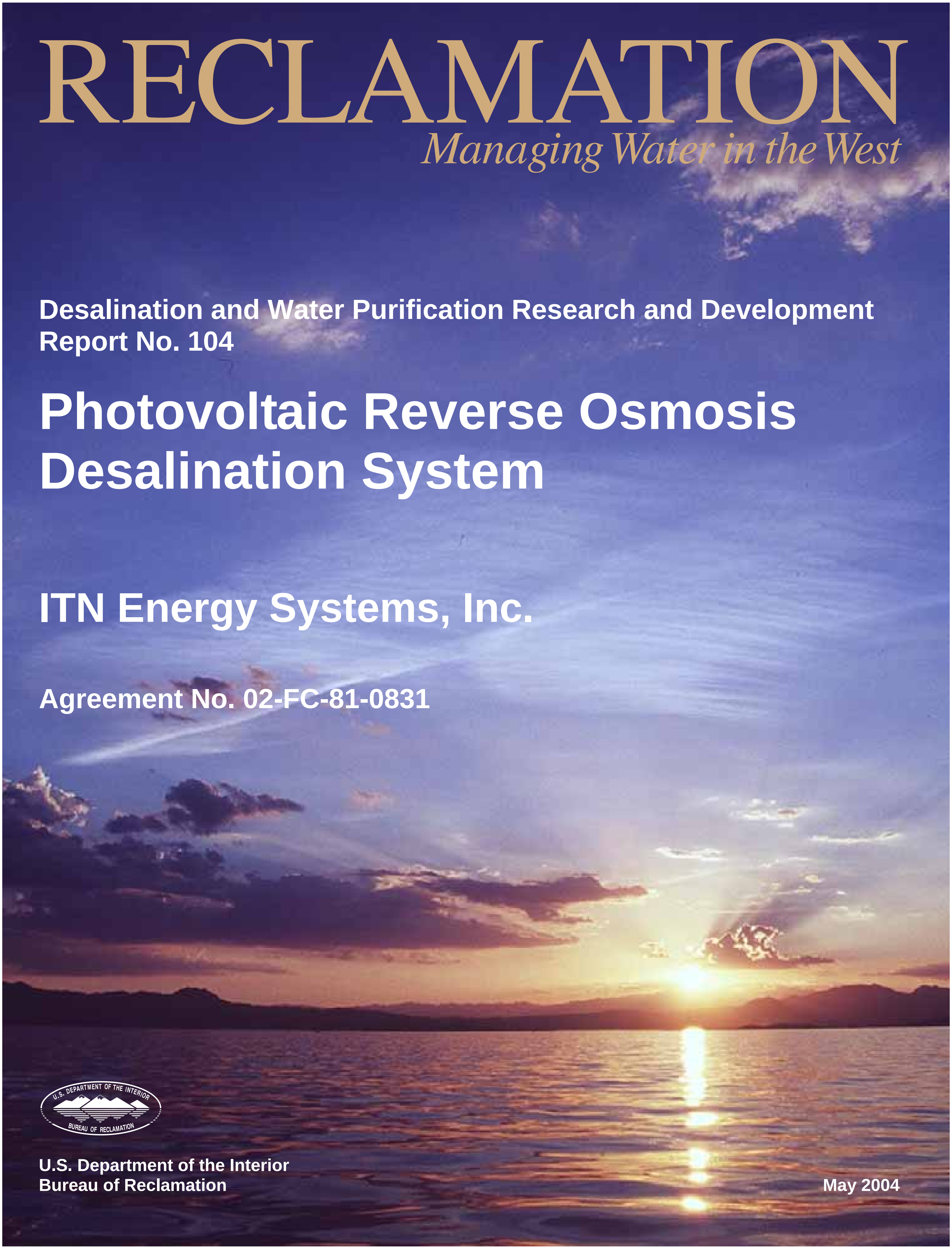

RECLAMATION
Managing Water in the West

Desalination and Water Purification Research and Development
Report No. 104

Photovoltaic Reverse Osmosis Desalination System

ITN Energy Systems, Inc.

Agreement No. 02-FC-81-0831

U.S. Department of the Interior
Bureau of Reclamation

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14. ABSTRACT

An energy efficient, cost competitive, modular, small-scale photovoltaic reverse osmosis (PVRO) desalination system has been developed and field tested. This PVRO system will fit the needs of off-power-grid communities that face drinking water shortages due to saline water problems. The system is powered directly by a photovoltaic (PV) array, without an inverter or battery. A variable-flow pump was utilized to compensate for the variable power output due to daily and seasonal solar intensity fluctuations. To ensure efficient system operation, a linear current booster or maximum power point tracker was used to match power available with load requirements. A solid state circuit was designed to detect a suitable power level set by the user and to activate a membrane rinsing cycle prior to shutdown.

The PVRO system was field tested for 3 months in Mesquite, Nevada. The PVRO system performed well overall, consistently desalinating water at Mesquite, which has a salinity of 3,500 parts per million (ppm) total dissolved solids (TDS), to water of 100 ppm TDS. During the field test, energy use per volume of water produced was 1.38 kilowatt-hours per cubic meter, which is low for a small system.

15. SUBJECT TERMS
desalination, reverse osmosis, photovoltaic, solar desalination, linear current booster, maximum power point tracker, scaling prevention

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Abbreviations and Acronyms

µS	microSiemens
AC	alternating current
Ah	ampere-hour
cm	centimeter
CREST	Critical Research on Economic and Social Transformation
DC	direct current
EDS	electron dispersive spectroscopy
EDTA	ethylenediaminetetracetate
gpd	gallon per day
gpm	gallon per minute
kW	kilowatt
kWh	kilowatthour
m^3	cubic meter
mg/L	milligram per liter
ND	not detected at the reporting limit
ppm	part per million
psi	pound per square inch
PV	photovoltaic
PVRO	photovoltaic reverse osmosis
Reclamation	Bureau of Reclamation
RO	reverse osmosis
SES	Solar Energy Systems
TDS	total dissolved solids
TSP	trisodium phosphate
UV	ultraviolet
V	volt
W	watt
WaTER	Water Treatment Engineering and Research Group

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1. Executive Summary

ITN has developed an energy efficient, cost competitive, modular, small-scale, photovoltaic reverse osmosis (PVRO) desalination system. This PVRO system will fit the needs of off-power grid communities that face drinking water shortages due to saline water problems. ITN's approach was to design a system powered directly by a photovoltaic (PV) array, without an inverter or battery. A variable-flow pump was utilized to compensate for the variable power output from PV due to daily and seasonal solar intensity fluctuations. To ensure efficient system operation, a linear current booster or maximum power point tracker was used to match the power available with load requirements. A solid-state circuit was designed to detect a suitable power level set by the user and to activate a membrane rinsing cycle prior to shutdown.

The PVRO desalination system, designed and built by ITN, was field tested for 3 months in Mesquite, Nevada, in collaboration with the Bureau of Reclamation (Reclamation) and the Virgin Valley Water District. The PVRO system performed well, despite a calcium sulfate scaling problem that occurred in early September. The PVRO system consistently desalinated water at Mesquite (which has a salinity of 3,500 parts per million (ppm) total dissolved solids [TDS]) to 100 ppm TDS. The PVRO system produced water at 1.38 kilowatt hours per cubic meter (kWh/m^3), which is low for a small system.

It was concluded from the field test that a method of automatically controlling water recoveries will be crucial to prevent membrane fouling when treating water with high scaling potential. The operating cost of the system can be reduced by using a passive tracking solar array and converting to a solid-state control system. Using nanofiltration or low energy reverse osmosis (RO), membranes could reduce energy use further. Designing solar-powered pretreatment modules will be essential for the application of this system in various environments.

2. Background and Introduction to Potential Solutions

Many regions of the world, such as parts of the southwestern United States and the Middle East, face the problem of saline water. A small-scale, solar desalination system is applicable to areas that have (a) saline water problems; (b) no access to the electricity grid; and (c) ample solar resources. In addition to these remote communities, a renewable, energy-powered desalination system could be very useful for a number of other applications, such as remote resort areas, national parks and forests, and military operations.

Electricity and heat are the most commonly used energy sources for desalination. While the desalination methods that require electricity (RO, electrodialysis) are typically more energy efficient than thermal desalination, a number of water scarce areas do not have access to the electrical grid. Using diesel generators in such situations constitutes a lower capital investment, but fuel transportation logistics and maintenance costs make their operational cost high. Solar electricity is a very attractive approach. Solar energy is a widely available renewable resource, and low maintenance of PV collectors makes it suitable for remote applications.

Traditionally, implementation of PV-powered desalination units is coupled with a battery and an inverter. This approach results in high cost of water production, reduced energy efficiency, and increased system complexity. In the PVRO system ITN designed, a high-pressure pump capable of variable flow was coupled directly to photovoltaic panels. This eliminates the need for the inverter and battery, resulting in a low-cost, energy-efficient system.

2.1 Current Technologies

Currently, there are few installations of photovoltaic reverse osmosis technology around the world. A number of them are “one-of-a-kind” systems; therefore, the capital and engineering costs are high [1][2]: typically greater than $100,000 for the installation of a 3 m^3/day facility (e.g., the installation in Tan Tan City, Morocco [3], or other installations listed in Reference [2]. number of these installations also use batteries or multiple energy backup [4] to run the system 24 hours per day. Consequently, the water production costs tend to be high (see table 1), and there are additional problems arising from failure of batteries, inverters, and other components such as wind generators.

To lower the cost of PVRO desalination, one of the most significant steps is to produce standard commercial units. For remote communities that need a solar desalination unit, the cost of a “one-of-a-kind” installation can be 5 to 10 times the cost of a mass-produced commercial unit. There is a great need for a small-sized unit that is carefully designed and tested. In the last few years, a number of companies have begun developing or started commercializing small-scale, photovoltaic powered desalination systems. Independent of ITN, these companies had determined that operation without storage batteries is optimal.

Solar Energy Systems (SES) in Australia is commercializing a PVRO unit, developed at Murdoch University, that is capable of producing 100 gallons per day of water from feedwater containing up to 5,000 ppm TDS. They have installed approximately 20 systems, primarily in the desert area of Australia. The system is designed for 15 to 20 percent water recovery. Part of the reasoning for the low water recovery is to reduce problems with scaling. One of the problems SES encountered were biological fouling of prefilters during field testing in Western Australia and Indonesia [5]. They also reported problems with plunger pump (manufactured in-house by SES) failure. They have since changed the design, so perhaps these failures are no longer a problem. Their brochure, available on the Web [6], estimated a cost of $0.01 per liter, which translates to approximately $30 to $40 per 1,000 gallons.

