BATTERYLESS PHOTOVOLTAIC REVERSE-OSMOSIS DESALINATION SYSTEM

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Contractors
CREST
Dulas Ltd

Prepared by
M Thomson
M Miranda (CREST)
&
J Gwillim
A Rowbottom
I Draisey (Dulas Ltd)

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EXECUTIVE SUMMARY

The aim of this project was to design an efficient cost-effective batteryless photovoltaic-powered seawater reverse-osmosis desalination system, to deliver in the order of 3 m³ of fresh drinking water per day.

The desalination of seawater to produce fresh drinking water is extremely valuable on islands and in coastal regions wherever natural freshwater is scarce. Existing small-scale desalination equipment, suitable for areas of medium and low population density, often requires a copious and constant supply of energy, either electricity or diesel. If supply of these fuels is expensive or insecure, but the area has a good solar resource, the use of photovoltaic power is an attractive option.

Existing demonstrations of photovoltaic-powered desalination generally employ lead-acid batteries, which allow the equipment to operate at a constant flow, but are notoriously problematic in practice. The system developed in this project runs at variable flow, enabling it to make efficient use of the naturally varying solar resource, without need of batteries. In a sense, the freshwater tank is providing the energy storage.

In this project, we have reviewed the merits of a wide variety of reverse-osmosis system configurations and component options. We have completed extensive in-house testing and characterisation of major hardware components and used the results to construct detailed software models. Using these, we have designed a system that meets the above project aim, and we have predicted its performance in detail.

Our designs show that a system costing £23,055 will produce 1424 m³ of fresh drinking water annually – an average of just over 3.9 m³/day. The system has no fuel costs and no batteries. The overall cost of water, including full maintenance, is £2.00 per m³. The energy consumption (photovoltaic-electricity) is typically between 3.2 and 3.7 kWh/m³ depending on the solar irradiance and feed water temperature. These figures are excellent for a system of this size.

We conclude that the batteryless photovoltaic-powered seawater reverse-osmosis desalination system described in this report will be commercially viable.

We recommend that a pilot scheme based on our design be implemented.
# CONTENTS

Executive Summary ........................................................................................... i  
Contents ............................................................................................................ ii  
1 Introduction ..................................................................................................... 1  
2 System overview .......................................................................................... 3  
  2.1 Operation .................................................................................................. 3  
3 Cost analysis ................................................................................................. 4  
  3.1 Capital costs ............................................................................................. 4  
  3.2 Cost of the water over the lifetime of the equipment ......................... 4  
4 Performance predictions .............................................................................. 6  
  4.1 Basis........................................................................................................... 6  
  4.2 Site conditions .......................................................................................... 6  
  4.3 Product water flow .................................................................................... 7  
  4.4 Product water quality ............................................................................. 10  
  4.5 Energy flows – Sankey diagram .......................................................... 11  
  4.6 Power usage – average day .................................................................. 12  
  4.7 Specific Energy ..................................................................................... 13  
5 Design considerations ................................................................................... 14  
  5.1 RO modules ............................................................................................. 14  
    5.1.1 Alternative membrane technologies ............................................. 14  
    5.1.2 Alternative membrane brands ....................................................... 14  
    5.1.3 RO Module size and number ....................................................... 14  
    5.1.4 Variable pressure/flow ................................................................. 15  
    5.1.5 Fouling ........................................................................................... 15  
    5.1.6 Membrane flushing, cleaning and replacement ....................... 15  
  5.2 Energy recovery mechanism .................................................................... 16  
    5.2.1 Danfoss hydraulic motor .............................................................. 16  
    5.2.2 Clark pump ..................................................................................... 16  
  5.3 High-pressure plunger pump .................................................................. 17  
  5.4 Medium-pressure Moineau pump ......................................................... 17  
  5.5 Pulsation dampeners (accumulators) .................................................... 18  
  5.6 Inverters ................................................................................................. 18  
  5.7 Maximum power point tracking (MPPT) ............................................. 18  
  5.8 Recovery-ratio control ........................................................................... 19  
  5.9 Feed water and pre-treatment ............................................................... 20  
  5.10 Product tank chlorination ..................................................................... 20  
  5.11 Feed water pre-heating ......................................................................... 20  
  5.12 Batteries ................................................................................................. 21  
    5.12.1 Transportation and storage ........................................................... 21  
    5.12.2 Charging ....................................................................................... 21  
    5.12.3 Maintenance ............................................................................... 21  
    5.12.4 Life cycle costs ............................................................................ 21  
    5.12.5 Energy efficiency ....................................................................... 21  
6 Market potential ............................................................................................ 22  
  6.1 Developing-world market ....................................................................... 22  
  6.2 Luxury market ........................................................................................ 23  
  6.3 SWOT Analysis ..................................................................................... 23  
  6.4 Comparative costs of desalination technologies .................................. 24  
7 Conclusions and future work ....................................................................... 25  

