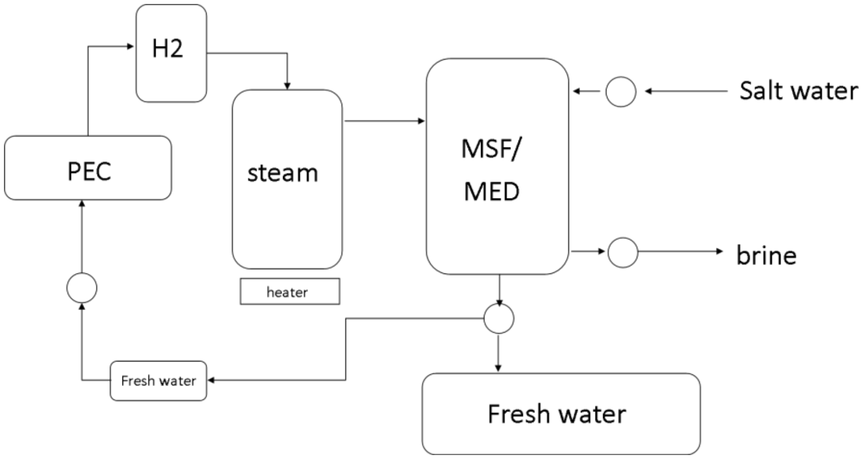


Figure 1.11: PEC-MSF/MED System

Table 1.12: Hydrogen Combustion Reaction Energy

Reaction		
$H_2(g) + ½ O_2(g) \leftrightarrow H_2O(g)$	242 kJ/mol	3.75 kWh/kg
$H_2(g) + ½ O_2(g) \leftrightarrow H_2O(l)$	286 kJ/mol	4.37 kWh/kg

Theoretically, the combustion of hydrogen produces 286 kJ/mol or 4.37 kWh/kg of hydrogen. Using the values from Table 1.10 to estimate the amount of hydrogen needed to supply the energy for MSF and MED processes is shown in Table 1.13. The MSF process would roughly require an average of 4.5 kg of hydrogen per 1 m^3 of fresh water produced; the MED process requiring roughly an average of 2 kg/m^3.

Table 1.13: Hydrogen Requirements by Distillation Process

Process	Energy Consumption [kWh/m^3]	Hydrogen Required [kg/m^3]
MSF	13.5 – 25.5	3.09 – 5.84
MED	6.5 – 11	1.49 – 2.52

Hydrogen is produced by the dissociation of water, or splitting water. The thermal dissociation of water is shown in Figure 1.12, requiring very high temperatures, around 4000°C. Generally, ceramic membranes are used to separate hydrogen gas from oxygen gas to prevent them from reforming water. The use of a catalyst can reduce the temperatures to 800-1200°C. These catalysts are usually iron oxide containing 8-14% weight of CrO_3, though Cr^{+6} is highly toxic and harmful to human health and the environment. There are many alternative catalysts being developed. The extremely high temperatures needed to thermally dissociate water impose strict constraints on the materials used in the system, not to mention high energy costs. Because of the high temperature required for hydrogen production by thermolysis, large-scale hydrogen production is often coupled with other reactors, such as nuclear-thermal and solar-thermal. Hydrosol II, a 100 kW hydrogen production pilot plant in Spain that has been in operation since 2008, uses concentrated solar power to split water.

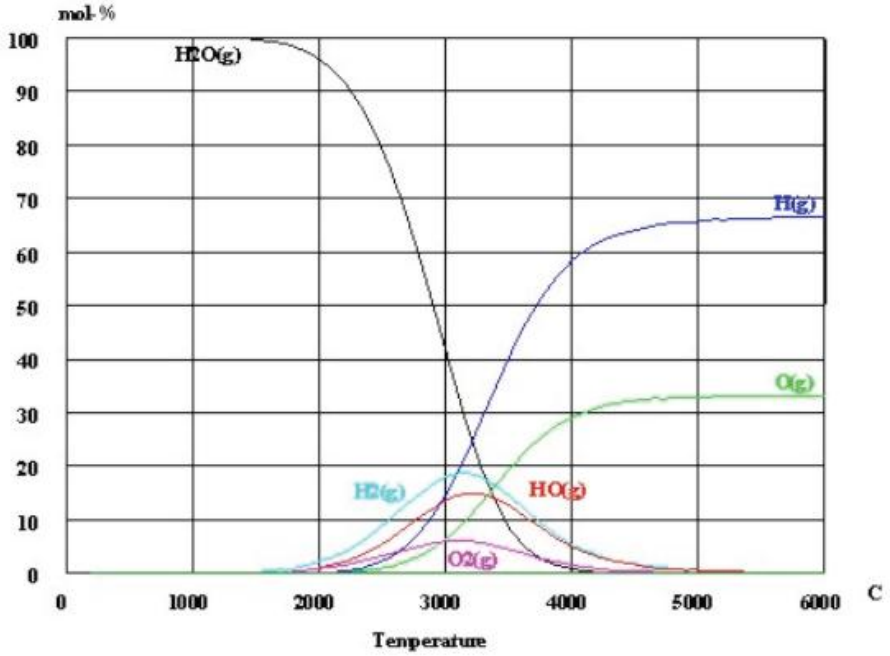


Figure 1.12: Thermal Dissociation of Water[15]

Electrolysis is also used to split water. An electric current passing through water can decompose it into oxygen and hydrogen. Producing hydrogen from water requires large amounts of energy making it uncompetitive compared to production from coal or natural gas. High-temperature electrolysis has been demonstrated in a laboratory at 30 kWh per kg of hydrogen produced. Knowing that the combustion of hydrogen gives 4.37 kWh/kg shows that the electricity consumed in hydrogen production is worth more than the hydrogen produced.

Electrolysis accounts for only about 4% of global hydrogen production, the bulk using natural gas at 48% and oil at 30% as shown in Table 1.14, according to the U.S. Department of Energy. Table 1.15 outlines the energy requirements and costs per hydrogen gasoline gas equivalent. The most cost effective method is using coal to produce hydrogen. This seems counterintuitive since hydrogen is used as a clean fuel source but coal and natural gas are used to produce it; both sources being fuels that produce greenhouse gases. Table 1.16 shows the fossil fuel emission levels for natural gas, oil, and coal.[16] The use of fossil fuels to produce hydrogen negates the purpose of using hydrogen as a clean fuel source.

Table 1.14: Global Hydrogen Production by Source

Source	**Hydrogen Produced in billions Nm^3/year**	**Percent**
Natural Gas	240	48
Oil	150	30
Coal	90	18
Electrolysis	20	4
Total	**500**	**100**

Table 1.15: Hydrogen Production Requirements

Energy Source	Requirements	Cost per H2 GGE
Natural Gas	Uses steam reformation. Requires 15.9 million cubic feet (450,000 m3) of gas, which, if produced by small 500 kg/day reformers at the point of dispensing (i.e., the filling station), would equate to 777,000 reformers costing $1 trillion dollars.	$ 3.00
Nuclear	Provides energy for electrolysis of water. Would require 240,000 tons of unenriched uranium — that's 2,000 600-megawatt power plants, which would cost $840 billion.	$ 2.50
Solar	Provides energy for electrolysis of water. Would require 2,500 kWh of sun per square meter, 113 million 40-kilowatt systems, which would cost $22 trillion.	$ 9.50
Wind	Provides energy for electrolysis of water. At 7 meters per second average wind speed, it would require 1 million 2-MW wind turbines, which would cost $3 trillion dollars.	$ 3.00
Biomass	Gasification plants would produce gas with steam reformation. 1.5 billion tons of dry biomass, 3,300 plants which would require 113.4 million acres (460,000 km²) of farm to produce the biomass. $565 billion dollars in cost.	$ 1.90

Table 1.15: Continued

Energy Source	Requirements	Cost per H2 GGE
Coal	FutureGen plants use coal gasification then steam reformation. Requires 1 billion tons of coal or about 1,000 275-megawatt plants with a cost of about $500 billion.	$ 1.00

Table 1.16: Fossil Fuel Emission Levels[16]

	Fossil Fuel Emission Levels – Pounds per Billion Btu of Energy Input		
Pollutant	**Natural Gas**	**Oil**	**Coal**
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0.000	0.007	0.016

1.4 Solar Energy: PEC vs. PV

Solar energy is just as important to life as water. Photosynthesis is a process that uses sunlight to convert carbon dioxide into organic compounds, which occurs in plants, algae, and many species of bacteria. This process allowed for the proliferation of life on Earth. Sunlight is also useful for natural lighting, heating, and electricity production. More energy from sunlight strikes Earth in one hour than all of the energy consumed by humans in an entire year.[17] This awesome fact is perhaps the main reason the potential for solar power is boundless. As a clean energy source, solar power is inexhaustible, fairly constant, and not as geographically restrictive. The disadvantages are that power production is lower on cloudy days and during the winter season; and currently, solar power is not yet cost competitive to fossil fuel.

In California, renewables accounts for about 10.6% of power generation, as shown in Figure 1.13; of that, only about 2% is solar, the details shown in Table 1.17.[18] There are many solar photovoltaic power plants internationally and in the United States. A list of the largest plants by power capacity is shown in Table 1.18.[19] Since the passing of Assembly Bill 32 in 2006, it has been a goal to reduce greenhouse gas emissions to 1990 levels by 2020. The desire to be more environmentally conscious and responsible will increase the use of renewables for energy sources, including solar power. Also, the goals of continued research in solar technology are to make solar power more efficient and cost effective.