Table 1. Summary of renewable energy powered desalination systems

Renewable energy desalination	**Feed-water TDS (ppm)**	**Total RO installed power (kilowatts)**	**Water output per day (gallons)**	**Water cost (/$1,000 gallons)**	**Note**	**Advantages**	**Disadvantages**
PV-wind RO in Maagan Michael, Israel [4][10]	4,000	1.9-kW PV, 600-kW wind turbine, 3.5-kW diesel generator	847	25.9	Average 4 to 8 hours of daily operation.	Two different technologies for backup ensure continuous operation.	High cost. Wind turbine takes more maintenance than PV.
PV RO in Sadous Village, Saudi Arabia [1]	5,800	10.08			Intermittent operation.	Simple system.	High energy requirement with large PV panels translates to high cost. Intermittent operation only.
PV Electro-dialysis, Reversal [11] [12]	900	0.095	720		24-hour operation with battery.	Simple system. Low energy use for TDS < 2,000 ppm. Robust with different types of water.	Energy use gets very high as TDS increases; hence, not suitable for saline water with TDS > 2,000 ppm or seawater.
Solarflow units, Australia [13]	1,500–5,000	0.1	106	30 to 40	Day time operation only. 15% water recovery.	Simple system.	High energy use. Low water recovery. Piston and valve assembly have to be adjusted individually for different quality feedwater.

Recently, the government-sponsored research institute Critical Research on Economic and Social Transformation (CREST), in the United Kingdom and Dulas Ltd., had performed extensive modeling and simulation, selected components, and designed a 800-gallon-per-day seawater reverse osmosis unit powered by photovoltaic panels. They published their modeling result in 2002 [7][8] and were trying to obtain funding to build a research/pilot unit. From their modeling, they estimated water production costs of $12 per 1,000 gallons.

2.2 Proposed Solutions

Water production cost is a major factor when considering whether to use a renewable energy powered water desalination system. System costs may be reduced by several methods, including (1) RO system optimization, (2) improving the integration between PV and RO, and (3) lowering the cost of PV. In this project, ITN worked on measures to address energy efficiency and cost. Some of these measures include (1) using a direct current (DC) positive-displacement pump and energy recovery device, (2) cooling PV panels and preheating feedwater to reduce the RO energy requirement and to improve PV performance (and, hence, reduce the size of PV required and overall cost), and (3) using linear current booster. Using a linear current booster allows the system to function at low light conditions and improves energy output from the system by 15 to 20 percent. The linear current booster is also used to address the issue of solar energy fluctuations during the day.

Another part of the PV and RO integration involves using the feedwater to cool the PV panels and preheating the feedwater at the same time. ITN did an extensive literature survey on this topic, since there is a lot of interest in PV cooling in the industry. The additional cost to install PV cooling and feedwater preheating could be as much as 10 percent of the system cost. The gain in electrical output would be approximately 3 percent [9]. The main benefit of this method is that it will increase the feedwater temperature, resulting in approximately 20 to 30 percent higher water output in the RO process (based on temperature correction factor data of RO membrane). Overall, this approach should still be economically advantageous, even though it does increase system complexity.

3. System Description

3.1 Overall System Description

Figure 1 is a schematic of the first generation system designed, built, and tested in this research project. The PVRO system is a variable flow system (figure 2) that uses a DC pump powered directly by PV without intermediate battery storage. A linear current booster is used to convert the low-current, high-voltage power produced by the PV panels at low light conditions (early morning, late afternoon, and cloudy times) to higher-current, lower-voltage power that the pump needs for running under partial power conditions. This maintains high operating efficiency throughout the day.

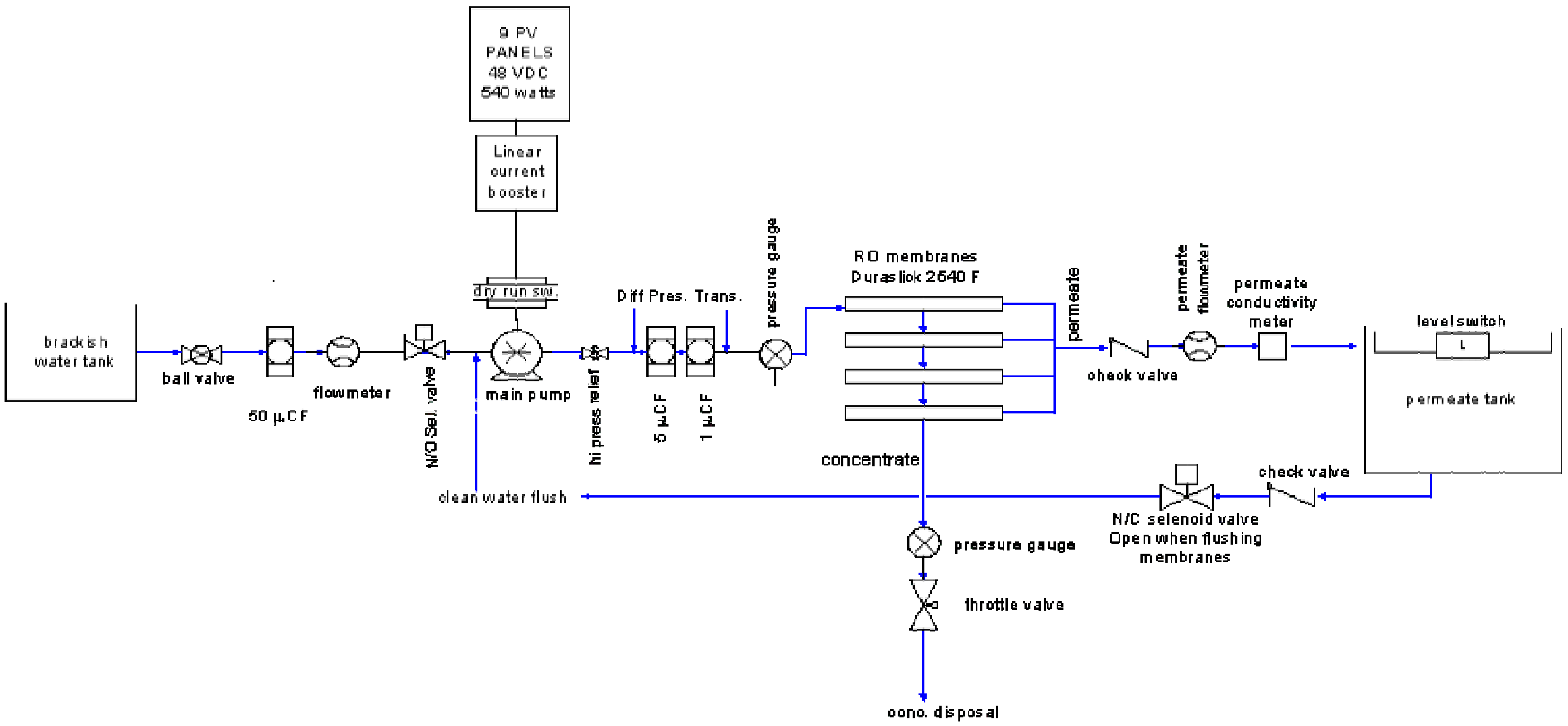

Figure 1. Schematics of first generation PVRO system built and tested in this research project.

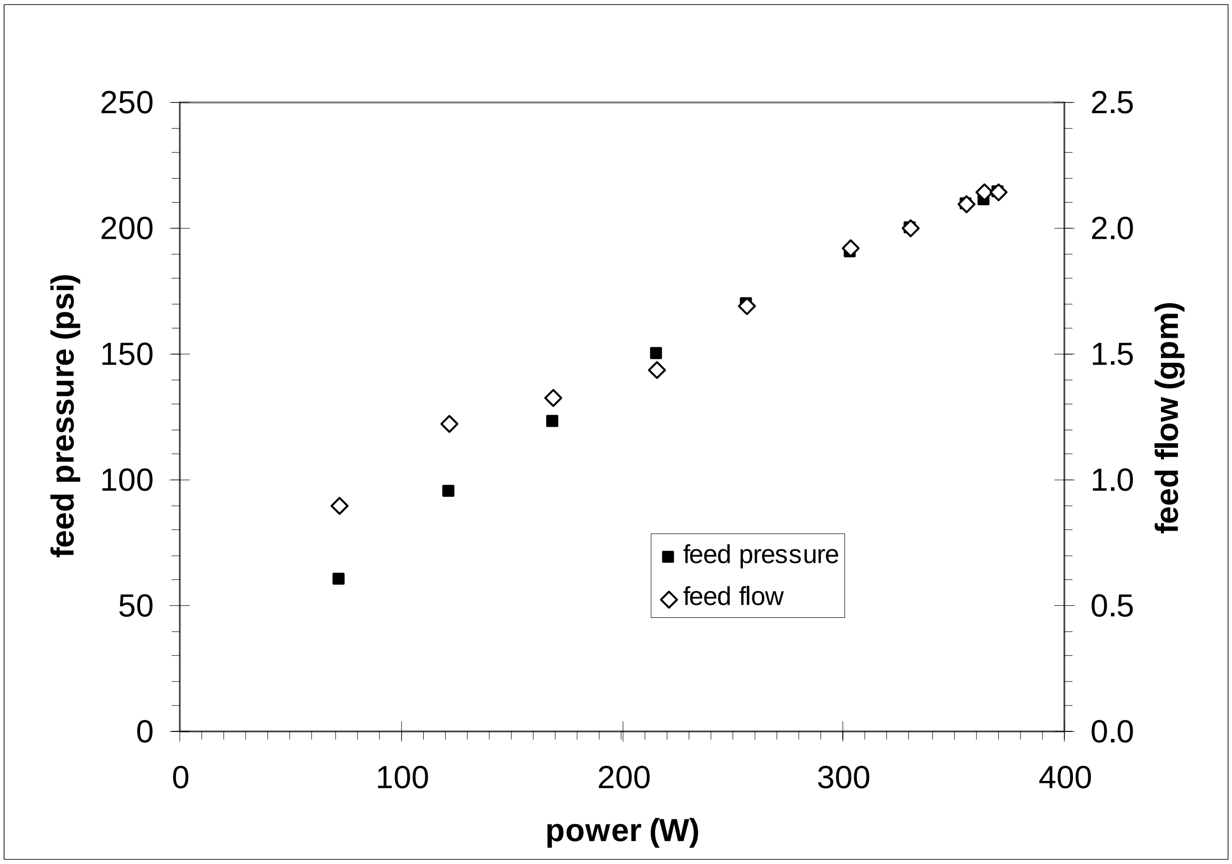

Figure 3. Data showing variable flow and pressure of the pump as a function of power generated from the PV panels. This set of data was collected between September 12 and October 1 in Mesquite, Nevada. Strictly, the data are not pump curves as feed pressure and flow rates will change if water recoveries were adjusted to higher (or lower) values.

3.1.1 Pump, linear current booster, and basic electrical schematics

ITN selected and tested a motor and pump combination called the Dankoff Solar Slow Pump 1403. This pump uses DC current, has good efficiency, and was well tested in solar water pumping applications. Equally important, both the pump and the motor have a reputation of having very few maintenance problems, with motor brush replacements needed typically every 3 to 5 years. Unfortunately, despite the Dankoff specification for a pumping capacity of 2.5 gallons per minute (gpm), the maximum flow rate was consistently 2.2 gpm. Data from the original pump manufacturer (Procon) indicated that the pump has a capacity of 2.3 gpm, with maximum pressure generated at approximately 250 pounds per square inch (psi). The next generation PVRO will use a larger pump to help produce more water.