(ii)
References........................................................................................................25
A Hardware test facilities ..................................................................................A-1
B Matlab-Simulink model ...............................................................................B-1
  B.1 Scope........................................................................................................B-1
  B.2 Structure..................................................................................................B-1
  B.3 Solar irradiance......................................................................................B-2
  B.4 PV modules............................................................................................B-2
  B.5 Maximum power point tracking.............................................................B-3
  B.6 Inverters...............................................................................................B-3
  B.7 Motor........................................................................................................B-3
  B.8 Plunger pump.........................................................................................B-3
  B.9 Moineau pump.......................................................................................B-3
  B.10 Clark pump............................................................................................B-3
  B.11 Reverse osmosis membrane modules................................................B-4
C Chemical analysis of water from a seawater well in Massawa..................C-1
1 INTRODUCTION

The desire for fresh drinking water in parts of the world where only seawater is available has led to the growth, over the last 40 years or so, of a thriving desalination industry. It is dominated by large-scale municipal plants supplying large centres of population. The most-used technologies are thermal distillation and reverse-osmosis membrane filtration.

Briefly, seawater reverse osmosis uses a very fine filter membrane that allows pure water to pass through, while mostly rejecting the relatively large salt molecules. The seawater feed must be pressurised (69 bar / 1000 psi is typical), firstly, to force the water through the mechanical constriction presented by the membrane and, secondly, against the natural osmotic pressure (hence the name: reverse osmosis). Not all of the feed water can be forced through the membrane; some, typically more than half, must be allowed to pass over the membrane (cross-flow) in order to remove the salt. This water, known as the concentrate or brine, comes out of the reverse osmosis module at a pressure only slightly below that of the feed pressure.

Desalination inherently consumes a lot of energy, the theoretical minimum for seawater being around 0.8 kWh/m³. In practice, figures greater than 2.0 kWh/m³ are typical. Thus, energy costs normally dominate the total cost of desalinated water and the industry is most successful in parts of the world with large fossil-fuel resources: the Gulf States and the US.

The benefits of using renewable energy sources are well known and it is often suggested that these be used for desalination. A comprehensive review of numerous permutations of renewable-energy and desalination technologies was carried out by CRES 1.

Photovoltaic-powered reverse osmosis (PV-RO) is considered one of the more promising approaches, particularly for small systems where other technologies are less competitive. In practice however, small-scale PV-RO presents two technical challenges.

Firstly, solar power is intermittent and variable while reverse-osmosis plant is generally designed to run continuously and at constant flow. Batteries are often proposed, and indeed used, to address this, but in our experience, batteries are very problematic in the field. A main aim of this project was to design a system that would work efficiently without batteries.

Secondly, the energy efficiency of a reverse-osmosis system is heavily dependent on recovering energy from the pressurised concentrate. In large systems, pelton-wheel turbines are common and ERI’s Pressure Exchanger 2 is gaining acceptance, but neither is available in small sizes. In a previous project 3, Dulas demonstrated the use of a Danfoss hydraulic motor for energy recovery in a reverse-osmosis system, and the original intention of this project was to further develop this approach. However, about midway through the project, we learned of the Spectra Clark Pump 4. We obtained one and tested its performance. Its efficiency is truly excellent and, importantly, this is maintained over a very wide range of flow rate. We consider that the Clark Pump is very well suited to PV-RO and it is now central to our system design.
Figure 1 - System overview

- Photovoltaic Array
- Solar Tracker
- Inverter
- Controller
- Inverter
- Induction Motor
- Induction Motor
- Pulsation Dampener
- Captive Acceleration Tube
- Ix Valve
- Plunger Pump
- Moineau Pump
- Fine Filter
- Coarse Filter
- Beach-well Seawater Intake
- Concentrate Discharge
- Reverse-Osmosis Modules
- Pressure Relief Valve
- Clark Pump
- Product Tank
2 SYSTEM OVERVIEW

The system configuration shown in Figure 1 represents one of the main achievements of this project. There are a vast number of possible configurations of motors and pumps etc that could be used in a reverse osmosis system and we considered many of these in the course of our design. We considered cost, performance, simplicity and numerous practicalities, which are discussed throughout this report.

