Experimental evaluation of a low pressure desalination system (NF-PV), without battery support, for application in sustainable agriculture in rural areas

U. Dehesa-Carrasco, J. J. Ramírez-Luna, C. Calderón-Mólgora, R. S. Villalobos-Hernández and J. J. Flores-Prieto

ABSTRACT

Desalination driven by solar energy represents an appealing solution for agricultural irrigation in remote areas. In this work, a desalination system based on a photovoltaic-powered nanofiltration (NF-PV) membrane is studied. The experimental work explored the effect of the influent concentration and solar radiation on permeate production, energy consumption, recovery rate and quality of the permeate product. Four cases of different inlet conditions of influent concentrations were studied. In each set, the influent concentration was kept constant, varying only the irradiance along the solar day. In addition, a unit cost of permeated water was estimated. The maximum tested energy consumption was 1.55 Kwh m\(^{-3}\), with a concentration of 2,539 mg L\(^{-1}\) of total dissolved solids. The NF-PV system produces 2.16 to 4.8 m\(^3\) d\(^{-1}\), with a permeate water unit cost of 1.05–0.47 US$ m\(^{-3}\).

Key words | agricultural irrigation, brackish water desalination, low pressure desalination, nanofiltration, photovoltaic solar desalination, sustainable agriculture

INTRODUCTION

Water scarcity is a real challenge for the current state of agriculture in the world. Climate change, population growth and ongoing industrialization are factors that put pressure on existing water resources. It is estimated that about 70% of available freshwater is used for agriculture. Irrigation with brackish water from aquifers of marginal quality is practiced in Middle Eastern countries, India and in some regions of northern Mexico (Shaffer et al. 2012; Zarzo et al. 2013). However, the potential of the technique is limited by a variety of drawbacks. These limitations range from the choice of crops according to the specific salinity tolerance, the negative impacts on the soil surface by salt deposition, and the high volume of water required to leach excess salts. Such requirements may make irrigation with brackish water unsustainable.

Desalination is an alternative that has been used to increase the availability of fresh water and provide opportunities for handling high-value crops. However, desalination in agriculture has not been widely adopted due to economic aspects. The associated costs represent close to 40–45% of the total cost (Zarzo et al. 2013). Nevertheless, some countries like Spain, Israel and the United Arab Emirates have significantly increased the volume of desalination water for agriculture (Ghermandi & Messalem 2009; Birnhack et al. 2010).

Currently, a variety of commercial technologies are available for desalination, including nanofiltration (NF), reverse osmosis (RO), flash multi-stage, multi-effect distillation, electrodialysis, vapour compression, and others (Veza 2004; Garcia et al. 2011). NF membranes confer significant
advantages to the desalination process for irrigation (Ghermandi & Massalem 2009). First, NF membranes do not entirely reject influent ions, so that compounds which are essential for plant growth can cross. Second, NF membranes work with lower pressures than RO membranes; as a consequence, specific energy consumption is lower. These characteristics allow us to design and build less robust systems where solar energy produced with photovoltaic panels is very attractive, especially for small-scale applications in remote areas (Richards & Schafer 2003).

Photovoltaic-powered nanofiltration (NF-PV) systems have previously been evaluated. Koyuncu et al. (2001), IEA-ETSAP & IRENA (2012) and Silva et al. (2013) demonstrated the feasibility of NF-PV for treating water for human consumption in isolated places. Richards & Schafer (2003) reported a desalination study of a hybrid membrane configuration of NF and RO. The specific energy consumption ranged from 2–8 kWh per 1 m³ of disinfected and desalinated water. Ghermandi & Massalem (2009) studied the advantages of NF membranes over RO membrane desalination for irrigation. These authors concluded that energy consumption in NF systems was 40% lower than conventional RO desalination, reducing by 34% the currently abstracted groundwater volumes, and increasing by 18% the total biomass production of the irrigated crops. Flores-Prieto et al. (2015) reported an experimental study of an alternative treatment of brackish water for irrigation using an NF-PV system. The study focused on understanding the behavior of the system, keeping the amount of sulphate in the influent constant (1,863 mg L⁻¹), which mainly affects water quality. The authors report an average production of 3.2 m³ per day with 6.3 solar peak hr, allowing cultivation in the study region of up to 15 tons of tomatoes at a rate of 35 kg/m³.