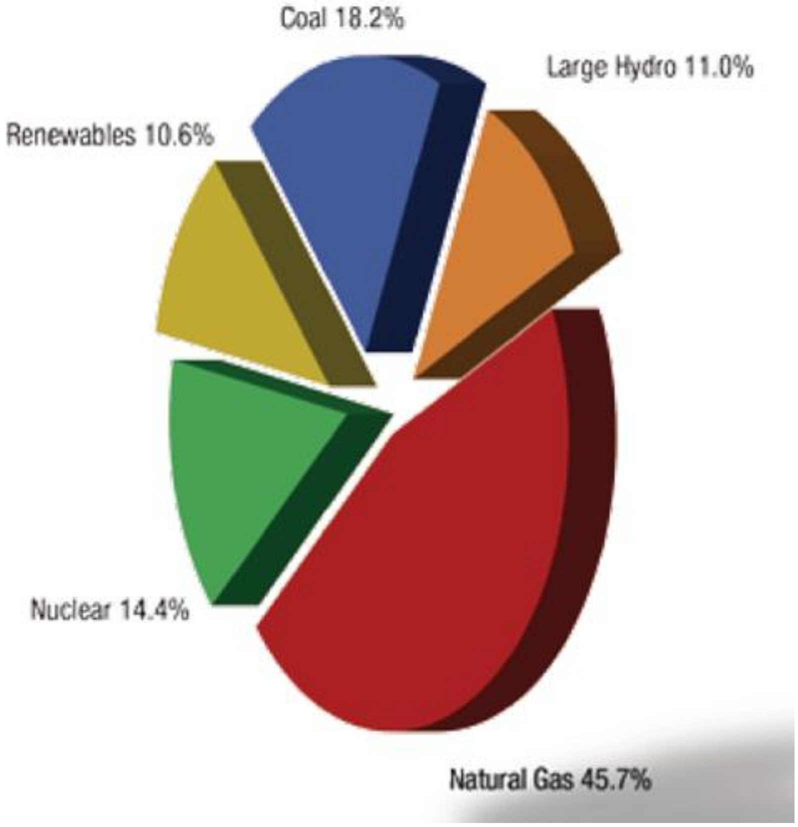


Figure 1.13: California Power Generation by Source 2008[18]

Table 1.17: California 2008 Total System Generation[18]

Fuel Type	**In-State**	**Northwest Imports**	**Southwest Imports**	**Total Energy System**
Coal	3,977	8,581	43,271	55,829
Large Hydro	21,040	9,334	3,359	33,733
Natural Gas	122,216	2,939	15,060	140,215
Nuclear	32,482	747	11,039	44,268
Renewables	28,804	2,344	1,384	32,532
Biomass	5,720	654	3	6,377
Geothermal	12,907	0	755	13,662
Small Hydro	3,729	674	13	4,415
Solar	724	0	22	746
Wind	5,724	1,016	591	7,331
Total	**208,519**	**23,945**	**74,113**	**306,577**

Table 1.18: Largest PV Power Plants[19]

Power (MW)	Location	Description	Constructed
Largest in the World			
97	Canada, Sarnia (Ontario)	Sarnia PV power plant	2009-2010
84.2	Italy, Montalto di Castro (Lazio)	Montalto di Castro	2009-2010
80.7	Germany, Finsterwalde	Solarpark Finsterwalde I, II, III	2009-2010
70	Italy, Rovigo	Rovigo	2010
60	Spain, Olmedilla (Castilla-La Mancha)	Parque Fotovoltaico Olmedilla de Alarcon	2008
Largest in the U.S.			
48	USA, Boulder City, NV	Copper Mountain Solar Facility	2010
25	USA, Arcadia, FL	DeSoto Next Generation Solar Energy Center	2009
21	USA, Blythe, CA	Solar electric power plant, Blythe	2009
16	USA, San Antonio, TX	Blue Wing solar electric power plant	2009
15.01	USA, Jacksonville, FL	Jacksonville Solar Energy Generation Facility	2010

Systems that produce electricity from solar energy potentially offer the cleanest way to produce hydrogen. This can be done using photovoltaic systems or by a photoelectrochemical cell (PEC) process. Of course, photovoltaic systems convert sunlight directly into electricity and are made of semiconducting materials, such as silicon. High efficiency PEC systems produce hydrogen directly from water using sunlight; a schematic of this process is shown in Figure 1.14.[20] Sunlight shining on a photoelectrode comprising a semiconductor photovoltaic generator coated with catalytic thin films produces electric current which drives the hydrogen and oxygen evolution reactions at the respective surfaces (Figure 1.14a).[20] Figure 1.14b shows the design for a large scale reactor where arrays of photoelectrodes are arrange in tubular reactors with include gas-separating membranes to collect the high-purity hydrogen and oxygen.[20]

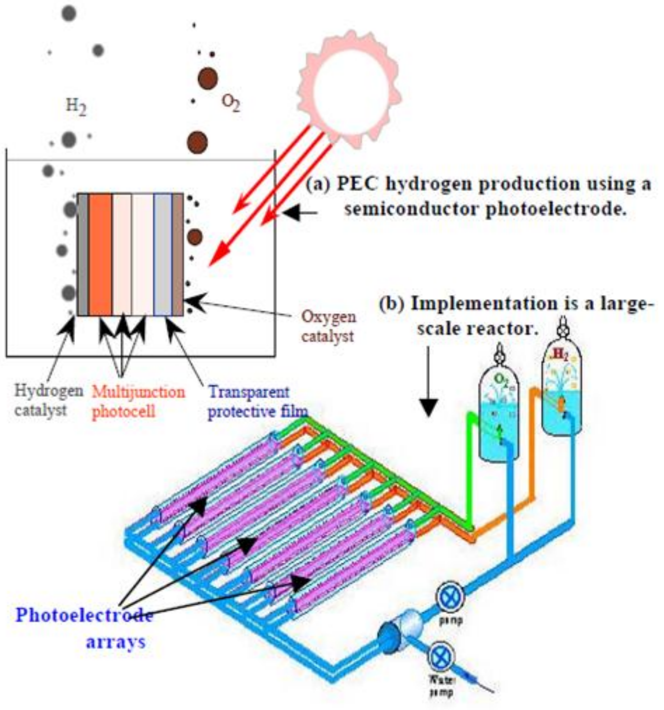


Figure 1.14: Photoelectrochemical Hydrogen Production[17]

There are a few developers of solar desalination systems with a variety of power sources, desalination processes, and fresh water production capacity, which is summarized in Table 1.19. In developing our own solar powered desalination system, we purposed three questions.

(1) What are the overall requirements for the MSF, MED, and RO methods for water desalination?

(2) Which route would be more energy effective: PEC with hydrogen combustion for distillation or PV with pumps for separation by membrane?

(3) What will be the area of the devices needed for one million gallon a day (1 MGD) production of fresh water?

Table 1.19: Solar Desalination Systems

Developers	Power	Desalination Process	Capacity
MIT	Solar PV cells	Reverse osmosis	1,000 gallons/day
BARC	Solar PV cells	Reverse osmosis	3-4 families
IMB	10 MW solar farm	(not specified)	7.9 million gallons/day
Francisco Suarez	Solar pond	Membrane distillation	(not specified)
Alan Williams	Large area solar collector	Multi-effect humidification	100,000 m^3/day (about 24.6 million gallons/day)

1.4.1 Question 1

The first question can be answered from the information in Table 1.10, which is simplified in Table 1.20 by taking the average values. MSF requires an average of 19.5 kWh/m^3 total energy equivalent, MED an average of 10.25 kWh/m^3, and RO an average of 4.25 kWh/m^3. The MSF process is the most energy intensive, requiring the most electrical and thermal energy, however has the largest production capacity, as most MSF desalination plants are typically larger compared to MED and RO plants. The MED process requires the least amount of electrical energy, less thermal energy compared to MSF, but more total energy compared to RO. Typically, MED plants are smaller scale compared to both MSF and RO. The RO method requires no thermal energy and least amount of total energy compared to the two distillation processes, MSF and MED; however typical large-scale RO plants have only about half the production capacity as most MSF plants.

Table 1.20: Energy Requirements of Desalination Methods

Method	MSF	MED	RO
Electrical Energy (kWh/m^3)	5	2	4.25
Thermal Energy equivalent (kWh/m^3)	14.5	8.25	0
Total Energy equivalent (kWh/m^3)	19.5	10.25	4.25

1.4.2 Question 2

To answer the first part of the second question, we looked to the techno-economic evaluation of four PEC systems done by Directed Technologies Inc. under contract to the U.S. Department of Energy.[21] Type 1 and 2 system configurations utilize aqueous reactor beds containing colloidal suspensions of PV-active nanoparticles, each nanoparticle being composed of the appropriate layered PV materials to achieve sufficient band gap voltage to carry out the electrolysis reaction.[21] Type 3 and 4 system configurations use multi-layer planar PV cells in electrical contact with a small electrolyte reservoir and produce oxygen gas on the anode and hydrogen gas on the cathode, which is shown in Figure 1.15.[21]

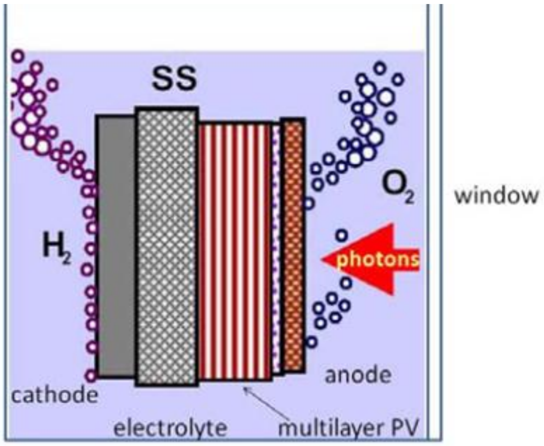


Figure 1.15: Schematic of a Generic PEC Photocell[21]

The Type 1 system reactor is a single bed colloidal suspension reactor where both hydrogen and oxygen are evolved from the surface of the nanoparticles. An end view of three baggie/bed structures is shown in Figure 1.16. A single baggie/bed is 1060 ft long and 40 ft wide; the system for 1 tonne per day (TPD) hydrogen yearly average production would require 18 baggies. The assumed baseline solar-to-hydrogen (STH) conversion efficiency is 10%. (STH conversion efficiency is power in/power out, where the power in is the incident light intensity and power out is they hydrogen production photocurrent.[22]) The Type 1 reactor is the simplest PEC embodiment and has the lowest capital cost.