2.1 Operation

The Moineau (progressing cavity) pump sucks seawater from a beach well and raises it to a medium-pressure. A submersible version of the same pump is available, at extra cost, and could readily be substituted.

The Clark pump raises its medium-pressure feed water to high-pressure by virtue of the energy it recovers from the concentrate.

The flow ratio of the Clark pump is fixed by design, which normally gives a 10% water recovery ratio* at the membranes.

However, the plunger pump, shown in Figure 1, injects an additional high-pressure feed, which increases the water recovery ratio to any desired value.

Separate speed control of the two rotary pumps provides full control of:

- the energy drawn from the photovoltaic array, for maximum power point tracking, and
- the water recovery ratio, for maximum product water flow.

Appropriate control of the two pump speeds is critical in maximising the overall system efficiency.

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* In desalination circles, recovery ratio = quantity of product water / quantity of feed water. In this report, it is often referred to as water recovery ratio, to distinguish it from energy recovery.
3 COST ANALYSIS

3.1 Capital costs

A detailed cost analysis of the system outlined in Figure 1 has been completed and is summarised below.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaic (PV) Array</td>
<td>£ 7,319</td>
</tr>
<tr>
<td>Reverse osmosis elements and pressure vessels</td>
<td>£ 2,796</td>
</tr>
<tr>
<td>Pumps (all three)</td>
<td>£ 2,290</td>
</tr>
<tr>
<td>Motors and Inverters</td>
<td>£ 806</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>£ 2,537</td>
</tr>
<tr>
<td><strong>Total Components and Materials</strong></td>
<td><strong>£15,748</strong></td>
</tr>
<tr>
<td>Manufacturer’s mark-up on Components and Materials</td>
<td>£ 3,150</td>
</tr>
<tr>
<td>Manufacturer’s Labour at cost including overheads</td>
<td>£ 2,906</td>
</tr>
<tr>
<td>Mark-up on Labour</td>
<td>£ 872</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>£23,055</strong></td>
</tr>
</tbody>
</table>

Table 1 – Capital cost summary

As may be expected, the largest single cost is that of the photovoltaic (PV) array, but this must be considered in context. Firstly, it will offset all fuel costs for the whole life of the equipment. Secondly, it is less than one third of the total capital costs.

The size of the PV array, and hence its cost, could be reduced, and the system would still achieve full output at the height of the day. However, when the overall cost per cubic metre of product water is considered, our study shows that a slightly larger PV array is optimum.

3.2 Cost of water over the lifetime of the equipment

A maintenance programme was devised in order to estimate the cost per cubic metre of product water over the expected lifetime of the equipment. A 20-year life was chosen to reflect the expectancy of the PV array. This figure is a little pessimistic for a high-quality installation, but reflects the possibility of harsh environmental conditions in a tropical maritime climate. The major points of the maintenance schedule are shown in Table 2.
Table 2 – Outline maintenance schedule

The dominant yearly cost is the replacement of the membranes. It is possible that they will not need to be replaced so frequently, but as the effect of the proposed cyclic mode of operation has not been characterised, caution has been applied.

The average annual expenditure on replacement parts and consumables is estimated at £1643. The annual labour costs are much lower, £293 based on an hourly wage of £3. This is probably higher than expected in developing countries but the difference in cost between this and a more likely rate is small, and allows some contingency.

The Net Present Value (NPV) of the maintenance costs is calculated using an 8% discount rate. The calculations of the cost per cubic metre of product are shown below.

<table>
<thead>
<tr>
<th>Life cycle costs based on 20 years of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual product volume (m³)</td>
</tr>
<tr>
<td>Total amount of water produced (m³)</td>
</tr>
<tr>
<td>Initial hardware cost</td>
</tr>
<tr>
<td>Estimated shipping and installation costs</td>
</tr>
<tr>
<td>NPV of maintenance costs</td>
</tr>
<tr>
<td>NPV of Total investment</td>
</tr>
<tr>
<td>Cost per cubic metre</td>
</tr>
</tbody>
</table>

Table 3 – Calculation of cost per cubic metre

We believe that an overall cost of £2.00 per m³ of desalinated seawater is very impressive for a system of this size, however powered. A comparison with competing technologies is presented in Section 6.4.
4 PERFORMANCE PREDICTIONS

4.1 Basis

The following performance predictions are based on:

- extensive in-house component characterisation;
- a very detailed Matlab-Simulink model of the entire system;
- other established software models, including Meteonorm 5, PVSYST 6 and ROPRO 7;
- manufacture’s data.