All of the previously described NF-PV studies aim to demonstrate the feasibility of the systems. However, there are no reports of experimental studies carried out to elucidate the role of the exogenous variables (i.e., influent concentration and solar radiation) in the removal of specific substances that detract from the quality of irrigation water. In this study, a NF-PV system was evaluated. The experimental work studied the effect of the influent concentration on permeate production, energy consumption, recovery rate and quality of the permeate product. Four cases of different inlet conditions of influent concentration were studied. In each set, the influent concentration was kept constant, with variations only in the irradiance along the solar day. Finally, a unit cost of permeated water was estimated.

MATERIALS AND METHODS

Description of experimental set-up

A direct coupled PV water pumping and NF desalination system was built. The system is integrated with a pretreatment unit, NF modules, photovoltaic solar cell and pumping system. The prototype was designed to operate with a nominal capacity of permeate close to 12 liters per min, with a supply of brackish water of 60 liters per min. A diagram of the experimental device is shown in Figure 1.

Pretreatment unit

Pretreatment can reduce fouling potential in the NF membrane and increase the potential recovery rate of the system. This stage is integrated by a 5 micron pore size filter and one activated carbon filter. The carbon activated filter was included as a safety measure to protect the membrane from free chlorine. However, disinfection of the influent is performed upstream of the desalination plant.

NF modules

Four ESNA1-LF-4040 polyamide membranes with stainless steel housings were used. Membranes were connected in
parallel configuration in one pressure vessel. The membranes were selected for their relatively high salt retention capacity for brackish water desalination, evidenced by measurements in previous studies (Flores-Prieto et al. 2015). The membranes are designed to operate at a standard pressure of 75 psi with a permeate flux of $6.1 \text{ m}^3 \text{d}^{-1}$ and a permeate recovery rate of 15%.

Power supply and pumping system

The power supply of the desalination system was designed based on pumping requirements. A photovoltaic plant integrated by eight polycrystalline silicon modules of 240 W each provided a nominal power of 1.92 kW. An SQFlex 16 SQF-10 direct current submersible centrifugal pump was used to pressurize the desalination system. Due to the pump’s characteristics, the coupling of the PV plant and the pumping system was direct, without battery support. A control box for an on-off switch was included.

Methodology

Santa María Río-Verde in northern Mexico has clear examples of marginal quality aquifers; local wells supply with brackish water the 049 irrigation district. Carrera-Villacrés et al. (2015) measured salinity in this hydrologic system. Based on the results of water salinity studies conducted by Carrera-Villacrés et al. (2015), four representative samples were selected. Table 1 shows these samples taken from the above mentioned aquifer. Synthetic mixtures were developed from these samples in order to evaluate the NF-PV system.

The nominal values of the evaluated synthetic mixture concentrations were 525 mg L$^{-1}$, 1,170 mg L$^{-1}$, 1,750 mg L$^{-1}$, and 2,539 mg L$^{-1}$, respectively. These synthetic mixtures are based on a variety of compounds, mainly sulphates. To evaluate the system, the effectiveness of sulphate removal was determined, as well as the specific energy consumption, the permeate recovery rate and the quality of the produced permeate for irrigation. The experiment was performed outdoors. In each test, the concentration was kept constant while solar radiation was a free parameter with a variation throughout the solar day, in a range of 300–1,000 W m$^{-2}$. The radiation was measured over the plane of the PV solar cell with a first class Kipp & Zone pyranometer, with an uncertainty of ±1.0%.

In order to calculate the power supplied by the PV plant, voltage and electrical current were directly measured with an Agilent 34972A Data Acquisition datalogger. The volumetric flow was measured using an AQF-600-105 flow meter with a resolution of 0.25 liters per min, and, to measure the pressure, Ashcroft G2 pressure transducers were installed at the system’s input and output ports.

Energy consumption was defined as the ratio of permeate flow and the electric power supplied to the pumping system according to Equation (1):

$$EC = \frac{W_{PV}}{m_d}$$

where $m_d$ represents the average permeate flow through time as a function of solar radiation, and $W_{PV}$ is the average electric power supplied to the pumping system in the same time.