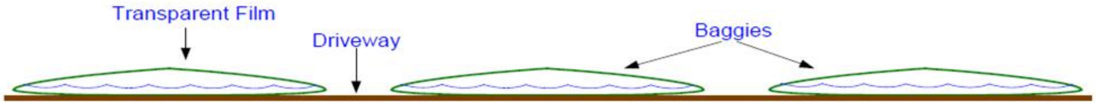


Figure 1.16: Type 1 PEC System Reactor, Single Bed Colloidal Suspension, End View[21]

The Type 2 system reactor is a dual bed colloidal suspension reactor that employs separate beds for oxygen and hydrogen gas production reaction. The beds are linked together with diffusion bridges to allow the transport of ions but prevent gas and particle mixing. A schematic of the system is shown in Figure 1.17, consisting of one half-baggie (H_2), one full size baggie (O_2), a second full size baggie (H_2), and a second half-baggie (O_2). Dimensions of the baggie/bed assembly are 200 ft long and 20 ft wide. Type 2 system requires approximately double the solar absorption area as Type 1 because of the separation of the complete reaction into dual beds; this and other factors make they Type 2 reactor about 4 times the cost of the Type 1 reactor. The STH efficiency for the Type 2 system is 5% and the system for 1 TPD hydrogen average production consists of 347 such assemblies.

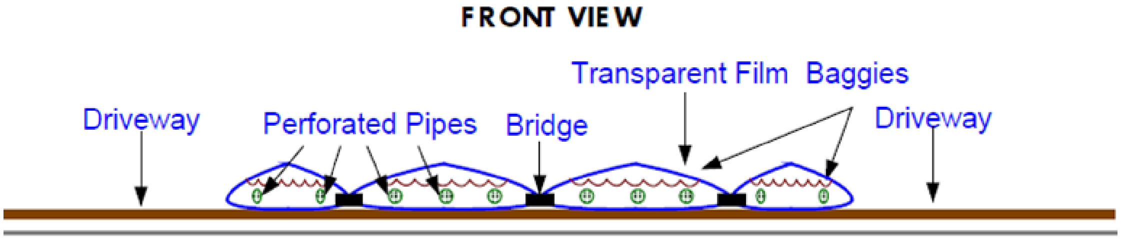


Figure 1.17: Type 2 PEC System Reactor, Dual Bed Colloidal Suspension, Front View[21]

The Type 3 reactor uses planar PEC arrays that are fixed in place and inclined toward the sun at a tilt angle from horizontal equal to the local latitude. A schematic is shown in Figure 1.18 and each individual panel is 1 m wide and 2 m in length, having a baseline STH efficiency of 10%. They system for 1 TPD hydrogen average production requires 26,923 panels.

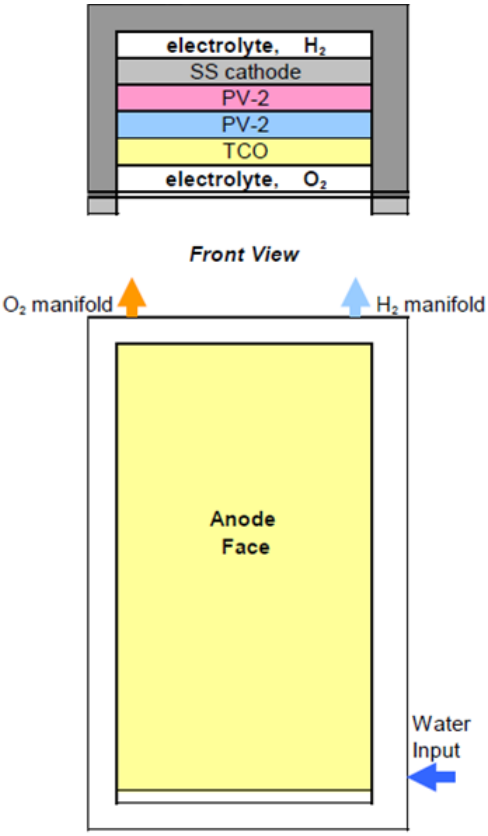


Figure 1.18: Type 3 PEC System Reactor, Fixed Flat Panel[21]

The Type 4 reactor uses a solar concentrator reflector to focus direct solar radiation onto the PEC cell and tracking is used to maximize direct radiation capture. Solar concentrators reduce the cost impact of the PV component of the system by focusing solar energy, but add to the cost of the steering systems. This system uses a concentration ratio of 10 suns, however a PEC concentrator system can potentially use a concentration ratio of 10-50 suns. Figure 1.19 shows the concentrator PEC design, which uses an offset parabolic cylinder array to focus radiation on a linear PEC receiver. Each individual concentration array is 6 m wide and 3 m in height with a baseline STH efficiency of 15%. The system for 1 TPD hydrogen average production needs 1,885 such reactors.

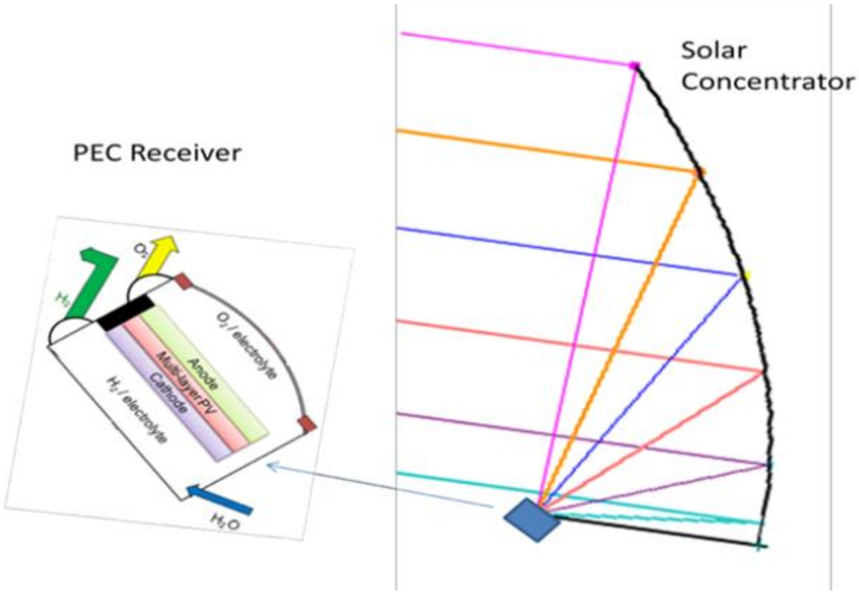


Figure 1.19: Type 4 PEC System Reactor, Tracking Concentrator[21]

Comparing these four types of PEC systems for a net production of 1 TPD hydrogen is summarized in Table 1.21. Types 1 and 2 have substantially lower capital and hydrogen production costs but require more photon capture area. Type 4 has the highest STH efficiency, as well as requiring the least photon capture area and electrical power consumption. Both the hydrogen production costs and total capital costs are higher compared to types 1 and 2 but less than Type 3.

Table 1.21: PEC Hydrogen Production[21]

	Type 1	Type 2	Type 3	Type 4
Net H_2 produced (kg/day)	1000	1000	1000	1000
Photon capture area (m^2)	70,540	126,969	53,845	33,924
Electrical power consumption (kWh/kg H_2)	3.29	2.01	2	0.16
PEC efficiency (kg/m^2)	0.01	0.01	0.02	0.03
Hydrogen Production Costs (\$/kg H_2)	1.63	3.19	10.36	4.05
Total capital cost (\$)	1,081,814	1,710,807	9,607,621	3,476,291
STH Efficiency (%)	10	5	10	15

Electrical power consumption for these PEC systems is primarily for the gas processing subassembly, items consuming power being the compressor, water pumps, slurry circulation pumps, and control systems. Consumption per kg of H_2 produced is included in Table 1.21. Considering the theoretical 4.37 kWh per kg of hydrogen produced, it is obvious that the PEC method for producing hydrogen is advantageous from an energy and environmental point of view compared to the traditional electrolysis and thermolysis methods. In the best case, the Type 4 system, only 0.16 kWh/kg H_2 is consumed, making the energy gain over 20 fold. In other words, in the ideal case, for every unit of energy input into producing hydrogen, the hydrogen can provide over 20 units of energy.

Considering this, it is definitely energy effective to produce hydrogen by PEC and then combust that hydrogen to produce the thermal energy needed for desalination by distillation. However, in addition to thermal energy, MSF and MED systems as well as they PEC system would require electrical energy. A combustion engine or turbine can be used to convert thermal energy into electrical energy, but system efficiencies need to be considered.

Also, the water consumption for the PEC hydrogen production system should be considered. A combined system can run on a cycle, as shown in Figure 1.11. Fresh water is needed to produce hydrogen, and then the combustion of hydrogen is used to desalinate water. Calculations were done to ensure that this system produces more fresh water than the amount of water needed to produce hydrogen and power the system. Table 1.22 shows the water requirements of hydrogen production for the four types of PEC systems; which is about 2.3 gallons of water for each kilogram of hydrogen produced. Based on hydrogen combustion energy and hydrogen requirements for distillation systems, as shown in Tables 1.12 and 1.13, the water requirements for a PEC-MSF/MED system can be calculated. This calculation is summarized in Table 1.23. For a PEC-MED desalination system, for every gallon of fresh water produced, about 0.02 gallon of water was needed to produce the hydrogen powering the system. This shows that much more fresh water is produced than consumed.