Further details of our hardware test facilities and Matlab-Simulink system model are given in the appendixes.

4.2 Site conditions

The performance of a PV-RO system is greatly affected by:

- the solar resource (available sunlight);
- the salinity of the seawater feed;
- the temperature of the seawater feed;
- the ambient temperature.

The following performance predictions are based on a site at Massawa on the Red Sea coast of Eritrea.

A chemical analysis of water from a seawater well in Massawa (see Appendix C) shows a total-dissolved-solids concentration of nearly 40,000 mg/L, which is as expected in the Red Sea region. This is isosmotic with 34,300 mg/L of pure NaCl.

An annual temperature profile for the Red Sea has also been obtained. It shows a summer maximum of over 33 °C and a winter minimum of around 17 °C.
4.3 **Product water flow**

The following product water flow rate predictions, from our Matlab-Simulink model, are based on in-house measured data and are rather pessimistic by comparison to ROPRO \(^7\) and ROSA \(^8\). We therefore believe that the following predictions are realisable.

We predict a total annual flow of 1424 m\(^3\), which is an annual average of just over 3.9 m\(^3\)/day.

![Figure 2 - Product water flow – Monthly averages](image)

The increase in the summer is due to the increase in seawater feed temperature, not solar resource.
It is apparent that the daily production is fairly consistent, except for two consecutive cloudy days in August. In order to meet demand through this period, a product tank of at least 6 m³ is required. In practice, it may well be prudent to have a significantly larger tank to allow for even more erratic weather conditions, unplanned system downtime and variability in consumption.
Figure 4 – Volume in product water tank

This graph assumes a product water tank of 6 m³ and that water consumption is a constant 3.0 m³/day. In practice, consumption is likely to be seasonal and influenced by the level in the tank.
4.4 Product water quality

Figure 5 – Salt concentration in product water tank

This graph assumes that all of product water is directed into the tank (no concentration-controlled diverter valve is included). It shows that the predicted quality of the water in the product tank is generally very good, except for the two cloudy days in August.

The actual threshold of acceptability is largely a matter of taste and is therefore very dependent on the consumer. Neither the World Health Organisation nor Water Aid makes any specific health-based recommendation for the maximum allowable salt concentration in drinking water. Target salinity figures of 200 to 500 mg/L are often used to achieve satisfactory taste for Western consumers. However, in areas with no alternative supply, a salinity of around 1000 mg/L may well be perfectly acceptable, especially if this can be produced in greater quantity or with improved reliability.

The concentration of the product water can be expected to rise slightly as the membranes age.

There are various straightforward techniques that could be used to limit the concentration in the product water tank, should this prove necessary.
4.5 Energy flows – Sankey diagram

![Sankey diagram](image)

The figures and line widths shown in the above Sankey diagram represent the annual-average energy flow in kWh per m³ of product water. These figures can readily be converted to annual kWh simply by multiplying by 1424 m³, which is the predicted annual product volume.

Starting on the left, 4.01 kWh/m³ (5710 kWh) is available from the PV array. A tiny proportion of this, 0.01 kWh/m³, is unused, representing the rare occasions when there is insufficient power available to start the rig.

Next, a further 0.49 kWh/m³ is unused, representing the times when there is an excess of power available: the rig is operating at its maximum flow and pressure. A reduction in the size of the PV array would reduce this figure and so improve the annual-average energy efficiency; however, as already noted, the PV array size is chosen to minimise the overall cost of the water, which is a slightly different goal.

Neither of the above unused powers are necessarily losses, since they represent electrical power that is available for other purposes, such as battery charging for lighting.

Thus, the 3.51 kWh/m³ may be regarded as the total electrical energy consumption for the desalination system. This specific energy is discussed more fully in Section 4.7.

Next, it can be seen that the inverter and motor efficiencies are good, particularly considering that these are very small induction motors, each delivering around 500 W on average.
The plunger pump is also very efficient. The additional 0.23 kWh/m³ that feeds the plunger pump represents the work done by the Moineau pump in raising the feed water to medium pressure.