The quality of the permeate for irrigation was evaluated as a function of the following parameters: electrical conductivity

<table>
<thead>
<tr>
<th>Num.</th>
<th>pH</th>
<th>CE $\mu$S cm$^{-1}$</th>
<th>mmol l$^{-1}$</th>
<th>mg l$^{-1}$</th>
<th>SDT</th>
<th>IS</th>
<th>RAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.6</td>
<td>723</td>
<td>2.53</td>
<td>4.2</td>
<td>0.15</td>
<td>0.26</td>
<td>5.39</td>
</tr>
<tr>
<td>2</td>
<td>8.1</td>
<td>1,700</td>
<td>8.2</td>
<td>3.7</td>
<td>4.63</td>
<td>0.27</td>
<td>6.73</td>
</tr>
<tr>
<td>3</td>
<td>7.7</td>
<td>2,729</td>
<td>16.76</td>
<td>8.9</td>
<td>1.2</td>
<td>0.1</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>7.2</td>
<td>3,945.45</td>
<td>7.48</td>
<td>20.69</td>
<td>10.12</td>
<td>0.72</td>
<td>11.53</td>
</tr>
</tbody>
</table>
(EC), total dissolved solids (TDS), pH and sodium adsorption ratio (SAR). The SAR is evaluated with the content of sodium cations, calcium and magnesium, according to Equation (2), as reported by Carrera-Villacrés et al. (2013) and Silva et al. (2013).

\[
SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}
\]  

(2)

**Economic evaluation**

The cost of obtaining desalinated water is a function of several factors, such as plant capacity, feed water quality, pretreatment process, technology, energy cost, plant life, investments and amortisation. The major costs related to the desalination plant are the capital cost and annual operating costs (Banat & Jwaied 2008). The capital cost covers the purchase cost of equipment, auxiliary equipment, installation and the water pretreatment stage. However, annual operating costs cover all additional costs generated after installation and during operation. These include the amortisation or fixed charges, operating and maintenance (O&M) and membrane replacement. Banat & Jwaied (2008) proposed a methodology to estimate an effective cost of the desalinated water for a small-scale autonomous Membrane Distillation solar-powered plant. The economic analysis presented by Banat & Jwaied (2008) is conveniently adopted in the present work and discussed in the results section.

**RESULTS AND DISCUSSION**

The experiment focused on the behaviour of the NF-PV desalination unit as a function of the influent concentration and solar radiation. Four sets of experiments were carried out for this purpose. In each set, the concentration of influent was kept constant, varying only the irradiance along the solar day in a range from 300 to 1,000 W/m². The fixed nominal influent concentrations corresponding to the four sets were 525 mg L⁻¹, 1,170 mg L⁻¹, 1,750 mg L⁻¹ and 2,539 mg L⁻¹, respectively. As mentioned above, each reported data point corresponds to an average of over 3,000 measurements during a 500 min period.

**Water quality**

In order to quantify water quality, the pH, EC and TDS were measured. In each set, the measurements were carried out at the beginning, middle and end of the test. The concentration remained at a maximum standard deviation of ±10 mg/L (±19.9 μS/cm). The experimental results are shown in Table 2.

Based on experimental observations, the ‘fouling’ in pre-treatment filters has an important effect on water quality. The suspended solids can eventually saturate the filters, as shown in Figure 2. Consequently, effective working pressure is reduced.

Typical maintenance of the system involves changing the pre-treatment filter for a new one. This modification led to an increment in the inlet pressure on the NF membrane. The NF membranes do not entirely prevent the flow of salt, monovalent compounds present in the mixture, from crossing through the membrane. Water and salt have different rates of mass transfer across a NF membrane; it allows the ‘rejection’ phenomenon. As working pressure increases, the water transfer rate increases without changing the salt flow rate. As a consequence, salt permeation through the membrane was lower, as shown in the fourth experiment (Table 2).

<table>
<thead>
<tr>
<th>Test</th>
<th>pH</th>
<th>EC (μS cm⁻¹)</th>
<th>TDS (mg L⁻¹)</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1</td>
<td>8.54</td>
<td>1,105</td>
<td>525</td>
<td>30.8</td>
</tr>
<tr>
<td>B 1</td>
<td>8.55</td>
<td>1,217</td>
<td>565</td>
<td>31</td>
</tr>
<tr>
<td>C 1</td>
<td>8.53</td>
<td>154</td>
<td>85</td>
<td>30.9</td>
</tr>
<tr>
<td>A 2</td>
<td>8.45</td>
<td>2,330</td>
<td>1,170</td>
<td>29.7</td>
</tr>
<tr>
<td>B 2</td>
<td>8.42</td>
<td>2,630</td>
<td>1,320</td>
<td>29.7</td>
</tr>
<tr>
<td>C 2</td>
<td>8.38</td>
<td>350</td>
<td>180</td>
<td>29.7</td>
</tr>
<tr>
<td>A 3</td>
<td>8.37</td>
<td>3,490</td>
<td>1,750</td>
<td>28</td>
</tr>
<tr>
<td>B 3</td>
<td>8.35</td>
<td>4,100</td>
<td>2,050</td>
<td>28</td>
</tr>
<tr>
<td>C 3</td>
<td>8.31</td>
<td>320</td>
<td>160</td>
<td>28</td>
</tr>
<tr>
<td>A 4</td>
<td>8.1</td>
<td>4,885</td>
<td>2,539</td>
<td>25.2</td>
</tr>
<tr>
<td>B 4</td>
<td>8.1</td>
<td>5,759</td>
<td>3,003</td>
<td>25.2</td>
</tr>
<tr>
<td>C 4</td>
<td>8.1</td>
<td>281</td>
<td>96</td>
<td>25.2</td>
</tr>
</tbody>
</table>