ITN designed two sets of electrical connection schematics for the PVRO system that comply with the National Electrical Code. One of the schematics is for direct connection to the pump with appropriate disconnect, breakers, and grounding for safety. The other schematic connects the PV panel to a 12-volt, 104 ampere-hour battery via charge controller. This separate power supply is for all the electronics, gauges, meters, motorized valve (only needed temporarily when equipment goes into "night time mode"), and an ultraviolet (UV) disinfection unit because the electronics function best with a stable power source. The battery in the final production unit is likely to be much smaller because many of the gauges and sensors are for data collection, which will not be necessary in the final production unit.

3.1.2 Membranes

Fouling of RO membranes is a challenging issue for a reverse osmosis system that may be used to treat a variety of water sources including surface water. There are a number of low-fouling membranes available from different manufacturers. However, Osmonics is the only manufacturer that makes a "low-fouling" membrane element in the 2.5-inch-diameter size under the brand name Duraslick™. The principle behind the low-fouling design is an ultra-smooth membrane surface that reduces colloidal and microbial attachment. The pressure required to desalinate water using Duraslick™ is higher than for other thin film polyamide membranes, but not excessively so, and it is certainly lower than for cellulose acetate RO membranes. Consequently, Duraslick membranes were selected for the PVRO system, with four 2.5-inch Duraslick membrane elements in series to achieve an overall water recovery of approximately 50 percent.

3.1.3 On-off control and rinsing prior to shutdown

ITN included a design feature to allow permeate water to flush the membranes prior to evening shutdown to reduce fouling potential. This cycle needs to be activated when there is still sufficient power available for the pump to flush the membrane without wasting energy that could otherwise be used for water production.

The on-off cycle was initially controlled using a commercial light intensity sensor, which contains a photoresistivity device to detect daylight levels. These levels are then utilized to turn the system on and off and to initiate flushing of the RO membranes prior to shutdown. However, the commercial light intensity sensor, which is normally used to turn on or off outdoor or indoor lighting, was unsuitable for controlling the on-off cycle. It failed to initiate flushing of the membranes at repeatable power output levels from the PV panels. Therefore, ITN developed an electronic circuit that senses short-circuit current from a separate, small solar cell to initiate the on-off cycle. There is a built-in adjustable delay, so that passing clouds or short changes in current generated during the day would not cause the system to shut down repeatedly. The optimum length of delay and level of on and off can be determined by analyzing power output fluctuations over a number of days and measuring pump performance in the laboratory. We have arrived at an algorithm that can successfully flush the water almost 100 percent of the time. The less than 100-percent success rate is partly because of the rapid changes in weather at the testing site in the foothills of Colorado, where solar intensity can drop rapidly in a short time. In such cases, by the time the flush cycle is initiated, the PV panels are no longer receiving enough light to power the pump.

3.1.4 Other controls

Water recovery in the system was controlled by manually adjusting a throttle valve (or needle valve) at the outlet of the concentrate line. This setup is similar to the one used in the Reclamation trailer and at most other desalination facilities. For the Reclamation trailer, the water recovery rates are monitored closely via remote dial-in and manual adjustments of the throttle valve. Since the PVRO system is powered directly by solar energy, both the feed pressure and water recovery increase as the PV power output increases. Therefore, the water recovery rate was adjusted at a time when solar intensity was close to the most intense level and the maximum water recovery fixed in the system so that water recovery does not increase to a level that may scale the RO membranes.

Other controls include membrane protection features such as differential pressure sensors across the cartridge filters and also across the RO membrane elements. The cartridge filters are the only components that need to be changed periodically; failure to change these filters could shorten RO membrane life and damage the pump over a period of time. The differential pressure gauge senses the pressure differential across the cartridge filters, and if it exceeds a certain value, an orange/amber light is illuminated, alerting users to change the cartridge filters. Similarly, differential pressure readings across RO membrane elements were also meant to warn against RO membrane fouling or scaling problems. However, in the field test at Mesquite, Nevada, differential pressure across the RO membrane elements did not appear to be necessarily better than actual pressure readings as an indication of scaling problems.

The control system also includes control based on salinity. When the salinity of output water exceeds a certain value, the users are warned with an orange/amber alarm. When the salinity exceeds an even higher preset value, the system will be shut down to ensure it does not continue to operate under unsuitable conditions for prolonged periods of time. During the field test in Mesquite, Nevada, it was observed that the permeate that was used to flush the system prior to nightly shutdown dissolved some of the minerals overnight, resulting in the permeate salinity reaching upwards of 500 microsiemens per centimeter (μS/cm) for a short period (less than 5 minutes) in the morning.

3.2 PV Cooling and Feed Water Preheating

The application of PV cooling and feedwater preheating at Mesquite is doubtful because of the very high calcium and sulfate concentrations at the site (table 2). Since calcium sulfate precipitation has a reverse temperature profile (i.e., the higher the temperature, the more likely precipitate will form), cooling the PV panels while heating feedwater would increase the likelihood of scaling in the RO membranes. Under mutual agreement between the principal investigator and the Bureau of Reclamation, it was decided that this feature would not be tested during this study.

Table 2. Water analysis results of raw well water and RO feed at test site in Mesquite, Nevada. RO feedwater is raw well water that has been pretreated by Reclamation. The raw well water analysis was conducted in June 2002, while the RO feed analysis was conducted in September 2003

Analyte name	Raw well water (mg/L)	RO feed (mg/L)
pH	7.46	7.20
Aluminum	ND	ND
Arsenic		0.00535
Barium	0.029	0.0328
Beryllium	ND	ND
Boron	1.6	1.65
Cadmium	ND	ND
Calcium	490	514
Chromium	ND	ND
Copper	ND	ND
Iron	3.8	ND
Magnesium	180	186
Manganese	0.94	ND
Nickel	ND	ND
Potassium	40	37.8
Silver	ND	ND
Sodium	460	322
Zinc	ND	ND
Chloride	610	580
Fluoride	0.78	0.63
Nitrate, as N	ND	ND
Phosphorous, total	0.035	
Silica	22	
Sulfate	1,600	1,600
Alkalinity, bicarbonate (as $CaCO_3$)	200	360
Alkalinity, carbonate (as $CaCO_3$)	400	ND
Alkalinity, hydroxide (as $CaCO_3$)	0	ND
Alkalinity, total (as $CaCO_3$)	400	360
Specific conductance	4,600 µS/cm	4,800 µS/cm
Total dissolved solids	3,910	3,480

ND ≡ not detected at the reporting limit for:

aluminum: 0.025 mg/L;
chromium, copper, and silver: 0.005 mg/L;
zinc: 0.05 mg/L;
beryllium and cadmium: 0.0025 mg/L;
nickel: 0.02 mg/L;
nitrate as N: 5.0 mg/L

4. Testing and Research Findings

4.1 Testing

4.1.1 Testing onsite at ITN

In the third quarter of this project, a PV and battery system (for electronic monitoring and data recording instrumentation) was installed onsite at ITN, and the integrated PVRO unit was tested while being powered entirely by solar energy. Sodium chloride was used to make feedwater. To reduce the volume of water used for this onsite testing, concentrate and permeate produced from the RO process were recirculated and remixed with feedwater constantly. Even though the system was running from May to July, the data logging system was not completely functional at that period, and accurate water production data for that period is not available. Consequently, only water production for the period between mid-July and mid-August is shown in figure 3.

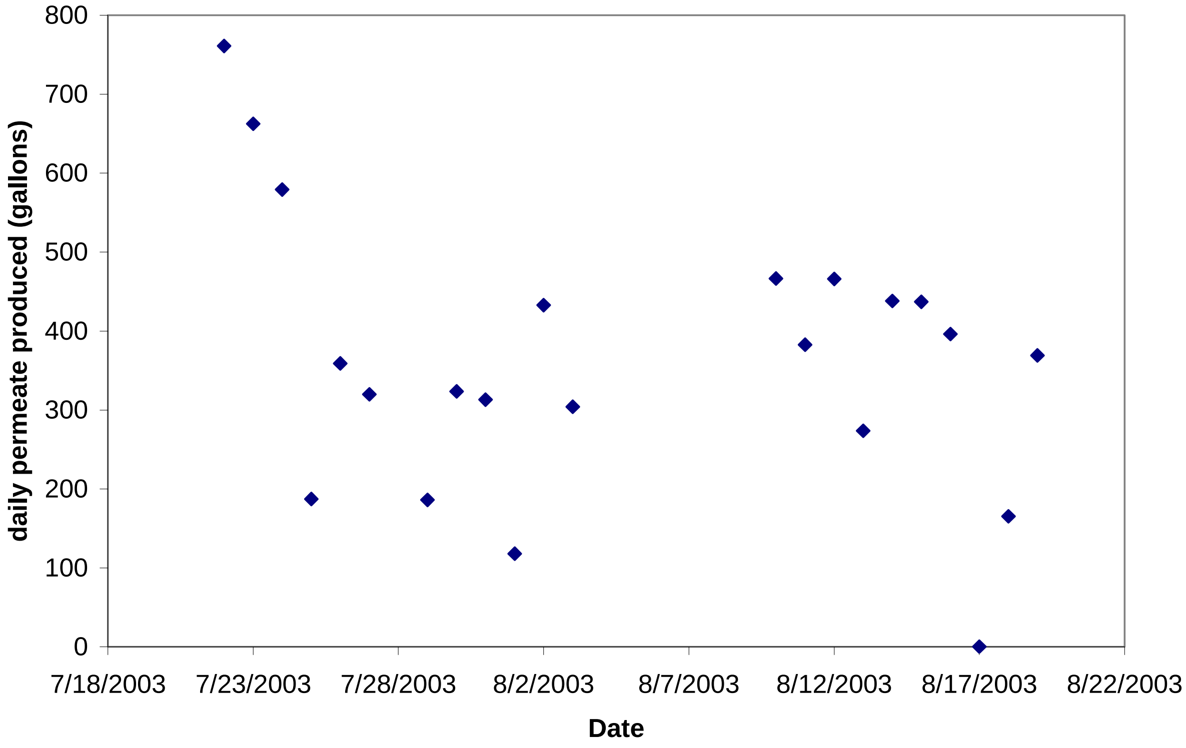

Figure 3. Water production at ITN campus.

The PVRO system (figure 4) was running at 40 to 50 percent water recovery, producing approximately 400 gallons per day (gpd) of permeate. There was no scaling or biofouling problem for the system during the 4-month test at ITN. Frequent summer thunderstorms in the afternoon in Denver reduced the daily production. The maximum power produced at Denver (49.5 volts [V], 8.83 amperes [A], 440 watts [W]) was close to the pump specifications (48.0 V, 10.0 A, 480 W).

Figure 4. PVRO research unit being tested at ITN campus from May to August 2003.