Table 1.22: Water Needed for Hydrogen Production

	Type 1	Type 2	Type 3	Type 4
Total Water Consumption (gal/day)	2637	2369	2369	2369
Average gross H2 production (kg/day)	1111	1000	1000	1000
Water use for H2 production (gal/kg)	2.373537	2.369	2.369	2.369

Table 1.23: Water Consumed and Produced in PEC-Distillation System

	MSF	MED
H2 needed per gal H20 produced (kg/gal)	0.016891	0.008879
H20 needed to produce H20 (gal/gal)	MSF	MED
Type 1	0.040092	0.021074
Type 2	0.040016	0.021034
Type 3	0.040016	0.021034
Type 4	0.040016	0.021034

The next part of question 2, considers a PV-RO system; a simple schematic can be seen in Figure 1.20. To assess this system, we have averaged local solar irradiance and estimated electrical production for a PV system. A project at UCSD by Bryan Urquhart created a Google Maps interface, the “Solar Energy Calculator.”[22] This computes the monthly and annual solar energy impinging upon a 1 m^2 tilted panel in San Diego. Using Google Maps, a spot is chosen and inputs are needed: panel tilt (degrees) and panel Azimuth (degrees). For a fixed panel, the optimal panel tilt (angle relative to horizontal) is the latitude of the location, allowing for maximum solar irradiance collection throughout the day. The Azimuth angle is the panel face angle relative to North. Regions in the Northern Hemisphere face South (giving an Azimuth angle of 180°) for optimal solar irradiance collection, and regions in the Southern Hemisphere face North.

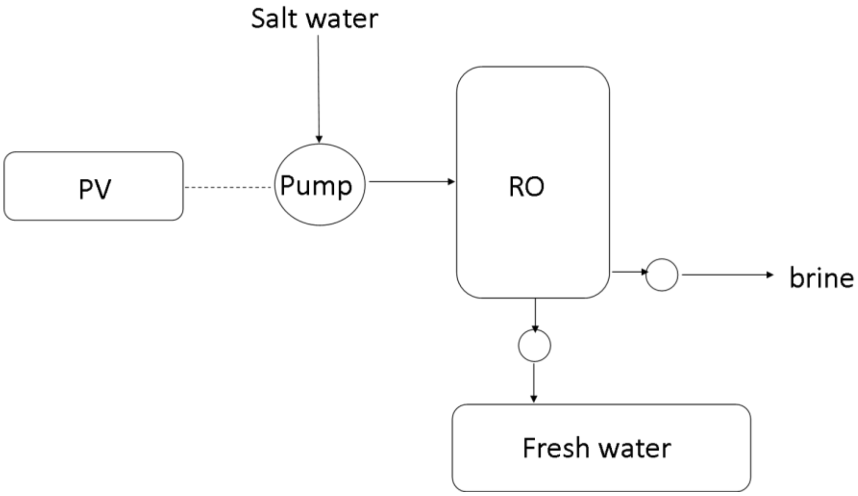
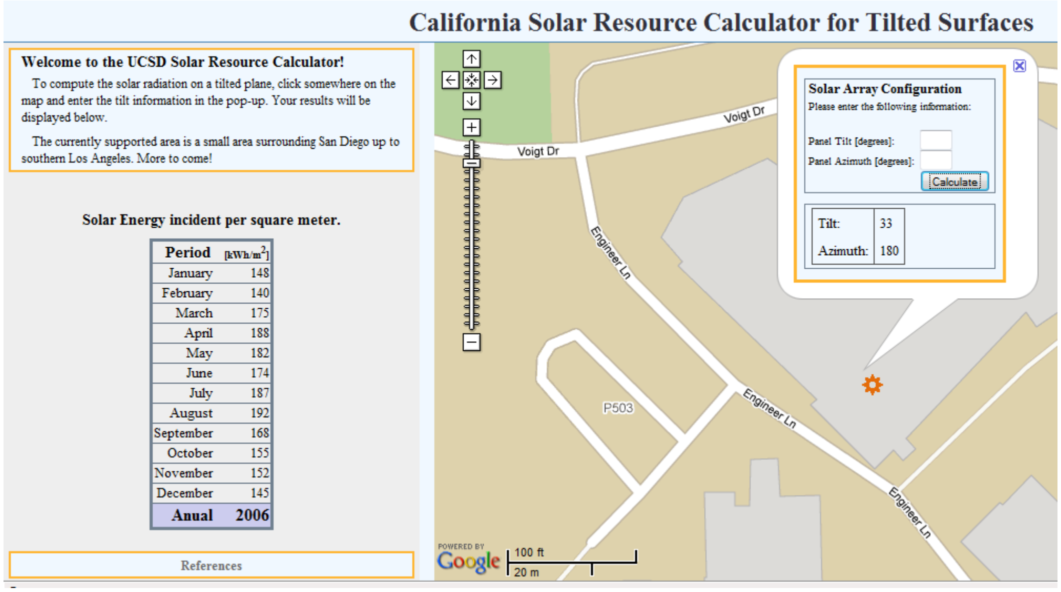


Figure 1.20: PV-RO System

A spot located in the parking lot north of Jacobs Hall was chosen, and tilt angle 33° and Azimuth angle 180° given to calculate the annual solar irradiance. A screen shot of the results can be seen in Figure 1.21. The result was an annual energy density value of 2006 kWh/m^2, giving an average daily irradiance of 5.5 kWh/m^2. Assuming an instillation efficiency of 90% and a labeled efficiency of 12% (efficiency for a PV system is a ratio of the electrical power output to the solar power input), a PV system will have 0.59 kWh/m^2 electric energy output density, these values are listed in Table 1.24. Since only electric power is needed for RO systems at a consumption rate of 4.25 kWh/m^3, it is feasible to power an RO desalination system using PV.



California Solar Resource Calculator for Tilted Surfaces

Welcome to the UCSD Solar Resource Calculator!

To compute the solar radiation on a tilted plane, click somewhere on the map and enter the tilt information in the pop-up. Your results will be displayed below.

The currently supported area is a small area surrounding San Diego up to southern Los Angeles. More to come!

Solar Energy incident per square meter.

Period	[kWh/m^2]
January	148
February	140
March	175
April	188
May	182
June	174
July	187
August	192
September	168
October	155
November	152
December	145
Anual	**2006**

Solar Array Configuration

Please enter the following information:

Panel Tilt [degrees]:

Panel Azimuth [degrees]:

Tilt:	33
Azimuth:	180

Figure 1.21: Solar Energy Calculator using Google Maps[23]

Table 1.24: PV System Power Production

Average Daily Irradiance (kWh/m2)	5.50
Instillation Efficiency	0.90
Labeled Efficiency	0.12
Output Electric Energy Density (kWh/m2)	0.59

1.4.3 Question 3

Considering solar powered MSF, MED, and RO desalination systems with the production capacity of one million gallons per day of fresh water, we can compare the energy consumption and area of devices needed, the area required by the PEC and PV system. The energy and area requirements for a PEC hydrogen production system coupled with a MSF and MED desalination process is shown in Table 1.25. The rough calculations were made using the values from Tables 1.20 and 1.21. The total energy equivalent values were used and all four types of PEC systems were compared. Since the Type 4 PEC system is the most efficient, it requires the least energy and area. A MED desalination plant producing 1 MG/day would require about 1,421 kWh and 301,205 m^2. A higher energy intense MSF plant of the same production capacity would require about 2,701 kWh and 573,025 m^2. The area requirement calculations for a PV system coupled with a RO desalination process is listed in Table 1.26. Using a PV system to power a RO plant production 1 MG/day would require 27,267.8 m^2.

Table 1.25: PEC System Requirement for 1 MG MSF and MED

Requirements for 1MG		
	MSF	MED
Total Energy equivalent (kWh/MG)	73,816	38,800
H2 required (kg/MG)	16,891	8,879
Energy required to produce needed H_2 (kWh)		
	MSF	MED
Type 1: single bed colloidal suspension	55,573	29,211
Type 2: dual bed colloidal suspension	33,952	17,846
Type 3: fixed flat panel	33,783	17,758
Type 4: tracking concentrator	2,703	1,421
Area required to produce needed H_2 (m^2)		
	MSF	MED
Type 1: single bed colloidal suspension	1,191,521	626,312
Type 2: dual bed colloidal suspension	2,144,687	1,127,336
Type 3: fixed flat panel	909,519	478,080
Type 4: tracking concentrator	573,025	301,205

Table 1.26: PV System Requirement for 1 MG RO

Total Energy equivalent (kWh/m3)	4.25
Total Energy equivalent (kWh/MG)	16,088
Electric Energy Density (kWh/m2)	0.59
Area Required (m2)	27,268

1.5 Conclusion

Looking at the energy consumption and area requirements for the purposed solar powered desalination systems, it is clear that reverse osmosis powered by photovoltaics is the best design. The RO desalination system requires the least total energy, all of which is electrical, which a PV system can provide. Though PEC is the most energy effective method to produce hydrogen, coupled with desalination by MSF/MED systems, it is not energy or space effective, especially compared to RO. A PEC-MED system would require over 11 times more area than a PV-RO system that produces the same volume of fresh water.

Chapter 2: Reverse Osmosis System

2.1 Reverse Osmosis System Set Up

Having determined that a PV-RO system would be the most energy and space efficient for a solar-powered desalination system, next is to build and test such a system. Aiming for a small-scale system, a 50 gallon per day system is sufficient.

For the reverse osmosis part of the system, the main components are the pump, filters, and the membrane. The pump needs to supply the required high pressure to drive the water across the membrane and preferably requires a direct current power supply, since it will be powered by the photovoltaic system. Also, a typical reverse osmosis system has five stages. The first stage consists of a sediment filter. These filters are made from thermally bonded fibers of polypropylene and are used to trap sediment. Second and third stage filters are carbon black filters which have a 5 µm nominal filtration. The filter is manufactured from high purity acid-washed activated carbon, finished with an outer polypropylene spun bonded prefiltration medium, and has a protective polypropylene netting as well as end caps with compression gaskets.

The fourth stage is the reverse osmosis membrane. As mentioned earlier, the spiral wound membrane is most common. Filmtec® provides advanced and reliable reverse osmosis membranes for home drinking water. Polyamide thin-film composite is the membrane type. The membrane has a maximum operating temperature of 45°C, maximum operating pressure of 300 psi, and works with a pH range of 2-11. The membrane has excellent salt and organic rejection, microbiological resistance, and usually lasts 3-5 years. Membranes also require housing, or membrane pressure vessels. These vessels need to be sealed and able to withstand high pressures. The inlet allows water to pass through the membrane and the outlet has an opening for the permeate, the fresh water, and an opening for the concentrate.