Influent (A), Effluent (B) and Permeate (C).
The effectiveness of sulphate removal, based on EC measurement, can be expressed as

\[ \eta = \frac{C_{E_R}}{C_{E_{Inf}}} \times 100 \] (3)

where \( C_{E_R} \) represents the amount of salts rejected and \( C_{E_{Inf}} \) the influent concentration. It can be observed that the highest efficiency (94%) was obtained in the 4th test. The results are presented in Table 3.

In order to quantify the amount of sulphates and chlorides, a detailed study for test 4 was conducted. According to NMX-AA-073-SCFI-2001 (Mexican standard NMX-AA-073-SCFI-2001 (2001)) chlorides were determined and NMX-AA-074-1981 (Mexican standard NMX-AA-074-1981 (1981)) was used for the sulphates. Considering the NMX-AA-051-SCFI-2001 and flame method (Mexican standard NMXAA-051-SCFI-2001 (2001)), the elements that were useful to figure the SAR were obtained. The results are presented in Table 4.

**Solar system**

The experimental test runs were conducted under conditions of sunny and cloudy days. During experimental tests the voltage provided by the photovoltaic panels remained at an average of 217.4 volts. The graph in Figure 3 shows a typical test day.

With respect to the power required, in Figure 4 a linear dependence is observed. Scattering effects were due to the radiation dispersed by cloudiness and the effects of the tilt of the PV system.

**NF system**

Permeate flow rate is affected inversely by the influent concentration. This is a characteristic of NF systems. Figure 5 shows permeate production with respect to the initial concentration. Based on the experimental results, the production of permeate relative to the supply pressure is a linear trend. Further, concentration inversely affects permeate production. Observe that the increase from 525 mg L\(^{-1}\) to 2,539 (mg L\(^{-1}\)) in TDS led to a decline close to 7 L/min in the permeate, which affects the system’s energy consumption.

Figure 6 shows power consumption per unit of permeate volume. We can see that power consumption is a linear function to influent concentration: higher sulphate concentration requires higher energy consumption. The maximum consumption was 1.55 Kwh m\(^{-3}\). In previous works by IEA-ETSAP & IRENA (2012), a consumption between 0.5–4 kWh m\(^{-3}\) has been reported.

The direct coupled configuration of the NF-PV system was established by the irrigation requirements. As a general rule, the crops should be irrigated when the irradiance is low, in order to reduce water losses from evaporation and to minimize plant stress. In this context, instead of accumulating electric energy in batteries for later use, water treated during the day can be stored in elevated tanks. In fact, it is cheaper to store water in tanks than accumulate energy in batteries. The NF-PV system produces from 2.16–4.8 m\(^3\) d\(^{-1}\), making it possible to irrigate between 1 and 2 hectares of crops.

**Economic evaluation**

In order to obtain the cost, production capacities and design features were considered. The economic assumption in the study is as follows:

- Plant life expectancy is 20 years.
Operation and maintenance costs are estimated at 20% of plant annual payment (Dessouky & Ettouney 2002). Near 13% is related to maintenance. The service system includes replacement of pretreatment filters. Annual rate of membrane replacement is 10% (Dessouky & Ettouney 2002).

- 7% interest rate, when financing is required.

Table 4 lists the components of the system and the total estimated construction cost for the NF-PV system. The costs are based on current purchase prices.

The solar desalination system is relatively expensive, compared to a non-solar desalination system (Kreith & Kreider 1978; Dessouky & Ettouney 2002). Based on Table 1, the cost of the pumping system with PV solar panels represents 63% of the total estimated construction cost.