4.1.2 Testing at Mesquite, Nevada

From late August to late October 2003, the PVRO system was field tested at Mesquite, Nevada (figure 5), in collaboration with Reclamation's Water Treatment Engineering and Research Group (WaTER) and Virgin Valley Water District. Water at the site came from a Ranney well near the Virgin River. It is quite saline, with high concentrations of calcium, sulfate, iron, and manganese (table 2), as well as high concentrations of sulfate-reducing bacteria. The high calcium, sulfate, iron, and manganese levels each can cause scaling problems. In addition, the sulfate-reducing bacteria can also cause biofouling problems.

Figure 5. Setup of PVRO system in Mesquite, Nevada.

Pretreatment of the raw well water was performed by equipment designed by WaTER. An ozone generator and contactor were used to reduce microbial population and to provide an oxidant that oxidizes iron and manganese in the system. The oxidized iron and manganese then form iron oxyhydroxide and manganese oxide precipitates that can be collected in a flocculation tank or filtered with multi-media and green sand filtration. Hypersperse™, an antiscalant from GE Betz, was added in a pretreatment step prior to nanofiltration or reverse osmosis to protect against scale formation and colloidal fouling. Water quality after pretreatment is shown in table 2 (RO feed). Calculations indicate that at a dosage of 3 milligrams (mg/L), water recovery of approximately 60 percent can be achieved with the use of Hypersperse™ antiscalant. In practice, using the Reclamation trailer to desalinate water from the site, WaTER concluded that to successfully prevent scale formation, 50-percent water recovery on the RO feedwater was the limit. Experience by WaTER also showed that if water recovery was set at 60 percent, scaling would occur.

Because the location of the PVRO system was slightly higher than the Reclamation trailer, an alternating current (AC) powered lift pump had to be installed to pump water from the Reclamation trailer to our feedwater tank (an elevation of approximately 7 feet and a distance of approximately 100 feet).

4.1.2.1 Chronological accounts of key events at Mesquite

A chronological list of key events at Mesquite is given below:

- The PVRO desalination system was installed at the Mesquite field site during the week beginning August 25, 2003. Initially, water recovery was set at 50 percent.
- Scaling of RO membranes by calcium sulfate occurred between September 1 and September 8. Resistance in the last of the four RO elements was so high that the connection between element number 3 and 4 burst. System was shut down on September 8. Analysis of the last membrane in the series showed that mineral scale had built up in the system. Electron dispersive spectroscopy (EDS) analysis on the mineral scale found in the membrane was conducted and indicated that the scale was calcium sulfate (figure 6).
- Burst water line repaired on September 12.
- System ran with only three elements at a total recovery of approximately 25 percent (the membrane was on factory backorder) from September 12 to October 1.
- The remaining three elements were taken out and cleaned with ethylenediaminetetraacetic acid (EDTA) and trisodium phosphate (TSP) on October 1. These three elements were put back in their original position.
- The lift pump (AC electrical power) that pumped water from Reclamation pretreated water tank to our site failed on October 6. System was shut down for 2 days until a replacement lift pump was put in place.
- During a cartridge filter change (every 2 weeks) on October 12, an O-ring was inadvertently left out of the cartridge filter holder. This led to cavitations of the pump and much lower feed pressure than otherwise could be produced by the pump. Consequently, water recovery and water production were low from October 12 to October 26.
- A new Osmonics Duraslick© membrane was put in the fourth element position on October 27. The water recovery was adjusted to 35 percent.

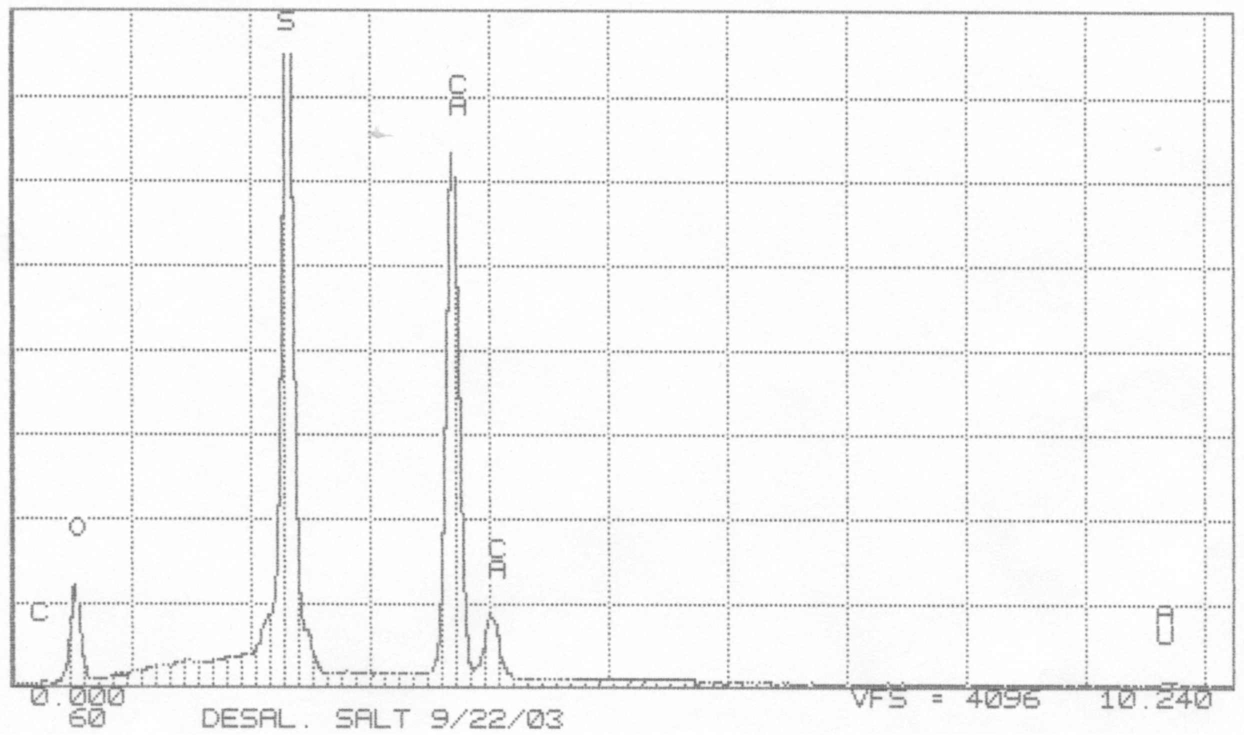

Figure 6. Electron dispersive spectroscopy spectrum of calcium sulfate scale in the RO membrane, showing dominance of calcium and sulfur lines. Oxygen and carbon were not determined quantitatively in this EDS scan.

4.2 Detailed Descriptions of Research Findings

4.2.1 Water production and storage

Figure 7 shows water production for the dates of the Mesquite field test. In a standalone photovoltaic powered desalination system, water is only produced when there is available solar energy. On cloudy days, the insolation available is either reduced or not sufficient to power the pump for reverse osmosis. For example, during the 4-day period of November 9 to November 12, permeate production was only at 156 gallons total (with no water production on November 9 and November 12 and a production of 149 gallons on November 10). For remote communities, the reduced water production during this period can present significant problems. Several options are available to overcome this problem:

- Storing excess water in a tank. This can be achieved by sizing the PVRO system slightly larger than the expected daily consumption and sizing the tank to hold sufficient water for 2 to 3 days of consumption.

- Storing excess energy in batteries. In this case, the PV array needs to be large enough to produce excess energy for storage in batteries. This option is expensive and inefficient for several reasons:

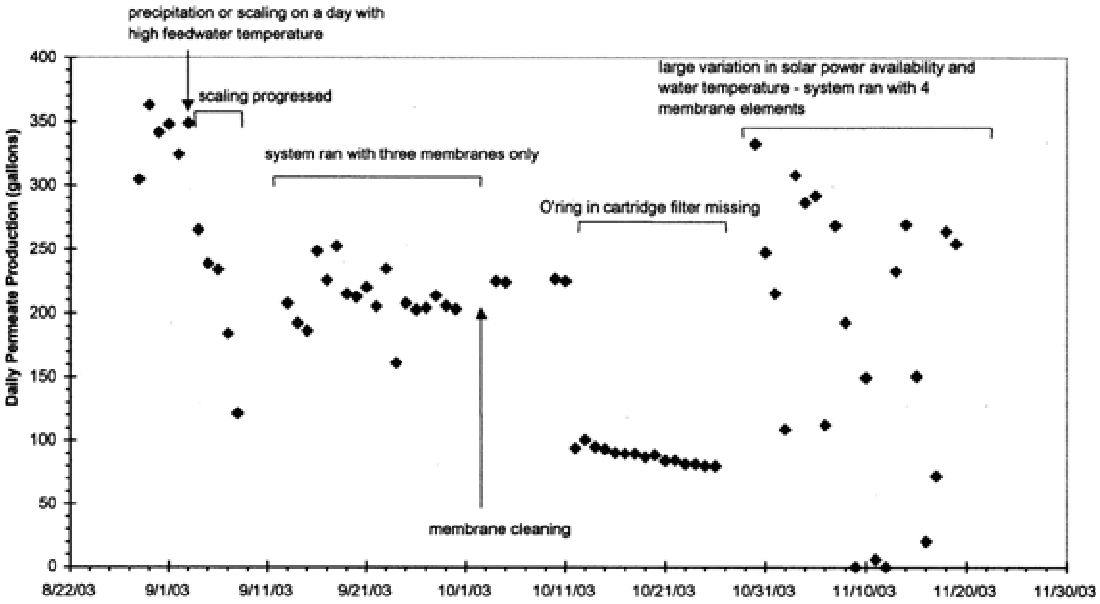

Figure 7. Daily permeate production at Mesquite, Nevada.

- Battery has a round-trip efficiency of 80 to 85 percent, (i.e., approximately 15 to 20 percent of electrical power is lost when it is being stored in batteries and when it is being discharged from batteries).

- Additional power stored in batteries is often measured in number of days of storage. The more days of storage, the higher the cost.

- Hybrid systems. These could involve a standby generator powered by propane or diesel. Another option would be a wind-PV hybrid system in regions where wind energy is also abundant. The decision to use a hybrid system is primarily dependent on two factors: (1) the size of the load (in this case the size of the pump), and (2) seasonal variability in solar insolation. Reference [14] has a graph that shows when it is economical to consider adding a generator into the PV system. In general, the larger the system, the more economical it is to build a hybrid system. This is because the control for a hybrid system is more complex, and the capital and maintenance cost is higher for a hybrid system.

By comparing our load data to that in Reference [14], our system would be more economical without a generator. Of the remaining two options, storing excess water in a tank is the least complicated and least costly. See table 3 for approximate cost comparison between larger tanks and larger battery banks.

Table 3. Cost comparison between storing water and storing electricity in batteries

	Tank storage of water	Battery storage of electricity
1-day storage	$396 (550 gallons)	$660 (4 of 12-volt, 104 amp-hour batteries)
2-day storage	$558 (1,100 gallons)	$1,320 (8 of 12-volt, 104 amp-hour batteries)
3-day storage	$670 (1,500 gallons)	$1,980 (12 of 12-volt, 104 amp-hour batteries)

Notes: First order comparison between tank and battery storage cost. Battery price is based on Concorde SunXtender sealed, deep-cycle battery. Other lower cost options are available but require more maintenance.