The fifth stage is another filter that removes chlorine, odor and taste. The brand OMNIPURE® supplies a fifth stage carbon filter composed of acid-washed carbon media designed for maximum chlorine, taste, and odor reduction. It also has its own versatile and disposable inline filter housing design. The other filters and the reverse osmosis membrane require separate housing.

The housing elements are typically made of polypropylene and can withstand the high pressures needed for the system. They feature a single inlet port and two outlet ports, one for the permeate, and one for the concentrate. The reverse osmosis membrane meets the NSF/ANSI Standard 58 for reverse osmosis drinking water treatment systems and all other elements meets the NSF/ANSI Standard 42 for drinking water treatment units. The reverse osmosis system components are listed in Table 2.1, which includes prices for the specific items purchased for this project.

Table 2.1: List of RO System Components

Item	Qt.	Price
Reverse Osmosis System		
Pump (Puroflo)	1	$115
Filter (PURTREX), stage 1 - sediment filter	1	$ 9
Filter (MATRIKX), stage 2/3 – traps particles	2	$15
Filter (OMIPURE), stage 5 – removes chlorine, odor, taste	1	$15
Filter Housing	4	$14
Membrane (FILMTEC)	1	$45
RO Membrane Housing	1	$20
Fittings and Tubing		
Valves/connectors	Est. 12	Est. $30
Tubing	10 ft. cut	$5
TOTAL		**$325**

This reverse osmosis system consists of a 10 pound pump and five separate filter elements. There are several options for the layout of this system, given that the elements will be fixed together. The line layout is most simple and material optimizing as the first three stages can be connected using a single connector, minimizing the need for tubing. The membrane housing and stage five filter do not line up like the first three stages. In the first three stages, the housing is designed so that both the inlet and outlet ports are located at the top. For the membrane housing and stage five filter, the inlet and outlets are located at opposite ends. They can be assembled in line with the other stages, however, tubing is necessary to connect them. Figure 2.1 shows a simple schematic of a reverse osmosis system using the line layout. The arrows show the flow of water and the location of the inlet and outlet at each stage. Figure 2.2 is a photo of the reverse osmosis system assembled.

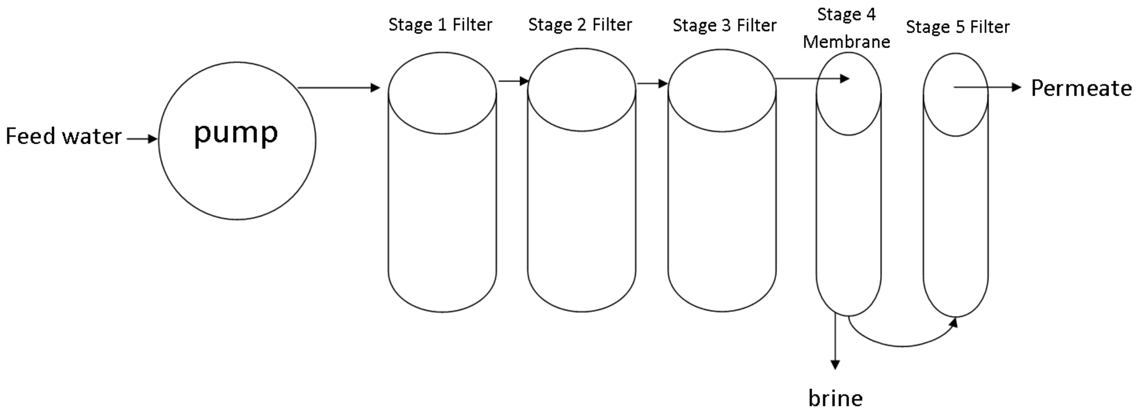


Figure 2.1: RO system line layout

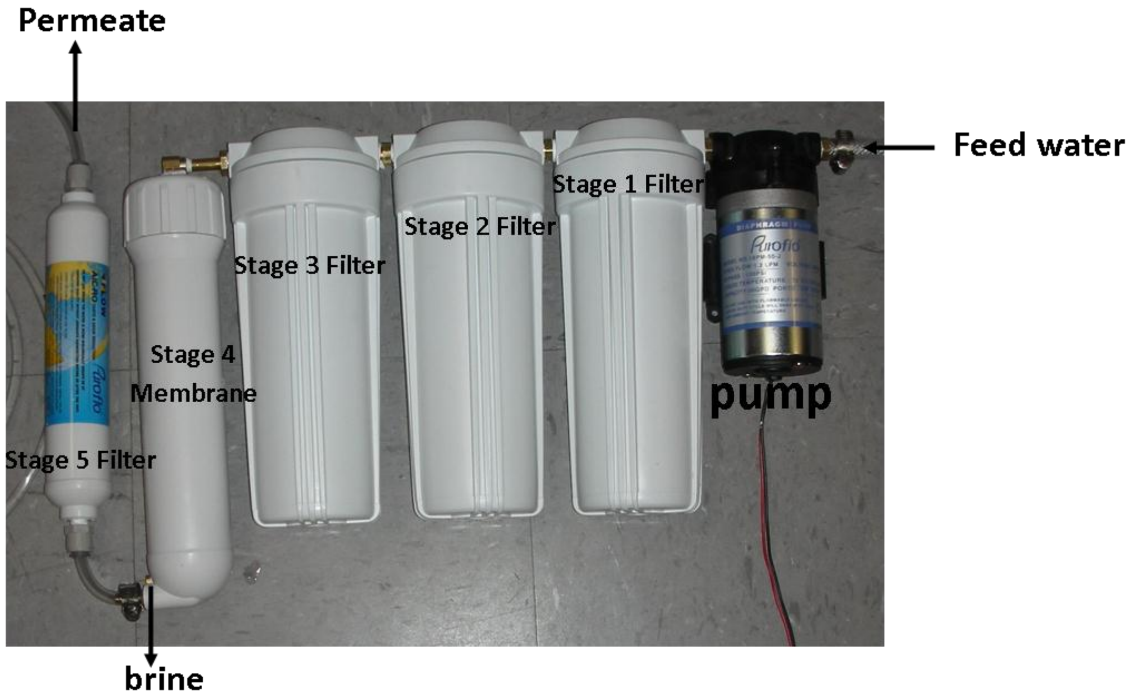


Figure 2.2: Photo of RO system

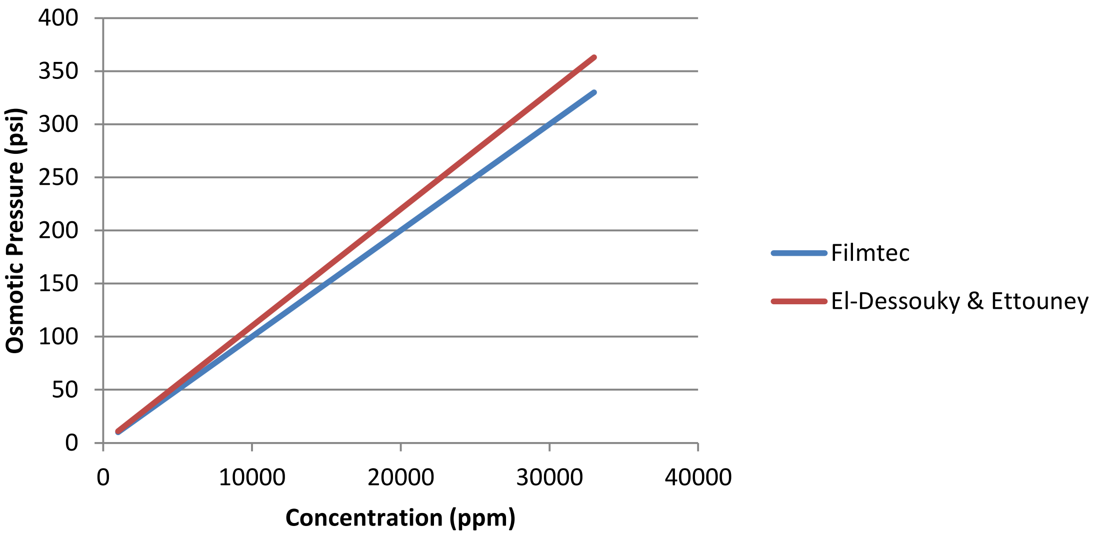
2.2 Feed Water

The operation of the system depends on the feed water concentration, which is typically represented as total dissolved solids (TDS) with units of parts per million, ppm, which for water is approximately milligram per liter (mg/l). The higher the concentration, the higher the osmotic pressure; the system should have a minimum capacity of the highest concentrated water in the system, the produced concentrate, or brine. The osmotic pressure (π) can be determined by the parameters: concentration (Σx_i), temperature (T), and using the universal gas constant (R), as the equation shows.

$$\pi = T\,R\,\Sigma xi^{1}$$

Given that the system is at a constant temperature, the osmotic pressure is linearly related to the concentration. The osmotic pressure for a solution with the concentration of 1,000 ppm can be approximated to be 75.84 kPa (about 11 psi).[1] Filmtec® also estimates 1 psi is required for every 100 mg/L of concentration. Graph 2.1 shows the linear relationship of concentration and osmotic pressure for both of these estimations.

Graph 2.1: Concentration vs. Osmotic Pressure



The system capacity should be greater than the osmotic pressure of the most concentrated solution, the concentrate. To determine the maximum concentration of feed water this system can accept, the Filmtec® and El-Dessouky & Ettouney estimations were used. The pump pressure capacity is 120 psi, therefore the osmotic pressure of the concentrated water must not exceed 120 psi. Using the Filmtec® estimation, the maximum concentration is 12,000 ppm. According to El-Dessouky & Ettouney, the maximum concentration is approximately 10,909 ppm. Water containing these concentrations, while not as concentrated as sea water, is too high to be classified as drinking water and would have to be filtered before acceptable for consumption. Natural sources of water that may have such concentrations are ground water, rain water, and water from streams, rivers, and lakes.