<table>
<thead>
<tr>
<th>Test</th>
<th>Chlorides (mg L⁻¹)</th>
<th>Sulphates (mg L⁻¹)</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>SAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>48.4</td>
<td>2,491</td>
<td>344.503</td>
<td>220.927</td>
<td>53.074</td>
<td>0.549</td>
</tr>
<tr>
<td>B</td>
<td>52.5</td>
<td>2,951</td>
<td>433.81</td>
<td>236.645</td>
<td>62.575</td>
<td>0.631</td>
</tr>
<tr>
<td>C</td>
<td>19.4</td>
<td>76.3</td>
<td>12.955</td>
<td>11.579</td>
<td>12.56</td>
<td>0.611</td>
</tr>
</tbody>
</table>

Table 5 lists the components of the system and the total estimated construction cost for the NF-PV system. The costs are based on current purchase prices.

![Solar irradiance on PV level (primary axis) and volts provided by panel (secondary axis).](image1.png)

![Production of permeate as a function of feed pressure.](image2.png)

![Power supplied to the system as a function of solar radiation. The test corresponds to one day of sparse cloudiness.](image3.png)

![Energy consumption for different influent concentrations. From top to bottom, the data correspond to 2,539, 1,750, 1,170, 525, TDS.](image4.png)
Expenditures incurred subsequent to the system’s start-up and expenses generated during the actual operation are called annual operating cost. The main subsequent costs are the O&M costs, membrane replacement and amortisation or fixed charges. These last charges are included when funds for the project need to be provided through a loan, and thus interest is generated (Banat & Jwaied 2008).

A summary of the main features, which is useful for cost estimation, is presented in Table 6.

In this work, two unit costs of permeate water were estimated, with and without amortisation. The first is based on total capital costs, membrane replacement and O&M. The second includes the annual fixed charges, membrane replacement and O&M.

The unit cost of permeate water (without amortisation) can be estimated as the sum of the total capital cost, membrane replacement and O&M costs divided by the total amount of permeated water produced during the lifetime of the desalination unit (Banat & Jwaied 2008). Table 7 shows a summary of the main cost.

On the other hand, the cost with amortisation was estimated as:

\[
a = \frac{i(1+i)^n}{(1+i)^n-1} = \frac{0.07(1+0.07)^{20}}{(1+0.07)^{20}-1} = 0.09439 \text{ yr}^{-1} \tag{4}
\]

In Equation (4), \(a\) is the amortisation factor, \(n\) represents plant life expectancy (20 years) and \(i\) is the 7% interest rate. Table 8 shows a summary of unit cost of permeate water with amortisation cost.

### Table 5 | Components of the NF-PV system

<table>
<thead>
<tr>
<th>Item</th>
<th>Descriptions</th>
<th>Cost basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane with stainless steel housings</td>
<td>Four membrane (ESNA1-LF-4040)</td>
<td>US$1,800</td>
</tr>
<tr>
<td>Pumping system with PV solar panels</td>
<td>Pumping system (16SQLF10-R1560-70 M) with eight PV modules that provide 1.92 kW of electrical power. The considered basis costs include the accessories needed for the pump system to operate at a maximum depth of 30 feet</td>
<td>US$5,135</td>
</tr>
<tr>
<td>Monitoring equipment</td>
<td>Two flowmeters (AQF-600-105) and two oil filled pressure gauges</td>
<td>US$198</td>
</tr>
<tr>
<td>Filters for pretreatment</td>
<td>One SBD-25-205 with a plastic housing</td>
<td>US$100</td>
</tr>
<tr>
<td>Hydraulic accessories</td>
<td>All hydraulic accessories</td>
<td>US$100</td>
</tr>
<tr>
<td>Installations</td>
<td>Installation of equipment</td>
<td>US$800</td>
</tr>
<tr>
<td>Total cost</td>
<td></td>
<td>US$8,133</td>
</tr>
</tbody>
</table>

### Table 6 | Main features for cost estimation

<table>
<thead>
<tr>
<th>Item</th>
<th>Capital cost (Cc)</th>
<th>Membrane module cost (Mc)</th>
<th>Capacity (M)</th>
<th>Plant availability (f)</th>
<th>Interest rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost basis</td>
<td>US$8,133</td>
<td>US$1,400</td>
<td>2.16–4.8 m³/d</td>
<td>90%</td>
<td>7%</td>
</tr>
</tbody>
</table>