The Moineau pump itself is less efficient. Its selection is discussed in Section 5.4.

Two losses are shown in relation to the RO membranes themselves. First, the 0.07 kWh/m³ represents the slight pressure drop found between the feed and the concentrate flows. This includes pressure drops in the interconnecting pipe work. Second, the 0.95 kWh/m³ represents the viscous losses associated with driving the product water through the membrane.

The 0.78 kWh/m³, on the far right of the diagram, represents the actual desalination.

The massive 3.33 kWh/m³, also emanating from the membranes, represents the energy contained in the pressurised concentrate water.

The Clark pump recovers this energy and delivers it directly back into the feed flow. It achieves an annual average of 93 % efficiency, which is truly excellent.

4.6 Power usage – average day

![Figure 7 – Analysis of power usage over an average day](chart.png)
4.7 Specific Energy

The concept of specific energy, measured in kWh/m³, has already been introduced in discussion of the Sankey diagram and is widely used in the reverse osmosis industry, where it is often referred to simply as energy consumption. We use the term specific energy to emphasise that it is on a per volume basis.

The graph below shows how the specific energy that the rig can achieve varies with the power available to the rig.

![Figure 8 - Specific energy vs. electrical input power](image)

This shows that the specific energy is typically between 3.2 and 3.7 kWh/m³. Moreover, it is near constant except under very low-power operation. Thus, the flow of product water is virtually proportional to the power available from PV array over a very wide range.

These are very impressive results when compared to traditional reverse osmosis systems. The credit for this goes firstly to the Clark pump but also to the selection of all the other system components and the recovery ratio control strategy, discussed in Section 5.8.

The slight spread of specific energy values for a given electrical input power (apparent in Figure 8) is due to the variation in feed seawater temperature (17 to 33 °C). This variation in specific energy is actually very small, again due primarily to the Clark pump.
5 DESIGN CONSIDERATIONS

5.1 RO modules

5.1.1 Alternative membrane technologies
In the early months of the project, we reviewed the technical and commercial merits of the three leading seawater RO membrane technologies:

- spiral-wound elements such as those from Dow-Filmtec;
- the disc-tube system from Pall-Rochem and
- the Permasep hollow-fibre system from Du Pont.

Our conclusion was that spiral-wound elements are the most appropriate for PV-powered seawater RO systems. Not only do they offer good energy efficiency, but also they are available from a range of manufactures, which prevents reliance on any particular supplier.

5.1.2 Alternative membrane brands
Spiral-wound elements from different manufactures are generally interchangeable and there is little to chose between the various manufactures. Their relative performances leapfrog each other year-on-year as the manufactures strive to lead the field. Right now, two companies with particular interest in energy efficiency (ERI and Spectra) both use Koch membranes and this guides our choice.

5.1.3 RO Module size and number
The operating pressure and feed flow rate of an RO system will directly affect the product flow rate and the specific energy (kWh/m³) of the product. The relative importance of these depends on the application. A small PV-powered system is rather different to a large grid-connected plant.

Generally, the pressure/flow operating point for a large grid-connected plant is chosen to give a high product flow for the installed membrane area. This keeps capital costs down but also leads to the specific energy (kWh/m³) and hence running costs being higher than they could be.

The specific energy can be significantly reduced by reducing both operating pressure and feed flow. This will reduce the product flow, but this can be compensated by use of a larger membrane area. Operation at reduced pressure will also increase the salinity of the product water, which must obviously be considered. Lastly, feed water temperature, which can vary considerably through the year, has a strong influence.

It is clear, therefore, that a PV-powered system is likely to benefit from use of a generous membrane area. To quantify this we used our Matlab-Simulink system model. The results led us to select four 4-inch by 40-inch membrane elements in our current system design. As expected, this is a large membrane area for the intended product flow rate.
5.1.4 Variable pressure/flow

A key objective of this project is to make optimum use of the varying energy available from the PV (and without using batteries). The strategy adopted involves controlling the speed of the two pumps and thus the reverse osmosis system must be able to operate with variable pressure and flow. This is a very uncommon requirement for reverse osmosis systems and again differentiates a batteryless PV-powered system from standard grid-connected and diesel-powered systems.

Membrane manufacturers have been reluctant to give any warranties regarding their products under variable pressure/flow conditions. However, our in-house test rig, which has been operated under variable pressure/flow conditions throughout the project, has indicated no problems.