Notes on approximate calculation for battery size:
Amp-hour load for pump: 10 Ah
Number of hours per day when pump is operating: 8 hours
Required battery capacity = amp-hour load / maximum depth of discharge = 10 * 8 / 0.7 = 114 Ah
System voltage is 48 V; therefore, approximately four 12 V, 104 Ah batteries are required.
No temperature correction is done for this calculation.

4.2.2 Water recovery and scaling control

Water recovery on the PVRO system is controlled by a needle valve on the concentrate discharge line. Because the pressure from the RO pump increases as the insolation increases (figure 2), and because water recovery also increases as pressure from the RO pump increases, water recovery for the PVRO system is directly dependent on the insolation and power produced (figure 8). Adjusting the water recovery using a DC power supply (setting the power to the high side of the pump limit), or at a time when solar intensity is highest, would essentially adjust for the highest water recovery in the PVRO system. If the temperature were to stay constant, then water recoveries at other times would stay below the maximum allowable limit. In this case, we did the water recovery adjustments during the week of August 25, 2003 to approximately 50 percent.

In the field test, both the insolation and water temperature affected the water recoveries. By examining the data from late August to early September, it seems likely that uncontrolled water recoveries led to scale formation in the system. Water recoveries started increasing on September 1, 2003, when there were brief periods when the insolation was higher than the level on August 28, 2003 (the day water recovery was set). On September 2 and 3, water recoveries in the system increased further. There are several possible explanations for this observation. One explanation was that as a thin layer of scale precipitated in the system, higher resistance for waterflow existed in the concentrate line and the pump compensated by producing higher pressure which, in turn, increased water recoveries. The other possible explanation was that a higher average temperature on September 2, 2003, increased water recoveries, which led to more formation of scale (figure 9). Furthermore, calcium sulfate has inverse solubility (i.e., the solubility decreases as temperature increases, which could also promote formation of scale on membrane surfaces when water temperature was high). The next several days' water temperatures were all higher than the previous few, which perpetuated the cycle (see Appendix). Overall, water temperature might have had a larger effect because the power available during the days when water recoveries started going out of control (September 2-4, 2003, was relatively constant, while water temperature on average was higher (see figures 9 and 10 and the Appendix).

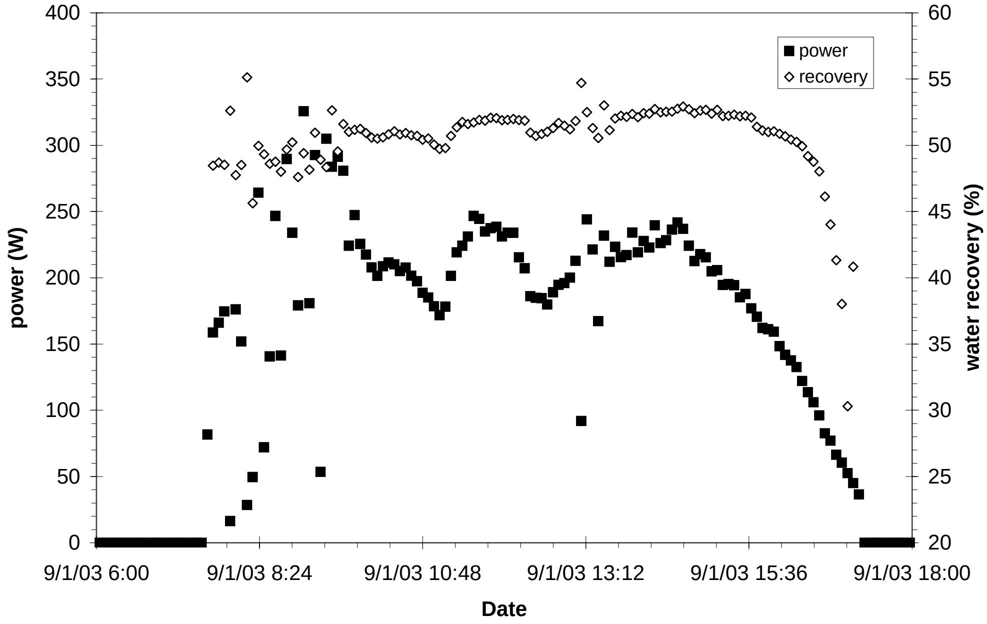

Figure 8. Relation between water recovery and power on a 5-minute interval.

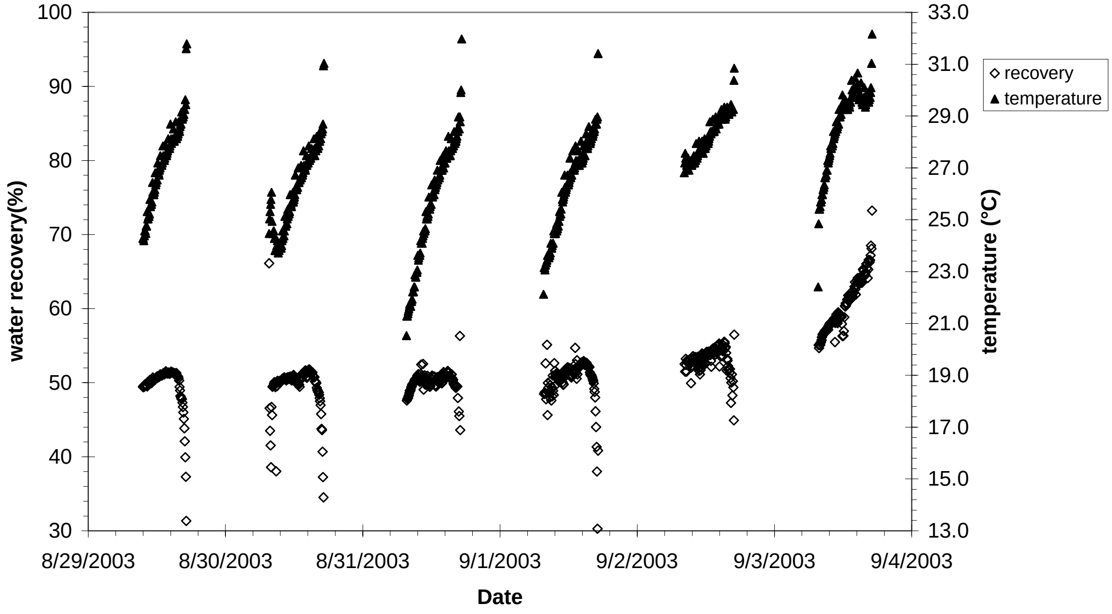

Figure 9. Relation between temperature and water recovery in the early part of Mesquite field test.

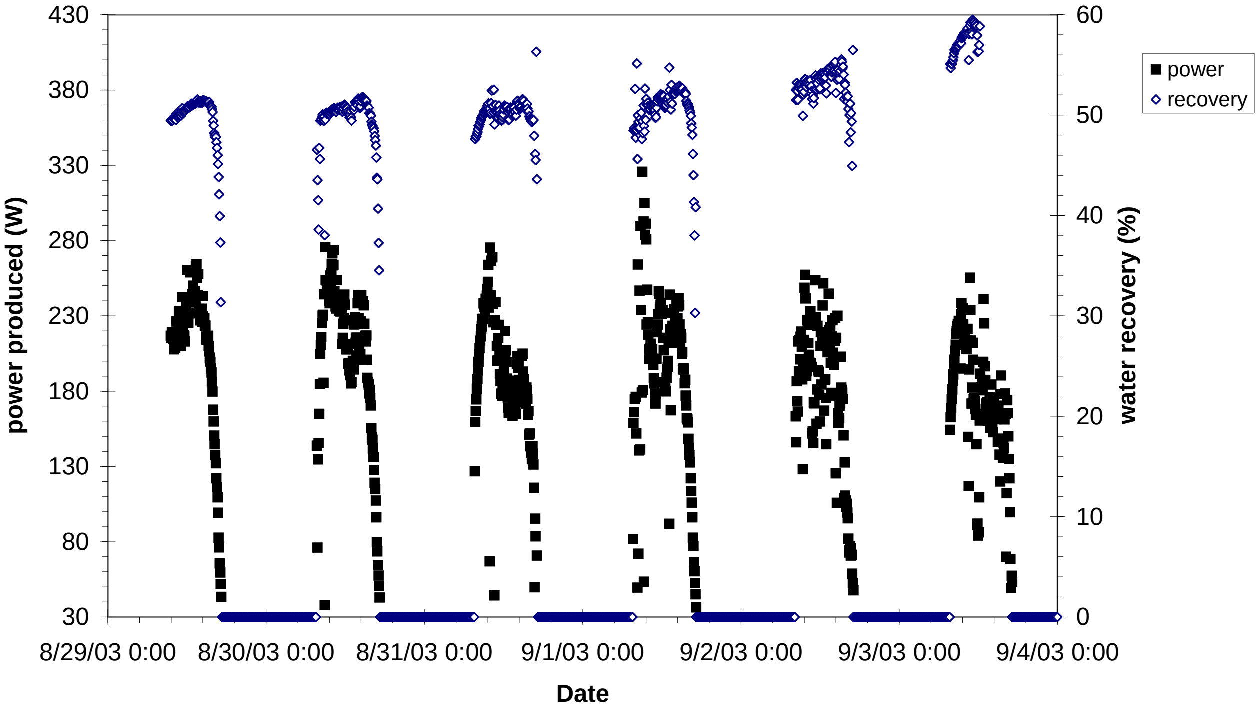

Figure 10. Water recovery and power produced during the period August 29, 2003 to September 4, 2003.

Regardless of the root cause of the scaling of the membranes, it is apparent that careful control of water recoveries would be crucial for the system. Even a battery-based system with the speed of the pump fixed would need this because water temperature could be a very important factor.

4.2.3 Water recovery and energy efficiency

In order to minimize the scaling potential, water recovery should be set as low as possible. On the other hand, it is well known that running the system at low water recovery can turn out to be quite inefficient. As shown in figure 11, energy per volume of permeate decreased as water recovery increased to 50 percent.