### Table 7 | Unit cost of permeated water without amortisation

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (US$ m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total capital investment</td>
<td>0.57–0.25</td>
</tr>
<tr>
<td>Membrane replacement</td>
<td>0.37–0.17</td>
</tr>
<tr>
<td>O&amp;M annual cost</td>
<td>0.11–0.05</td>
</tr>
<tr>
<td>Unit product cost</td>
<td>1.05–0.47</td>
</tr>
</tbody>
</table>

### Table 8 | Estimation of unit cost of permeate water with amortisation cost

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual fixed charges (US$ yr⁻¹)</td>
<td>(A_{\text{fixed}} = (a)(Cc)) 767.67</td>
</tr>
<tr>
<td>Membrane replacement (US$ yr⁻¹)</td>
<td>A_{\text{Mem.Rep}} = 0.1\times Mc 140</td>
</tr>
<tr>
<td>O&amp;M annual cost (US$ yr⁻¹)</td>
<td>A_{\text{O&amp;M}} = 0.2\times A_{\text{fixed}} 153.53</td>
</tr>
<tr>
<td>Total annual payment (US$ yr⁻¹)</td>
<td>A_{\text{total}} = A_{\text{fixed}} + A_{\text{Mem.Rep}} + A_{\text{O&amp;M}} 1,061.2</td>
</tr>
<tr>
<td>Unit product cost (US$ m⁻³)</td>
<td>(A_{\text{unit}} = (A_{\text{total}}/f\times M\times 365)) 1.49–0.67</td>
</tr>
</tbody>
</table>
The unit product costs presented in Tables 3 and 4 were estimated according to the system’s production capacity. Two costs were estimated relative to feed concentration, 2,539 mg L$^{-1}$ and 525 mg L$^{-1}$ respectively. When the initial concentration of influent increases, permeate production decreases, as shown in Figure 5. Therefore, the increment of the cost is proportional to the feed concentration.

Regarding a water price comparison, we need to point out that water cost strongly depends on the plant’s capacities and influent characteristics. Zarzo et al. (2013) estimated 0.24 US$ m$^{-3}$ for a large BWRO plant (brackish water RO) and 0.47 US$ m^{-3}$ for desalinated sea water for irrigation. According to the same report, for large applications NF is economically less interesting than RO due to further blending with water from other sources. However, a detailed economic study was not presented. In addition, an overview of solar desalination for agricultural applications in remote areas estimates that typical yields of solar would still produce water at 0.8–1.05 US$ m^{-3}$ (Chaibi 2000) and solar pond systems could provide water at 0.65–0.89 US$ m^{-3}$ for plants having a capacity of 200,000 m$^3$ d$^{-1}$ and 20,000 m$^3$ d$^{-1}$, respectively. With respect to small PV-RO desalination systems, experience shows that the permeate price is high. Table 9 shows cost comparisons between different PV-RO systems.

The water quantity and quality needed for irrigation is defined according to the crop and soil characteristics. The NF-PV systems have an important limitation – they are not effective when boron is present and this is the reason why in many plants a second pass of RO is required. However, when boron is not the problem, as in the case of this study, the NF-PV system may be an option for small irrigation areas at a relatively low cost.

### CONCLUSION

An experimental study of an NF-PV desalination system without electrical storage support was presented. This study was carried out to elucidate the role of the exogenous variables (i.e., influent concentration and solar radiation) in permeate production, energy consumption, recovery rate and quality of the permeate product. In addition, a unit cost of permeated water was estimated. Significant effects were observed during the present experiments and the following points were concluded:

- Permeate production is affected inversely to influent concentration. In fact, when TDS went from 525 mg L$^{-1}$ to 2,539 mg l$^{-1}$, a 7 L min$^{-1}$ decrement of permeate was observed. Fouling has an important effect on production; a maximum hydraulic head loss of 20.9 mH$2O$ was observed.
- Energy consumption is more strongly affected when the initial concentration occurs together with fouling in the pretreatment filters. With respect to energy consumption, the maximum value was 1.55 Kwh m$^{-3}$ with a concentration of 2,539 mg L$^{-1}$.
- The quality of the obtained permeate satisfies the standard norm for irrigation.
- The NF-PV system produces between 2.16–4.8 m$^3$ d$^{-1}$ with a unit cost of permeate water of 1.05–0.47 US$ m^{-3}$, making it possible to irrigate between 0.5 and 1 hectare of crops.

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