5.1.5 Fouling

Membrane fouling is a major concern in any reverse-osmosis system since it determines the frequency of required membrane cleaning and/or replacement. The rate of membrane fouling is very dependent upon feed-water quality and pre-treatment, see Section 5.9.

Also, in systems using brackish feed waters, where scaling is a problem, fouling can be greatly accelerated by use of excessive water recovery ratios, and this sets a limit on the recovery ratio.

In sea-water fed systems, on the other hand, the recovery ratio is limited primarily by the osmotic pressure in the last element, where the feed water is most concentrated. Operating at a lower recovery ratio will have little effect on the biological fouling, which tends to occur in the first element.

The control of water recovery ratio is discussed further in Section 5.8.

5.1.6 Membrane flushing, cleaning and replacement

Membrane fouling can sometimes be reduced by timely flushing of the membranes with fresh water, usually taken from the product water tank. Furthermore, large reverse osmosis plants generally have mechanisms that allow the membranes to be cleaned in place (CIP) on a regular basis. Lastly, it is common to periodically remove the membrane elements, clean them more vigorously (in a machine for the purpose) and then return them into service. Thus, an element is typically cleaned many times before it is finally discarded and replaced. In contrast, with very small reverse-osmosis systems, such as those found on yachts, it is much more common simply to replace the membranes.

A PV-RO system can be expected to run every day, assuming it is located in an area with a good solar resource. Thus, the system should never be standing idle for much over 16 hours. Based on this and on advice found in instruction manuals for other small RO systems, our current design does not to include any automatic flushing mechanism. Provision is required, however, for manual flushing in both planned and unplanned maintenance.
5.2 Energy recovery mechanism

Small reverse-osmosis systems are generally built without any energy recovery mechanism. They have a needle restrictor valve to provide the back-pressure in the concentrate. This keeps the capital cost down but is very wasteful of energy. Typically, 70% of the input power is wasted in the valve and, consequently, such systems often consume more than 10 kWh/m³, making them very expensive to run.

5.2.1 Danfoss hydraulic motor

In a previous project³, Dulas demonstrated the use of a Danfoss hydraulic motor for energy recovery. This reduced the specific energy from 13 kWh/m³, for a system using a needle valve, to around 5.6 kWh/m³ – a vast improvement in the context of PV-RO. The current project was founded on that success and, in the early stages, we worked with a similar Danfoss hydraulic motor. We found that its efficiency was significantly lower than the manufacturer’s claim and that it was occasionally difficult to start. Also, its long term compatibility with seawater remained questionable.

5.2.2 Clark pump

About midway through the current project, we learned of the Spectra Clark Pump, a new and extremely elegant device for use in reverse-osmosis desalination systems. It recovers the mechanical energy from the concentrate flow and returns it directly to the feed flow. The Clark pump has been developed by Spectra Watermakers of California, USA over the last five years and is covered by US patents 5,462,414 and 5,628,198.

![Figure 9 – General configuration of a Clark pump in a reverse-osmosis desalination system](image-url)

The above figure is one slide taken from an animation that may be found on the Spectra web site: [www.spectrawatermakers.com](http://www.spectrawatermakers.com).

We obtained a Clark pump and tested its performance thoroughly. We found that its efficiency is truly excellent and, importantly, that this is maintained over a very wide range of flow rate.
The flow ratio (concentrate-brine flow/seawater-feed flow) of the Clark pump is fixed at the design stage, by virtue of the ratio of areas between the two main pistons and the rod connecting them. In the simple system configuration shown in Figure 9, the standard Clark pump gives a 10 % water recovery ratio at the membranes. A 20 % model is now available, but again, the ratio is fixed. This simple system configuration is good in that only requires one feed pump, but is does restrict the product flow per Clark pump. It also prevents any adjustment of the water recovery ratio that might maximise the energy efficiency of the RO membranes themselves under variable flow conditions.

In the PV-RO system shown in Figure 1, the plunger pump injects additional feed water, which increases, and gives control over, the overall water recovery ratio.

When coupled with the variable-speed high-pressure injection pump, we consider that the Clark Pump is very well suited to a batteryless PV-powered system.

### 5.3 High-pressure plunger pump

The selection of the pump for the high-pressure injection duty is fairly straightforward. Plunger pumps offer excellent efficiency (typically over 85 %) and, since they are routinely used in small-scale reverse-osmosis systems, are readily available with full seawater compatibility.