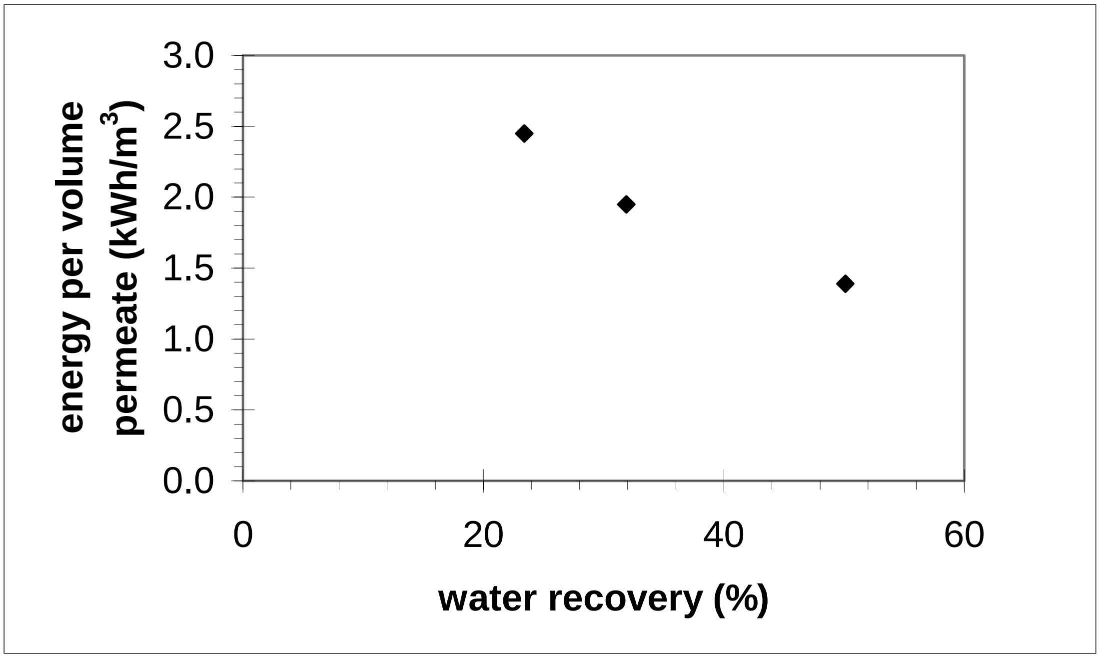

Figure 11. Energy per volume of permeate versus water recovery. Data obtained in Mesquite, Nevada, between August and November 2003.

4.2.4 Power produced and system sizing

Another important lesson from the Mesquite field test is that using PV panels larger than pump specification will most likely lower the water production cost. An examination of the day-to-day run data shows that the average power delivered to the pump is approximately 60 to 70 percent of the maximum power in the period (figure 12). The average permeate production rate is approximately 70 percent of the maximum permeate production rate. Making the PV panels larger will effectively increase the average amount of power produced. This is because power produced in the morning, evening, and on cloudy days will increase, which makes the overall average higher (e.g., in figure 13, the permeate production curve would approach a box function, rather than a bell shape function).

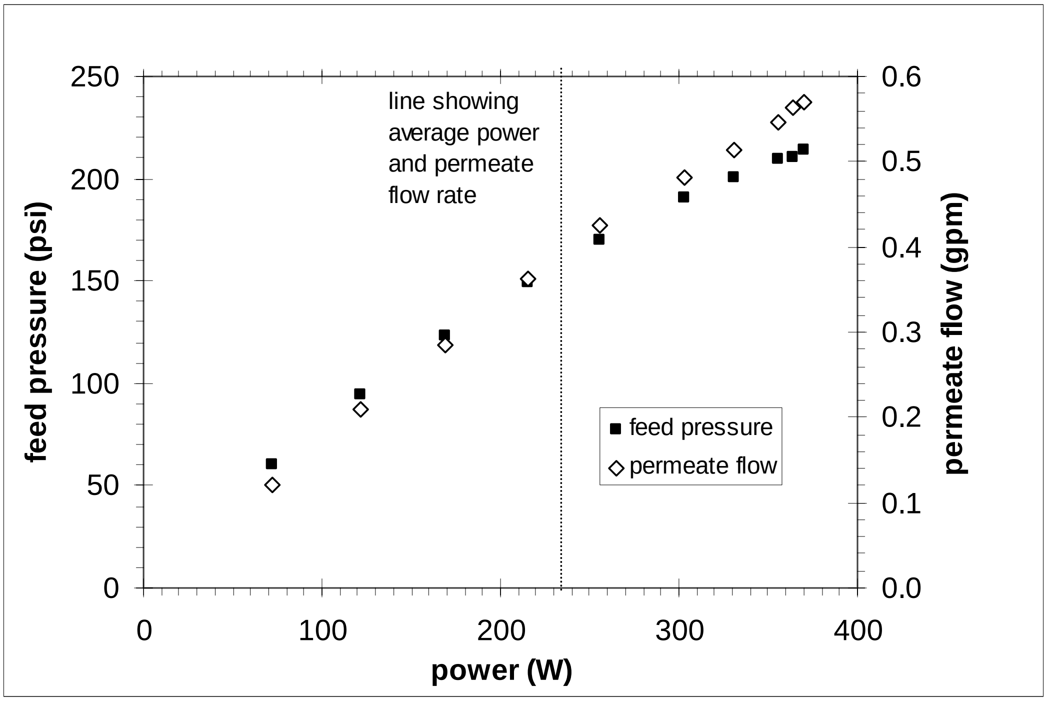

Figure 12. Average power and permeate production during the period September 12 to October 1, 2003 when water recovery was limited to only 27 percent.

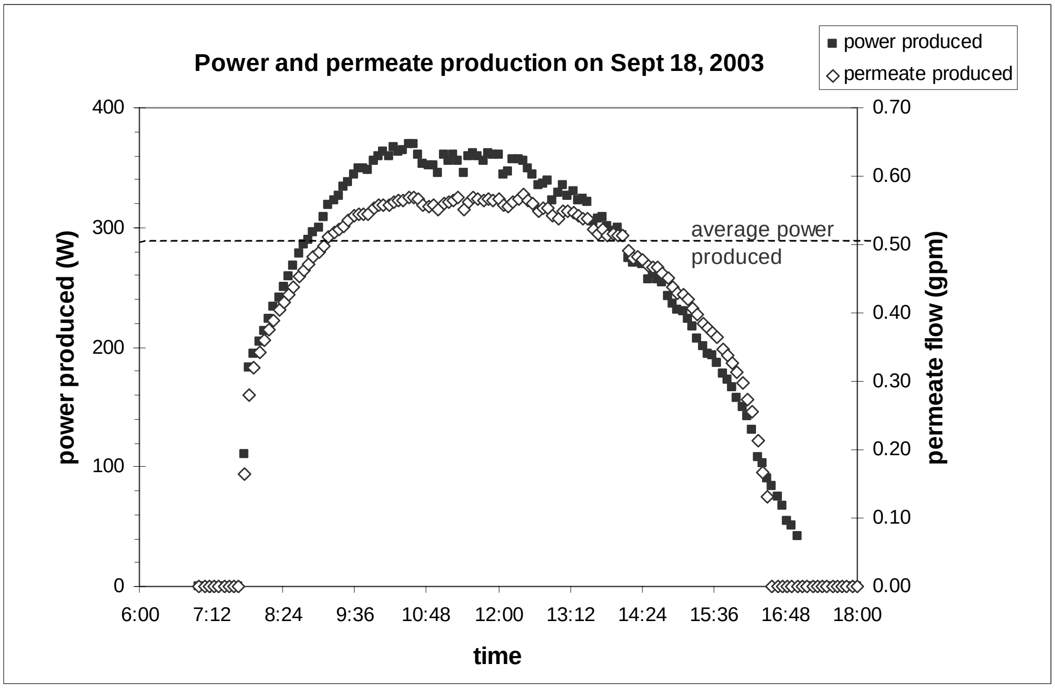

Figure 13. Hourly variation of permeate and power production on a typical day at Mesquite, Nevada (September 18, 2003). Using larger PV panels will increase energy production during the "nonpeak" hours and increase drinking water production.

It is estimated that increased average power production will increase the average amount of water produced by approximately 20 to 30 percent, while the increase in capital cost of the complete PVRO system will be approximately 6.4 percent. Consequently, the water production cost would be reduced from $13.80 per 1,000 gallons to 11.60 per 1,000 gallons, or a reduction of water production cost of 16.0 percent. Using larger panels will result in excess power (power in excess of the rated pump capacity) being produced at certain times. However, the linear current booster can limit the power delivered to the pump to prevent this excess power from damaging the pump. We may also include an algorithm for using excess power to charge the battery (for gauges and controls and UV disinfection), rather than having a dedicated PV panel for the battery.

4.2.5 Energy use for water of different salinities

Table 4 shows the energy use for three different salinities of feedwater. As expected, when salinity increased from 1,300 to 1,900 TDS, energy use per volume of permeate increased. When the equipment was moved to Mesquite, even though the salinity of feedwater increased substantially, energy use decreased slightly. This could be largely due to the feedwater tank being slightly higher than the pump (tank was 7 feet above pump at Mesquite, compared to 2 feet above pump at ITN), providing some additional head pressure and reducing the system energy needs.

Table 4. Comparison of energy expenditure for water production at different water recoveries

Time period	Conductivity (µS/cm)	Salinity* (TDS)	Average water recovery (%)	Energy use (kWh/m^3 permeate)	Notes
7/22 to 8/12	2,631	1,300	52.8	1.29	Feedwater tank 2 feet above pump; 6000-foot elevation
8/13 to 8/19	3,720	1,900	40.7	1.50	Feedwater tank 2 feet above pump; 6000-foot elevation
8/29 to 9/1	4,800	3,480	50.1	1.38	Feedwater tank 7 feet above pump

*Salinities from July 22 to August 19 were obtained by dividing conductivity by 2 (common multiplier for the relation between salinity and conductivity of pure sodium chloride at this low concentration range). Feedwater salinity at Mesquite was based on actual TDS measurements.

4.2.6 Conductivity of permeate

The permeate conductivity is shown in figure 14. During the initial operation of the system, permeate conductivity was consistently at approximately 30 to 40 µS/cm. Using a multiplier of 1.38 for water from this source, this corresponds to product water of approximately 25 µS/cm. On October 2, we cleaned the first three membrane elements left in place using EDTA and TSP.

Afterwards, conductivity of the water was in the range of 90 to 160 µS/cm, corresponding to water of approximately 90 TDS. The water is still well within drinking water standards, but it appeared that EDTA and TSP might be too harsh for the Duraslick© membranes.

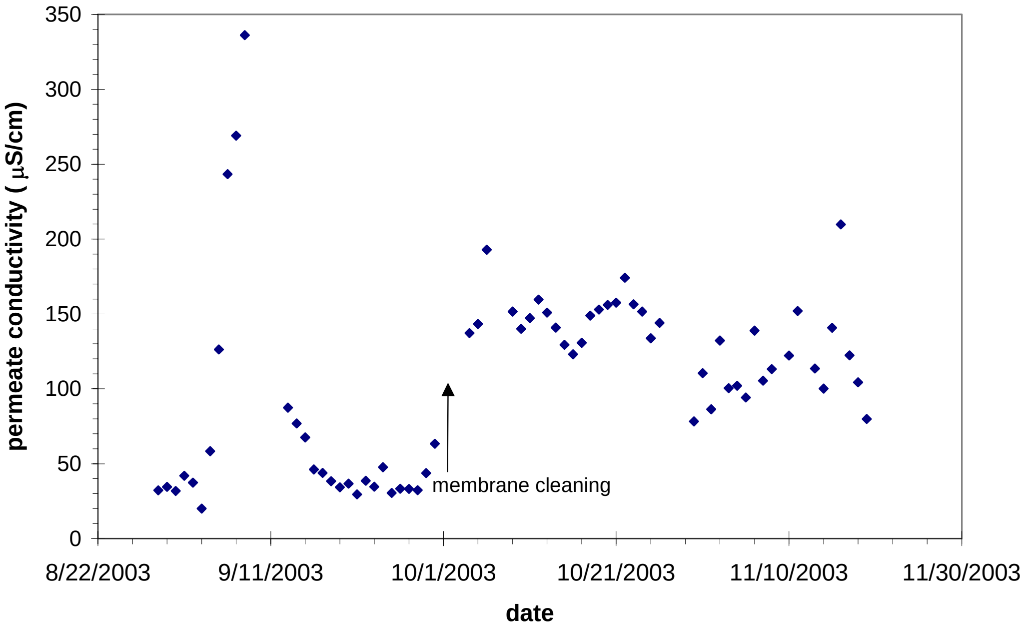

Figure 14. Conductivity of permeate produced.