2.3 Permeate Water

The percent recovery is the amount of water that permeates relative to the amount that is feed into the system. The percent recovery depends on the concentration of the feed water and the system capacity. For this system, with a pump pressure of 120 psi, Table 2.2 shows the percent recovery possible for different concentrations of feed water. Both Filmtec® and El-Dessouky & Ettouney (E&E) estimations are shown. For this system, the maximum concentration of feed water is about 11,000 ppm. This system can filter natural sources of water such as rainwater, groundwater, and streams, rivers, and lakes. A system with a pump capacity over 400 psi should be able to filter seawater.

Table 2.2: Percent Recovery of Feed Water

Feed Water Concentration (ppm)	Recovery (%)	
	Filmtec®	E&E
12,000	0%	-
11,000	8%	-
10,000	17%	8%
9,000	25%	17%
8,000	33%	27%
7,000	42%	36%
6,000	50%	45%
5,000	58%	54%
4,000	67%	63%
3,000	75%	72%
2,000	83%	82%
1,000	92%	91%

Salt rejection is an important measurement for a reverse osmosis system. This value, represented as a percentage, depends on the concentration of the feed water (X_f)

and permeate water (X_p). The equation below shows how to calculate the salt rejection (SR).

$$SR = 100\% \, (1 - \frac{Xp}{Xf})^1$$

Another parameter that is important in reverse osmosis systems is permeate recovery, also given as a percentage. The permeate recovery (R) is calculated using the permeate flow rate (M_p) and feed flow rate (M_f) as shown in the equation below.

$$R = 100\% \, \left(\frac{Mp}{Mf}\right)^1$$

Of course the quality of the permeate is important in determining the success of the reverse osmosis system. The permeate is used for consumption purposes and should be of safe drinking water quality.

2.4 Water Quality Testing

To test for water quality, Pro-Lab® offers a “Do It Yourself Test Kit.” This kit tests for pH, total alkalinity, total chlorine, total hardness, iron, copper, nitrates, and nitrites. The results of the test determine if the water is safe to drink or not. The pH test measures the acidic or basic character of water and values in the range 6.5-8.5 is generally accepted as safe. Total alkalinity is the ability of water to resist changes in pH; ideal values are 80-180 ppm. Chlorine affects the taste and odor of water and may irritate skin and eyes. A concentration of chlorine below 4 ppm is considered safe. Water hardness is a measure of calcium and magnesium in the water and a value of 50 ppm is considered ideal. Water hardness is measured for considerations to plumbing. Soft water, less than 54 ppm can be corrosive to plumbing, but is not considered dangerous to drink. Iron can be present in water from minerals in the ground but high levels can cause discoloration in water; values below 0.3 ppm are considered safe. Copper may be present in water but high levels can cause jaundice, pancreatitis, poisoning of the red blood cells, gastrointestinal problem and anemia. Levels under 1.3 ppm are considered safe. Nitrate/Nitrite nitrogen presence in water can result from fertilizer, waste, and other geological elements. High concentrations can cause blood poisoning and be fatal, but nitrate concentrations under 10 ppm and nitrite concentrations under 1 ppm are considered safe. Table 2.3 summarizes the Pro-Lab® water quality ideal test results as well as its nominal sensitivity.

Table 2.3: Pro-Lab® Water Quality Test

Test	Ideal Result	Measurement Range
pH	6.5-8.5	2.0-12.1
Total Alkalinity	80-180 ppm	0-240 ppm
Total Chlorine	0.2-4 ppm	0-10 ppm
Total Hardness	50 ppm	0-425 ppm
Iron	0-0.03 ppm	0-5 ppm
Copper	0-1.3 ppm	0-5 ppm
Nitrate	0-10 ppm	0-50 ppm
Nitrite	0-1 ppm	0-5 ppm

To test the reverse osmosis system, three solutions were prepared with various concentrations of dissolved solids, based on the test sensitivity. Solution 1 is the low concentration solution, or the control with no chemicals added, just deionized water. Solution 2 is the mid-range solution with very low amounts of solids added. Solution 3 is the high concentration solution, considered unsafe or dangerous to drink. For each solution, three liters of volume were prepared. Potassium chloride was used to supply the chlorine. Magnesium acetate contains magnesium, to contribute to water hardness, as well as acetate, which affects the water’s pH. Iron (III) nitrate nonahydrate was used to add iron and nitrate to the solutions. Cupric sulfate provided the source of copper and well as sulfate affecting the pH of the water. The list of chemicals added and the specific amounts are shown in Table 2.4.

Table 2.4: Prepared Solutions Contents

Chemical		Weight (g)		
Name	Formula	Solution 1: Low	Solution 2: Mid-range	Solution 3: High
Potassium Chloride	KCl	0	0.013	0.072
Magnesium Acetate	Mg(CH3COO)2	0	0.348	2.843
Iron (III) Nitrate Nonahydrate	Fe(NO3)3	0	0.004	0.077
Cupric Sulfate	CuSO4	0	0.008	0.033
Estimated TDS (ppm)		0	124	1,008

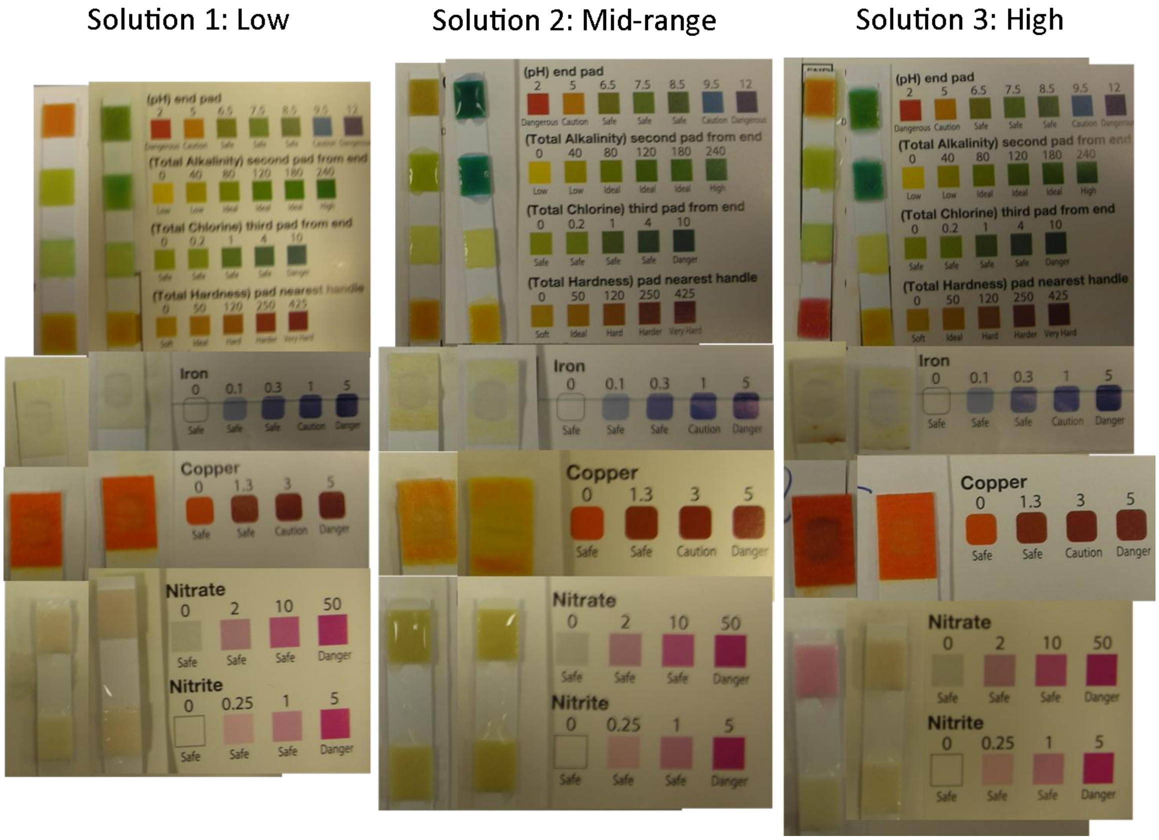
The solutions were tested as feed water, before entering the reverse osmosis system. The tests were performed using test strips where color hue and intensity can quantify chemical concentrations in the water, though the overall test is qualitative, determining whether the water is safe to drink or not.. The test results are summarized in Table 2.5, indicating where levels can be considered high/low or unsafe. Figure 2.3 shows the resulting test strips, before on the left and after on the right with the test key to compare.

Table 2.5: Water Quality Test Results

	Results					
	Solution 1: Low		Solution 2: Mid-Range		Solution 3: High	
Test	Before	After	Before	After	Before	After
pH	4 (caution)	8	6 (caution)	8.5	5 (caution)	8.5
Total Alkalinity	40 (low)	120	60 (low)	180	50 (low)	180
Total Chlorine	0.2	0.1	0	0	0.1	0

Table 2.5: Continued

	Results					
	Solution 1: Low		Solution 2: Mid-range		Solution 3: High	
Test	Before	After	Before	After	Before	After
Total Hardness	50	10 (soft)	50	10 (soft)	300 (hard)	10 (soft)
Iron	0	0	0	0	0.05	0.03
Copper	0	0	0	0	0.5	0
Nitrate	0	0	0	0	8	0
Nitrite	0	0	0	0	0	0


Solution 1: Low

Solution 2: Mid-range

Solution 3: High

Figure 2.3: Water Quality Test Result Strips

Generally, each solution before going through the reverse osmosis system had low pH and total alkalinity. Solution 3 had high total hardness. After going through the system, the permeate water was tested to be safe drinking water, having ideal pH, total alkalinity, and low concentrations for total chlorine, total hardness, iron, copper, nitrates, and nitrites. As expected, the reverse osmosis system produces safe drinking water.