### 5.4 Medium-pressure Moineau pump

The selection of the medium-pressure pump is rather less straightforward. Obviously, efficiency is paramount and, unfortunately, plunger pumps are much less efficient at reduced pressure. Seawater compatibility and tolerance of the occasional grain of sand is also important.

A multi-stage centrifugal pump would seem to be a possibility, but, these offer very poor efficiency (less than 40%) at the required flow/pressure. Furthermore, to achieve optimum efficiency with a centrifugal pump, the rotor speed must be matched to the flow/pressure operating point. This is not straightforward in a system where both the flow and pressure must vary according to the available sunlight. Lastly, since a centrifugal pump does not offer positive displacement, balancing the water recovery ratio with the injection system would be rather difficult.

We also considered a wide range of diaphragm and vane pumps but finally selected a Moineau (progressing-cavity) pump. These offer reasonable efficiency at the required duty and, importantly, this efficiency is generally maintained as the flow is reduced. Such pumps are often used in PV-powered systems. They can suffer from starting problems due to the static friction between the rubber stator and the metal rotor – once turning, the water being pumped acts as a lubricant. Starting should not be a problem in a system employing a variable-frequency inverter.

Submersible Moineau pumps are widely used and could be used in this application. However, if the well is shallow (less than 8m) and the rig can be
sited nearby, an above-ground Moineau pump may be preferable, since this will permit use of a much higher efficiency motor. Our costs and performance predictions are based on an above-ground Moineau pump.

5.5 Pulsation dampeners (accumulators)

As shown in Figure 1, two pulsation dampeners (accumulators) are required in the system. The first, on the feed to the Clark pump, serves to smooth the pressure as the Clark-pump piston reverses at the end of its stroke. The second serves to smooth the output pressure of the plunger pump. In a PV-powered system, it is important that both dampeners are correctly charged so that they are effective over the full range of the variable working pressure.

5.6 Inverters

Dedicated PV-pumping inverters are commercially available and have the advantage that maximum power point tracking (MPPT, see next section) is built in. However, since it is a relatively small market, these inverters tend to be rather expensive and offer little flexibility in control strategy. We chose, instead, to use standard industrial inverters (variable-speed drives) and to implement the MPPT separately.

Standard industrial inverters (of this size) are designed to operate from a standard 230 VAC supply. However, the first stage is typically a bridge rectifier and, provided this is the case, the inverter will operate equally well from a DC supply. (The DC just passes straight through the rectifier.) Direct connection of a PV array to a standard industrial inverter is a proven technique.

Firstly, it requires that the PV-array voltage range lies within the safe operational voltage range of the inverter. A typical rating is 230 VAC +/-15%, which translates to 276 to 374 VDC, but in practice, the lower boundary can often be extended.

Secondly, MPPT is required.

5.7 Maximum power point tracking (MPPT)

It is important, in all but the smallest PV systems, to include maximum power point tracking (MPPT) that will control the current drawn from the PV array so as to obtain the maximum power output under varying conditions, particularly irradiance and module temperature.

Our experience with commercial PV inverters shows that the implementation of MPPT is often crude and rather less effective that it should be. We therefore set about developing a MPPT algorithm from first principles.

The result is a very simple, yet effective, algorithm, which we implemented and demonstrated during the course of the project. Our demonstration was with the reverse-osmosis test rig, but the algorithm’s potential application is much broader. We are now developing the concept and testing it in other situations. We hope to publish these results separately later this year.
5.8 Recovery-ratio control

As noted earlier, the inclusion of the variable-speed high-pressure injection pump (the plunger pump in Figure 1) allows control over the water recovery ratio. This control is especially valuable in a batteryless PV-powered system because it enables the water production to be maximised as the available sunlight varies through the day.

![Figure 10 – Optimum recovery ratio vs. PV electrical power](image)

The figure above shows that, at low solar irradiance the system operates with a low recovery ratio: 10%. This is achieved by the running only the Moineau pump. As the irradiance increases, the plunger pump is started and its speed ratio, against the Moineau, is increased.

It can be seen that the optimum recovery ratio is not a simple function of power. Furthermore, it varies with feed-water temperature. It will also vary with membrane condition and feed-water concentration.

Our Matlab-Simulink system model allows us to identify the optimum recovery ratio under varying conditions and our performance predictions assume that this has been achieved. The algorithm to achieve this will be implemented in the microprocessor-based controller.
5.9 Feed water and pre-treatment

As noted earlier, the main operating cost of a batteryless PV-RO system is expected to be the replacement of RO membranes when they become fouled and can no longer be effectively cleaned. The rate of membrane fouling is very dependent upon feed-water quality and pre-treatment.