4.3 Economic Cost Analysis

ITN's economic cost analysis estimate is based on single unit component prices and direct labor costs. For this analysis, the system cost was estimated to be between $14,500 and $16,000, depending on the number of PV panels used and the incorporation of potential system improvements. Actual production costs and sales prices for finished systems in full production will depend on market conditions and order quantity. Water production, using the current system, was estimated as $13.80 per 1,000 gallons. This is assuming 8-percent yearly interest payment on the capital equipment, and average yearly cost of $400 by assuming membrane and battery replacement every 3 years (see table 5 for details). Using larger PV panels (as described in Section 4.2.4) will reduce the water production cost to $11.60 per 1,000 gallons. With the next generation of improvements, which include lowering the cost of the control system by moving the control from relay logic to solid state, and by increasing daily water production by using passive tracking array, the water production cost can be reduced to approximately $8.10 per 1,000 gallons.

Table 5. Water production cost of the PVRO system

	Capital cost	Amortized cost per year (8%)	Miscel-laneous cost per year	Winter water production (gpd)	Summer water production (gpd)	Cost of producing 1,000 gallons of water
PVRO (results of this study)	$15,030	$1509	$408	330	429	$13.80
PVRO (projection) with an additional 200-W PV panel	$15,990	$1,605	$408	413	536	$11.60
PVRO (projection) with next generation improvements	$14,880	$1,494	$408	557	724	$8.10

5. Conclusions and Recommendations

- ITN designed and built a photovoltaic reverse osmosis desalination system, in which the high-pressure pump uses power from photovoltaic panels directly without inverters and batteries.

- The system operates only during the day. A solid-state circuit was designed by ITN to detect when the solar intensity is at a level where not much more water will be produced, yet it is sufficient to flush the RO membranes. This activates a rinsing cycle prior to shutting down other sensors in order to conserve the battery charge. An algorithm to minimize unnecessary shutdown, due to passing clouds, was built in the circuit.

- The system performed well in onsite testing at ITN and during field testing at Mesquite, Nevada. These tests showed that the system was capable of desalinating 3,500 TDS water to 100 TDS. The energy usage of the system was 1.3 kWh/m^3 permeate (5.1 kWh per 1,000 gallons) when it operated at optimal conditions. The daily shutdown did not make the system more prone to fouling or scaling than the Reclamation trailer desalination system running at the Mesquite site (a system that operates 24 hours per day continuously).

- The system was operated normally and produced quality water a majority of the time during the field test—producing over 13,000 gallons of drinking water. The amount of drinking water produced would have been higher if some of the inefficiencies in running conditions had not existed. Water production in November had a large day-to-day variation because of the large variation in available solar power in the area.

5.1 Recommendations and Future Directions

- A mechanism to control water recovery autonomously, particularly when desalinating water with high scaling potential, would be crucial to ensure an energy efficient system that needs minimal maintenance. This control is necessary whether the system is using PV with batteries, PV without batteries, diesel generator, or wind power (i.e., irrespective of power source). Our experience shows that a one-time adjustment of water recovery, using the DC power supply in the laboratory or during a time of perceived maximum solar intensity, is not reliable because temperature, changes in salinity, or a later increase in solar intensity can all have an effect on water recovery rates. Similarly, running the system at fixed pressure will not guarantee the system will not run at higher recovery rate than what is considered safe. Our experience also shows that arbitrarily running the system at low water recovery can be costly, because energy consumed per volume of permeate produced can be high in this situation. (Running the system at low recovery could potentially be more economical in an very small system (e.g., 30 to 100 gpd), since not having water recovery control and pretreatment would significantly reduce system complexity.)

- Reducing capital cost of the system by using solid-state circuit for the control system.

- Reducing water production cost by using passive tracking array.

- Improving system robustness by incorporating a membrane cleaning system integrated with photovoltaics.

- Using nanofiltration and low-energy RO membranes could reduce energy use and produce more water.

Pretreatment:

- For very small systems, it is more economical to run without pretreatment. If fouling and scaling are a concern, based on data on the quality of water, it will be necessary to run the system at very low recoveries. This running mode is not optimal, but significant expenses can be spared when a small system is designed as simply as possible.

- For larger systems, some pretreatment will be necessary to allow the system to run at higher recoveries and with more efficient energy usage. The system size at which pretreatment will be more economical can only be determined after obtaining cost information for pretreatment (i.e., after pretreatment processes are selected, the equipment is assembled, and the processes are tested).

- For the water quality at Mesquite, Nevada, solar-powered pretreatment would most likely include aeration, settling, and slow sand filtration to remove iron, manganese, and microbes; antiscalant addition using metering pump (Dosatron type of injector could potentially replace electrical metering pump). Alternatively, ultrafiltration could also be considered for removing microbes.

6. References

[1] Energy Research Institute of King Abdulaziz City for Science and Technology (March 2002), Photovoltaic Water Pumping and Desalination at Sadous Village, Saudi Arabia, Newsletter of The Middle East Desalination Research Center.

[2] United Nations Educational, Scientific, and Cultural Organizations (2000), **Renewable Energy Powered Desalination Systems in the Mediterranean Region-Case Studies**, document prepared by Richard Morris & Associates, Energy & Environmental Consultants, Scotland.

[3] European Commission Joint Research Center web page, <www.jrc.es/projects/intersudmed/PROJECT11.html.>

[4] Dan Weiner, David Fisher, Eduard J. Moses, Baruch Katz, Giora Meron (2001), **Operation experience of a solar- and wind-powered desalination demonstration plant**, *Desalination*, 137: 7–13.

[5] Kuruvilla Mathew, Stewart Dallas, Goen Ho, and Martin Anda (2001), **Innovative Solar-Powered Village Potable Water Supply**, *Women Leaders on the Uptake of Renewable Energy Seminar*, Perth, Australia, June 2001. Available on the Web at http://acre.murdoch.edu.au/unep/papers/Mathew.pdf.

[6] http://www.sesltd.com.au/downloads/SolarFlow.pdf

[7] Murray Thomson and David Infield (2002), **A photovoltaic-powered seawater reverse-osmosis system without batteries**, *Desalination*, 153: 1–8.

[8] M. Thomson, M. Miranda, J. Gwillim, and A. Rowbottom (2001), Batteryless photovoltaic reverse-osmosis desalination system, DTI/Pub URN 01/1121, <www.dti.gov.uk/energy/renewables/publications/pubs_solar.shtml>, Department of Trade and Industry, United Kingdom.

[9] Tripanagnostopoulos, Th. Nousia, M. Souliotis, and P. Yianoulis (2002), Hybrid Photovoltaic/Thermal Solar Systems, *Solar Energy* Vol. 72, No. 3, pp. 217–234.

[10] United Nations Educational, Scientific, and Cultural Organizations (2000), **Renewable Energy Powered Desalination Systems in the Mediterranean Region**, document prepared by Richard Morris & Associates, Energy & Environmental Consultants, Scotland.

[11] Mark A. Lichtwardt and Harry E. Remmers (1996), **Water treatment using solar-powered electrodialysis reversal,** Conference Proceedings, Mediterranean Conference on Renewable Energy Sources for Water Production, Santorini, Greece.

[12] Mark A. Lichtwardt and Harry E. Remmers (1996), **Solar powered water treatment for remote sites and communities**, Bureau of Reclamation Information Booklet.

[13] Solar Energy Systems, Ltd. (2002), Website address: <http://www.sesltd.com.au/html/waterpure.htm.>

[14] Daystar, Inc. **Stand-alone Photovoltaic Systems—A Handbook of Recommended Design Practices** (1995), issued by Sandia National Laboratories.

Appendix

Mesquite Field Test Data

Date	Average Temp (C)	Max Temp(C)	Average Power (W)	Max Power (W)	Total Energy Produced (kWh)	Average Feed Pressure (psi)	Average Feed Flow (gpm)	Max Feed Flow (gpm)	Total Feed Flow (gpm)	Average Permeate Flow (gpm)	Max Permeate Flow (gpm)	Total Permeate Produced (gallon)	Average Water Recovery(%)	Average Permeate Conductivity (μS/cm)	Energy Per Volume Permeate (kWh/m^3)
8/29/03	27.3	31.8	205.8	264.4	1.6	168.8	1.30	1.54	605.2	0.65	0.79	304.4	49.8	32	1.39
	Not quite full day, started at 9:33 am														
8/30/03	26.2	31.0	200.0	275.7	1.9	165.9	1.25	1.49	724.2	0.62	0.76	362.8	49.7	35	1.41
8/31/03	25.5	29.9	182.4	275.4	1.7	161.5	1.19	1.48	679.3	0.60	0.75	341.4	50.3	32	1.34
9/1/03	26.3	31.4	190.5	325.7	1.8	162.9	1.20	1.45	682.6	0.61	0.76	347.8	50.7	42	1.38
9/2/03	28.2	30.8	177.0	257.2	1.6	156.2	1.13	1.45	606.7	0.61	0.78	324.1	53.4	37	1.28
9/3/03	28.8	32.2	172.4	255.3	1.6	163.4	1.01	1.33	577.6	0.61	0.79	348.8	60.7	20	1.24
9/4/03	28.4	29.9	189.9	396.6	1.3	187.9	0.82	1.48	352.4	0.61	0.87	265.1	75.3	58	1.35
9/5/03	28.4	30.2	210.6	288.7	1.6	187.7	0.61	0.82	271.6	0.53	0.68	238.6	87.0	126	1.74
9/6/03	26.1	29.3	229.6	382.5	1.9	222.1	0.55	0.94	262.1	0.48	0.56	233.9	82.7	243	2.17
9/7/03	25.2	28.0	226.9	363.5	1.9	194.6	1.10	1.72	554.1	0.36	0.60	184.3	37.0	269	2.74
9/8/03	21.3	21.8	139.0	378.0	1.4	143.0	0.51	0.94	29.3	0.27	0.48	121.5	51.7	336	3.01
	System shut down due to scale.														
	Worked on system 9/11 to 9/12. Conductivity probe failed around this time.														
9/13/03	24.4	26.1	278.0	356.2	2.4	180.9	1.8	2.0	920.9	0.40	0.49	207.4	22.3	88	3.06
9/14/03	23.4	25.9	248.8	308.7	2.1	167.9	1.7	1.9	887.4	0.38	0.48	192.5	21.5	77	2.89
9/15/03	23.5	27.1	226.8	281.9	1.9	156.1	1.7	1.9	857.2	0.37	0.47	186.6	21.7	68	2.69
9/16/03	24.9	27.2	275.9	356.0	2.4	172.8	1.6	2.1	838.9	0.47	0.56	248.5	26.6	46	2.56