With the proper test equipment, salt rejection and recovery could be measured accurately. Based on observation, the rate of intake of the feed water and rate of output of permeate were roughly the same, about 125 mL/min. Also, roughly 2.8 L of permeate were recovered from the feed water volume of 3 L for each of the three test solutions, giving a recovery of approximately 93%. This high recovery is due to the relatively low concentration of total dissolved solids in the feed water. With increasing concentration, the recovery will decrease.

2.5 Next Steps

2.5.1 PV Component

The reverse osmosis system was assembled and tested. Next steps include building/assembling a solar panel to power the pump. The pump can directly be powered by a PV system capable of supplying a load of 24 VDC.

Single solar cells can be obtained and arranged in a circuit to supply the required electricity to run the pump. The resulting photovoltaic panel can be made flexible for convenience and portability.

The RO system capacity of 50 GPD is significantly less than the previously calculated 1 MGD system. The same calculations, however, can be applied to determine the required area needed for the PV system to produce the electricity to run the RO system. Analogous to the calculations in Table 1.26, the values listed in Table 2.6 show the approximated size of PV panel needed to supple the 50 GPD RO system. This is assuming that the RO production of fresh water and energy consumption are scalable.

The calculation results show that about four by four feet square is the area needed, a feasible and manageable size.

Table 2.6: PV System Requirements for 50 GPD RO

RO System Capacity	50	gal
Fresh Water Production	0.19	m^3
Energy Required	0.80	kWh
Area Required	1.36	m^2
	14.6	ft^2

Once the PV panel is assembled and used to power the pump, the solar-powered reverse osmosis system can be taken to a fresh water source, a local lake or river, and be used to filter the water. The water produced should be of safe quality drinking water. This will be a proof of concept demonstration, assuming there is no energy lost. However, in reality, energy lost will need to be considered. Moreover, a battery will be needed to restore the solar electricity harvest at the hours of the peak solar power for the usage at later or evening time.

2.5.2 Additional Testing

In addition to water quality tests, other measurements can be taken to determine the overall efficiency of the system. The efficiency of the system will be a ratio of the theoretical energy required to desalinate the water and the actual energy required to desalinate the water, the equation shown below.

$$System\ Efficiency = \frac{T\hbar eoretical\ Energy}{Actual\ Energy} \times 100\%$$

The theoretical energy is the minimum power input required to produce fresh water. This can be calculated using the equation below, which calculates the minimum work required to produce fresh water[24]:

$$w_{min} = \frac{R_u T_0}{M_{product}} \left[\frac{\chi_{s,feed}\, \chi_{w,product} - \chi_{w,feed}\, \chi_{s,product}}{\chi_{s,feed}\, \chi_{w,brine} - \chi_{w,feed}\, \chi_{s,brine}} \left(\chi_{s,brine} \ln\left(\frac{(\chi_{s,brine})}{(\chi_{s,feed})}\right) + \chi_{w,brine} \ln\left(\frac{(\chi_{w,brine})}{(\chi_{w,feed})}\right) \right) + \chi_{s,product} \ln\left(\frac{(\chi_{s,product})}{(\chi_{s,feed})}\right) + \chi_{w,product} \ln\left(\frac{(\chi_{w,product})}{(\chi_{w,feed})}\right) \right]$$ [24]

where R_u is the universal gas constant (kJ/kmol K), T_0 is the temperature of the incoming water (K), $M_{product}$ is the mass of the produced fresh water (kg), χ_s is the mole fraction of salt, and χ_w is the mole fraction of water. The work is in units of kJ/kg of fresh water produced. Multiplying the minimum work by the mass flow rate of the produced water (kg/s) will give the minimum power input in kW. This will be the theoretical energy.

The mole fraction of salt and water of each of the three solutions, the feed water, the produced water, and the brine, can be determined based on the solution concentrations. A conductivity meter can be used to measure the conductivity of the solutions, which is proportional to the ion concentration of the solutions.

The actual energy is the electrical consumption of the pump. Knowing the pump potential (24 VDC for this system) and the current of the PV system, the power consumption can be determined. With all these measurements, the overall efficiency of the system can be calculated.

Chapter 3: Emergency Application Design

3.1 Single Element Design

There are several applications a solar-powered reverse osmosis system can be used for such as commercially, on sea vessels, or residentially. Also, with a small system, such as the 50 GPD system, a light-weight compact design can have other applications. A portable solar-powered reverse osmosis system can be used in remote locations near natural water sources, such as for camping, military, and emergency purposes.

A flexible photovoltaic panel is ideal for portable purposes. The option to fold or roll the panel allows for easy storage. Also, the 50 GPD system requires only a one-half foot square panel.

The reverse osmosis component does need to be optimized. The chosen pump should be as small and light-weight as possible while still having a high pressure capability. Also, the five stages can be compacted and combined into a single element. A "tube within a tube" design would work. The pre-filtration stages can be combined into a single filter, which would consist of the inner-most tube. Surrounding that would be the thin film reverse osmosis membrane, configured as a hollow tube. Surrounding the membrane would be the last filter. A cutaway schematic of the "tube within a tube" design is shown in Figure 3.1. These components layered as such combines the five stages into one element, requiring its own housing. This housing will be configured much in the same way as the standard filter housing with the inlet concentrated water feed in the center and the purified fresh water collecting at the outlet. An exploded view of the single element housing design is shown in Figure 3.2. The end cap is fully connected to the housing body, but cut of in the view to show the grooves to hold the single element and O-ring for a tight seal. Figure 3.3 shows the single element design with its housing.

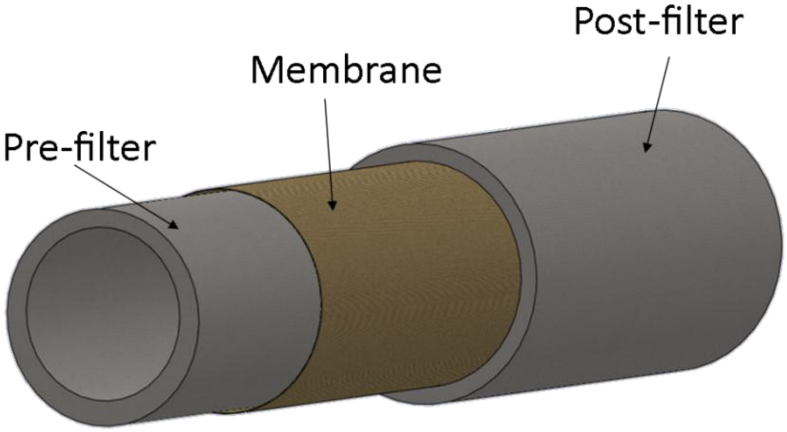


Figure 3.1: Tube within a tube design

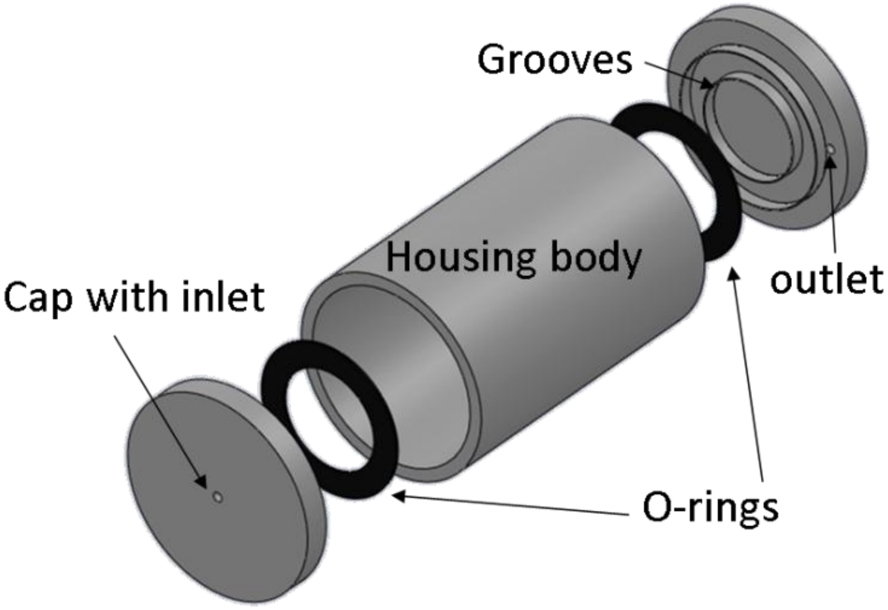


Figure 3.2: Single element housing design

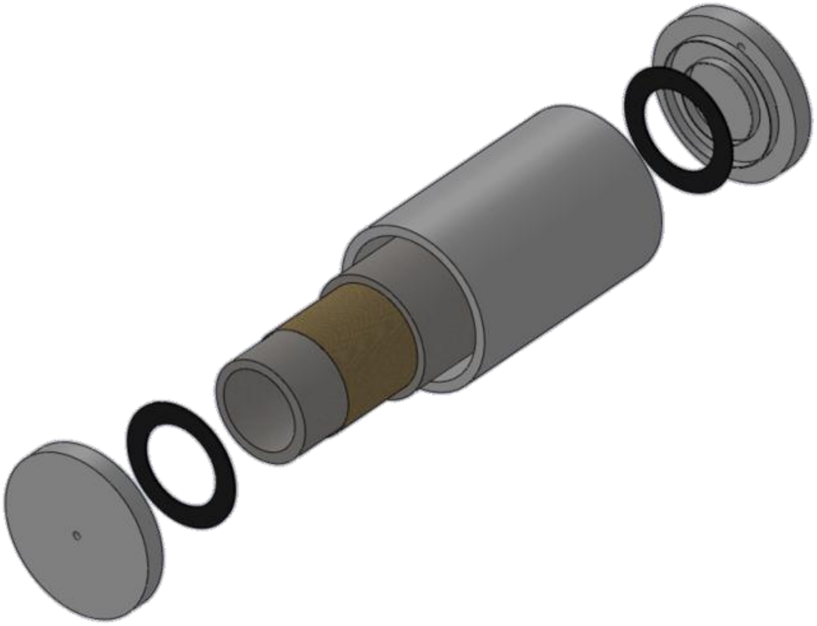


Figure 3.3: Single element with housing

Considerations for the single element design are the life time on each filter. The pre-filter, membrane, and post-filter parts should have close to the same life times to ensure maximum usage of the materials, since all three filters combine in a single part to be replaced at one time. Also, the housing may include a blockable output for buildup brine that can be opened and flushed to prevent highly concentrated solutions. Excess buildup will put unnecessary stress on the system, making it less effective over time.

The dimensions of this single element reverse osmosis system should be determined by the membrane size. The active surface area of the membrane correlates to the permeate flow capacity. In this specific case, a flow capacity of 50 GPD is used. Data from Filmtec was used to determine the relationship between membrane active surface area and permeate flow rate, shown in Table 3.1. Data was given for three commercial and light industrial reverse osmosis membrane model types: TW30/BW30 high rejection series, XLE low pressure series, and LP low energy/high solute rejection series. The three series were plotted, as shown in Graph 3.1, and trend lines added to determine a linear relationship. Given the desired flow capacity, the active surface area of the membrane can be calculated.

Table 3.1: Membrane Surface Area and Permeate Flow Capacity

Model	**Active Surface Area**		**Permeate Flow Capacity**	
	ft2	**m2**	**GPD**	**m3/day**
Filmtec TW30/BW30 Series High Rejection Commercial & Light Industrial RO Membranes				
Filmtec TW30-2514	7	0.7	200	0.76
Filmtec TW30-2026	7	0.7	220	0.83
Filmtec TW30-2521	13	1.2	325	1.23
Filmtec TW30-4014	20	1.9	525	1.99
Filmtec TW30-2540	28	2.6	850	3.2
Filmtec BW30-2540	28	2.6	850	3.2
Filmtec TW30-4021	36	3.3	900	3.4
Filmtec TW30-4040	78	7.2	2400	9.1
Filmtec XLE Series Low Pressure Commercial & Light Industrial RO Membranes				
Filmtec XLE-2521	13	1.2	365	1.38
Filmtec XLE-2540	28	2.6	850	3.2
Filmtec XLE-4021	36	3.3	1025	3.9
Filmtec XLE-4040	87	8.1	2600	9.8
Filmtec LP Series Low Energy/High Solute Rejection Commercial & Light Industrial RO Membranes				
Filmtec LP-2540	28	2.6	1000	3.8
Filmtec LP-4040	78	7.2	2900	11

Graph 3.1: Membrane Surface Area and Permeate Flow Capacity

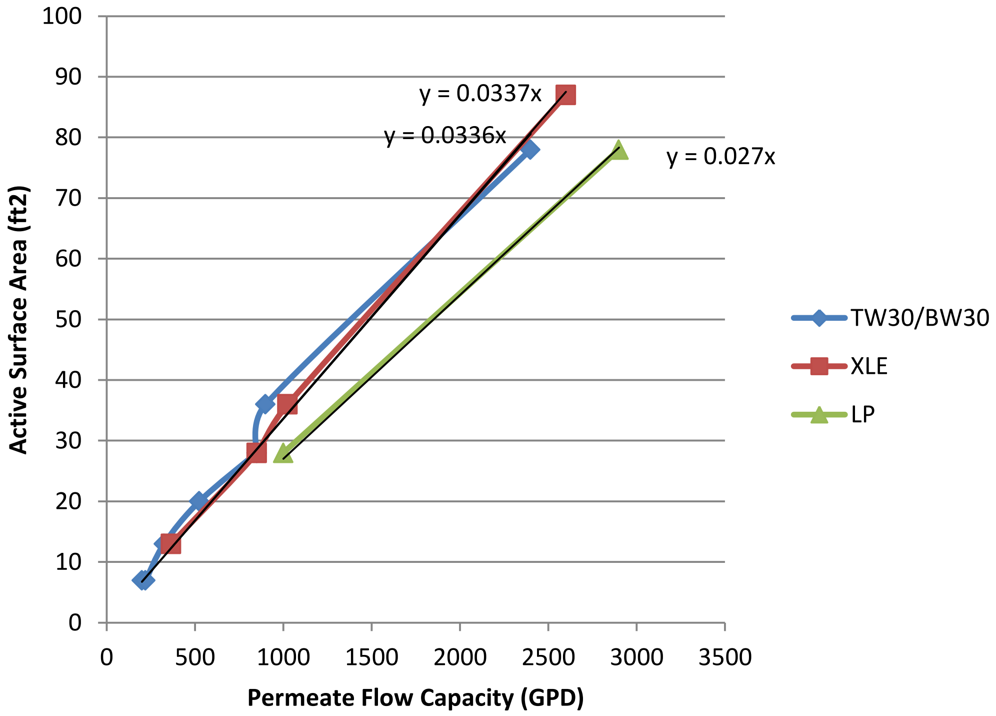


Table 3.2 shows the approximate active surface area of membrane needed for a permeate flow capacity of 50 GPD for the three model types, which is 1.35 ft^2 for the TW30/BW30 series, 1.685 ft^2 for the XLE series, and 1.68 ft^2 for the LP series.

Table 3.2: Membrane Surface Area for 50 GPD System

Needed Capacity (GPD)	50
	Surface Area (ft^2)
TW30/BW30	1.35
XLE	1.685
LP	1.68

For this, the dimensions of the single element reverse osmosis system can be designed. If the membrane is made to be one foot, or 12 inches, the radius and diameter of a tube configured membrane can be calculated, as shown in Table 3.3. The TW30/BW30 series gives the smallest dimensions. A tube configured membrane that is 1 foot in length would need to be approximately 5 inches in diameter to have a flow rate of 50 GPD.

Table 3.3: Dimensions for Membrane in 1 ft Tube Configuration

Radius	(ft)	(in)	(cm)
TW30/BW30	0.214859	2.57831	6.548908
XLE	0.268176	3.218113	8.174007
LP	0.26738	3.208564	8.149752
Diameter	(ft)	(in)	(cm)
TW30/BW30	0.429718	5.15662	13.09782
XLE	0.536352	6.436226	16.34801
LP	0.534761	6.417127	16.2995

Combined with the filters within, and surrounding, this single element housing can be approximated to be 1 foot in length and 6 inches in diameter, an entirely feasible size for a portable system. This single element along with the pump, rollable PV panel, and other necessary components, such as valves and tubing, can feasibly be stored together in a light-weight, sealable tube. This tube, containing everything necessary to provide quality drinking water, can be easily stored and carried, a strap can even be attached.

During an emergency situation, a 50 GPD system can provide drinking water to approximately 95 people, estimating that each person consumes about 2 liters (about 0.53 gallons) of water per day. Using a pump with a higher capacity will provide more water and can be used by more people. Needing only sunlight to run, such a device will be beneficial.

References

1. El-Dessouky, H.T. and Ettouney, H.M. *Fundamentals of Salt Water Desalination*. New York: Elsevier, 2002.

2. http://www.census.gov/ipc/www/idb/worldpopgraph.php (4.4.2011 12:18pm PDT)

3. Household Water Conservation. Penn State, College of Agricultural Sciences, Agricultural Research and Cooperative Extension (2008).

4. Residential Water Use Summary. *AWWARF Residential End Uses of Water study*. Aquacraft, Inc. and American Water Works Association Research Foundation, 1999.

5. The World's Water, Pacific Institute. The World's Water 2008-2009.

6. Carle, David. *Introduction to Water in California*. Los Angeles: University of California Press, 2009.

7. Lightbucket. *Large scale desalination: is there enough energy to do it?* Blog at WorldPress.com, April 4, 2008.

8. Lattemann, Sabine. *Development of an Environmental Impact Assessment and Decision Support System for Seawater Desalination Plants*. The Netherlands: CRC Press/Balkema, 2010.

9. Cooley, Heather; Gleick, Peter H.; Wolff, Gary. *Desalination, With a Grain of Salt: A California Perspective*. June 2006

10. Johnzactruba. *How Desalination by Multi-stage Flash Distillation Works*. Lamar Stonecypher, Bright Hub Inc., December 23, 2009.

11. Water-technology.net. *Umm Al Nar Desalination Plant, Abu Dhabi, United Arab Emirates*. Net Resources International, 2011.

12. Entropie Company. *Multiple Effect Distillation (MED)*. Veolia Water Solutions & Technologies – Water Treatment Specialist, 2010.

13. Wangnick, K. *2004 IDA Worldwide Desalting Plants Inventory No. 18*. Wangnick Consulting, June 2004.

14. Cipollina, Andrea; Micale, Giorgio; Rizzuti, Lucio. *Seawater Desalination, Conventional and Renewable Energy Processes*. New York: Spinger, 2009.

15. Thermal Water Dissociation. **H2 Power Systems Ltd**

16. Natural Gas Issues and Trends 1998. EIA – U.S. Energy Information Administration.

17. J. Goldenberg, T.B. Johansson, Eds. *World Energy Assessment Overview, 2004 Update*. United Nations Development Programme, New York, 2004.

18. California Energy Commission, *2009 Integrated Energy Policy Report*, Final Commission Report, December 2009, CEC-100-2009-003-CMF.

19. Pvresources® Copyright Denis Lenardic, 2011. http://www.pvresources.com/en/top100pv.php

20. Miller, Eric and Rocheleau, Richard. *Photoelectrochemical Hydrogen Production*. Proceedings of the 2000 Hydrogen Program Review. NREL/CP-570-28890.

21. James, Brian D.; Baum, George N.; Perez, Julie; Baum, Kevin N. *Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production*. Directed Technologies Inc., December 2009.

22. Bansal, A., Khaselev O., Turner, J.A. *Photoelectrochemical System Studies.* Proceeding of the 2000 DOE Hydrogen Program Review. NREL/CP-570-28890.

23. http://solar.ucsd.edu/

24. Cerci, Yunus, et.al. *Improving the Thermodynamic and Economic Efficiencies of Desalination Plants: Minimum Work Required for Desalination and Case Studies of Four Working Plants.* U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Environmental Services Division, Water Treatment Engineering and Research Group, D-8230. November 2003.