Date	Average Temp (C)	Max Temp(C)	Average Power (W)	Max Power (W)	Total Energy Produced (kWh)	Average Feed Pressure (psi)	Average Feed Flow (gpm)	Max Feed Flow (gpm)	Total Feed Flow (gpm)	Average Permeate Flow (gpm)	Max Permeate Flow (gpm)	Total Permeate Produced (gallon)	Average Water Recovery(%)	Average Permeate Conductivity (μS/cm)	Energy Per Volume Permeate (kWh/m^3)
9/17/03	24.1	26.3	239.9	311.8	2.1	159.1	1.7	2.0	890.9	0.43	0.53	225.7	23.9	44	2.46
9/18/03	22.8	25.0	290.2	369.9	2.5	180.4	1.9	2.2	973.3	0.48	0.57	252.5	25.0	38	2.62
9/19/03	22.5	25.8	242.3	307.1	2.0	161.6	1.8	2.0	906.6	0.43	0.50	214.7	23.6	34	2.46
9/20/03	23.1	26.1	231.6	295.5	1.9	155.4				0.42	0.52	212.4		37	2.37
	Feed flowmeter broke														
9/21/03	23.3	26.2	230.3	279.2	2.0	154.0				0.43	0.51	220.0		30	2.41
9/22/03	23.5	27.2	215.1	264.7	1.8	145.8				0.41	0.49	205.2		39	2.32
9/23/03	24.4	27.5	239.4	303.1	2.0	154.0				0.46	0.57	234.8		35	2.25
9/24/03	23.4	27.2	176.1	345.1	1.4	121.8				0.34	0.56	161.1		48	2.30
9/25/03	23.6	26.0	212.6	265.3	1.8	141.1				0.42	0.48	207.6		31	2.29
9/26/03	22.8	25.9	209.4	286.7	1.8	140.3				0.40	0.50	202.6		33	2.35
9/27/03	23.1	26.0	208.5	266.0	1.8	138.9				0.40	0.48	204.1		33	2.33
9/28/03	23.2	26.3	222.9	284.2	1.9	144.8				0.43	0.53	213.3		32	2.36
9/29/03	23.3	26.3	211.1	247.8	1.8	139.5				0.41	0.49	205.6		44	2.32
9/30/03	23.6	26.4	211.7	318.9	1.7	139.6				0.41	0.50	203.1		63	2.21
	Worked on system 10/1 to 10/3.														
10/4/03	22.5	24.6	250.0	295.8	2.0	157.6	1.9	2.1	934.7	0.46	0.54	224.8	23.9	137	2.35
10/5/03	22.8	25.1	242.7	303.8	2.0	153.6	1.9	2.1	922.1	0.46	0.52	223.8	24.1	143	2.36
10/6/03	21.3	23.3	187.5	320.0		125.7	1.6	2.2	320.6	0.34	0.57		20.8	193	
	Lift pump that lifted water to tank broke on 10/6, system shut down														

Date	Average Temp (C)	Max Temp(C)	Average Power (W)	Max Power (W)	Total Energy Produced (kWh)	Average Feed Pressure (psi)	Average Feed Flow (gpm)	Max Feed Flow (gpm)	Total Feed Flow (gpm)	Average Permeate Flow (gpm)	Max Permeate Flow (gpm)	Total Permeate Produced (gallon)	Average Water Recovery(%)	Average Permeate Conductivity (μS/cm)	Energy Per Volume Permeate (kWh/m^3)
10/9/03	23.0	24.7	230.5	295.4		146.8	1.8	2.0	589.8	0.43	0.53		23.6	152	
	New lift pump installed.														
10/10/03	22.9	24.6	266.5	326.9	2.1	159.8	1.9	2.2	921.1	0.48	0.57	226.5	24.3	140	2.45
10/11/03	21.6	23.6	269.4	332.7	2.2	161.8	2.0	2.2	955.4	0.46	0.54	224.9	23.3	147	2.59
10/12/03	24.8	32.4	199.2	229.7	1.6	93.9	1.6	1.8	764.4	0.20	0.30	94.1	12.4	160	4.50
10/13/03	24.0	29.3	212.0	231.4	1.7	97.4	1.7	1.8	830.5	0.20	0.22	100.5	12.1	151	4.47
10/14/03	22.0	29.5	202.6	228.2	1.7	96.2	1.6	1.7	802.0	0.19	0.21	95.1	11.9	141	4.73
10/15/03	23.2	30.9	199.7	223.3	1.6	95.5	1.6	1.7	782.6	0.19	0.21	93.4	11.9	129	4.53
10/16/03	23.5	31.2	195.2	223.1	1.6	92.9	1.6	1.7	781.8	0.19	0.21	90.3	11.6	123	4.69
10/17/03	23.6	31.9	191.8	223.2	1.6	91.6	1.6	1.7	784.4	0.18	0.20	89.6	11.4	131	4.72
10/18/03	23.6	30.8	194.0	216.7	1.5	90.7	1.6	1.7	774.8	0.19	0.21	89.7	11.6	149	4.42
10/19/03	24.0	30.2	184.8	215.3	1.5	88.5	1.6	1.7	752.1	0.18	0.20	87.0	11.6	153	4.56
10/20/03	23.7	30.8	191.4	220.3	1.5	91.4	1.6	1.7	756.0	0.19	0.20	88.7	11.8	156	4.47
10/21/03	24.0	31.7	185.4	211.8	1.5	87.9	1.6	1.7	775.8	0.18	0.19	84.1	10.9	158	4.72
10/22/03	24.1	31.8	187.8	212.8	1.5	88.2	1.6	1.7	784.8	0.18	0.19	84.4	10.8	174	4.70
10/23/03	22.7	28.7	189.5	211.4	1.5	86.6	1.6	1.7	759.6	0.18	0.19	81.6	10.8	157	4.86
10/24/03	24.2	29.5	191.1	209.8	1.5	86.9	1.6	1.7	782.0	0.17	0.18	81.6	10.5	152	4.86
10/25/03	23.0	26.1	198.4	210.8	1.6	87.8	1.7	1.7	792.4	0.17	0.18	80.0	10.1	134	5.29
10/26/03	22.2	27.8	196.7	211.7	1.6	87.7	1.7	1.7	790.6	0.17	0.18	79.9	10.1	144	5.30

Date	Average Temp (C)	Max Temp(C)	Average Power (W)	Max Power (W)	Total Energy Produced (kWh)	Average Feed Pressure (psi)	Average Feed Flow (gpm)	Max Feed Flow (gpm)	Total Feed Flow (gpm)	Average Permeate Flow (gpm)	Max Permeate Flow (gpm)	Total Permeate Produced (gallon)	Average Water Recovery(%)	Average Permeate Conductivity (µS/cm)	Energy Per Volume Permeate (kWh/m^3)
	Worked on system for most of 10/27, 10/28, 10/29														
10/30/03	21.9	23.0	280.4	370.4	2.3	163.1	1.92	2.25	960.7	0.67	0.81	332.6	34.0	78	1.86
10/31/03	19.8	21.0	297.7	383.7	1.9	171.8	1.89	2.24	729.2	0.64	0.79	247.4	33.2	110	2.04
11/1/03	19.3	21.7	302.2	421.3	1.7	170.9	1.89	2.24	643.4	0.63	0.79	215.0	32.9	86	2.11
11/2/03	17.8	20.2	198.4	429.1	0.8	131.8	1.61	2.15	370.1	0.47	0.75	108.8	29.1	132	1.85
11/3/03	18.9	20.7	295.9	399.0	2.4	173.0	1.89	2.22	926.8	0.63	0.79	308.0	32.5	100	2.08
11/4/03	18.6	20.7	281.2	374.1	2.2	169.5	1.93	2.29	895.8	0.62	0.76	286.4	31.5	102	2.01
11/5/03	18.5	20.7	278.9	352.9	2.3	168.8	1.90	2.14	923.3	0.60	0.74	291.9	31.0	94	2.04
11/6/03	17.6	19.7	196.2	413.4	0.8	126.5	1.57	2.23	400.0	0.44	0.75	112.5	27.6	139	1.96
11/7/03	18.3	21.6	261.8	351.3	2.1	160.0	1.84	2.12	866.1	0.57	0.70	268.4	30.6	105	2.02
11/8/03	18.1	20.8	206.0	349.8	1.4	135.2	1.67	2.13	675.6	0.48	0.71	192.9	27.9	113	1.91
11/9/03	System did not even turn on, not enough solar intensity														
11/10/03	19.9	22.5	175.4	355.9	1.0	120.1	1.48	2.23	494.6	0.45	0.72	149.8	30.1	122	1.73
11/11/03	11.2	11.9	127.5	193.9	0.0	107.9	0.92	1.41	18.5	0.31	0.41	6.2	41.3	152	1.82
11/12/03	System turned on but not enough to power anything.														
11/13/03	18.2	20.0	212.0	464.0	1.6	142.9	1.46	2.06	672.0	0.51	0.82	232.6	34.3	114	1.85
11/14/03	17.9	20.1	267.5	411.4	2.0	174.9	1.71	1.98	760.0	0.60	0.76	269.2	34.9	100	1.95
11/15/03	17.7	19.8	171.6	360.8	1.0	128.3	1.39	1.97	485.1	0.43	0.75	151.0	30.4	141	1.75
11/16/03	13.9	14.3	148.2	281.2	0.1	119.9	1.22	1.78	73.2	0.34	0.60	20.5	27.9	210	1.92
11/17/03	17.0	18.2	207.1	360.7	0.5	148.7	1.51	1.87	225.8	0.48	0.65	72.0	31.4	122	1.90

Date	Average Temp (C)	Max Temp(C)	Average Power (W)	Max Power (W)	Total Energy Produced (kWh)	Average Feed Pressure (psi)	Average Feed Flow (gpm)	Max Feed Flow (gpm)	Total Feed Flow (gpm)	Average Permeate Flow (gpm)	Max Permeate Flow (gpm)	Total Permeate Produced (gallon)	Average Water Recovery(%)	Average Permeate Conductivity (μS/cm)	Energy Per Volume Permeate (kWh/m^3)
11/18/03	15.8	19.5	288.0	355.5	2.2	184.1	1.80	2.02	811.6	0.59	0.68	263.8	32.3	104	2.17
11/19/03	18.2	20.7	283.2	362.4	1.9	177.2	1.85	2.09	758.1	0.62	0.73	254.3	33.3	80	2.01
11/20/03	15.9	18.8	261.6	378.0	0.9	167.9	1.72	2.04	336.0	0.55	0.72	106.8	31.7	106	2.11