Figure 1 shows the feed seawater coming from a beach well. This is generally considered preferable over an open-pipe sea intake – in a properly constructed beach well, the beach sand can act as an efficient pre-filter. If the native sand is not ideal, its performance may be enhanced by the inclusion of fine-grade filtration sand around a porous liner.

In the absence of a suitable sandy beach, construction of a slow sand filter could be considered, although this would require an additional pump.

The details of beach well and slow sand filter construction are beyond the scope of this project, but it is clear that good design in this part of the scheme will be critical to the overall success.

Ultraviolet (UV) disinfection of the feed water may also be considered for further refinement of water that is already well filtered. The effectiveness of UV depends on the clarity of the water. It should also be remembered that UV will only kill the organisms; they will then become food for any organisms that have already got through.

5.10 Product tank chlorination

At the time that the product water is produced by the RO system it should be almost free of biological activity. However, it will then be very prone to re-infection, particularly in the storage tank. UV could again be employed as a means of disinfection. However, it is considered that chlorination will be more appropriate in this case. Firstly, chorine has a residual presence in the water, which will continue to be effective throughout any pipes, storage bottles or whatever. Secondly, since the product water should already be in good condition, it should not need a lot of chlorine to maintain safety.

5.11 Feed water pre-heating

In the course of the project, we did consider using solar-water pre-heating for the feed water, particularly during the winter months. We drafted and modelled a system of heat exchangers but concluded that the additional complexity was not justified. The large increase in product water flow found in open-loop (no energy recovery) testing of a reverse-osmosis membrane does not occur in a system employing an efficient energy recovery mechanism (such as a Clark pump).

Thus, our current design does not include pre-heating of the feed water. Instead, the wide annual range of feed water temperature is accommodated by adjustment of the recovery ratio.
5.12 Batteries

The PV-RO system described in this report involves no batteries. This was always a central aim of the project and sets it aside from most other PV-RO systems. Our wish to avoid the use of batteries is based on years of practical experience with batteries. In particular, we have found that the performance of lead-acid batteries is poor in the following areas:

5.12.1 Transportation and storage
Real life experience with batteries indicates they are often kept in dockside containers for up to 2 years prior to in-country distribution. Storage for these periods at high ambient temperatures and humidities leads to mechanical and chemical decomposition of the battery’s electrode plates.

It has been found that, in remote areas, up to 30% of the batteries are damaged on arrival due to excessive vibration in transit.

5.12.2 Charging
Maximising the life expectancy of such a delicate part of the system is obviously a high priority. One of the only ways of doing this is to use sophisticated electronics to accurately control the charging, and discharging of the battery. This has the complications of measuring the battery temperature, and needing to vary the charge/ discharge regime according to the type of battery, making re-calibrating the control electronics for a replacement battery a skilled job that is not likely to be done properly.

5.12.3 Maintenance
Batteries require regular preventative maintenance throughout their working life. The main tasks are the checking and topping up of the electrolyte with distilled water, checking the connections for slackness or corrosion, and measuring individual cell electrolyte densities and voltages. Although this is straightforward it is often neglected as the degradation is slow and goes unnoticed unless objectively measured.

5.12.4 Life cycle costs
In typical usage, battery life is between 2 and 6 years, after which time funding must be sought for replacement batteries. Often, this is not possible and the installation falls into disrepair, the technology into disrepute.

5.12.5 Energy efficiency
In practice, the charge/discharge cycle efficiency of lead-acid batteries is around 75% at best.
6 MARKET POTENTIAL

Population International Action (PIA) report that 430 million people – eight percent of the world’s population – are living in water scarce countries. WaterAid estimates that, by the year 2050, between 25% and 60% of the world’s population will face water scarcity.

Dramatic growth can be expected in the desalination industry, particularly in coastal regions and on islands. Large-scale municipal desalination plants will continue to dominate the industry, but smaller systems will be appropriate in less densely populated regions.

Increasing use will be made of renewable-energy for desalination. Initially, this can be expected in areas without grid electricity and where fossil fuels are expensive, either nationally or due to local delivery costs to remote areas. For small desalination systems in these areas, photovoltaic power will be especially competitive.

The established reverse-osmosis industry makes a clear distinction between seawater and brackish water. Different membranes are used for brackish water and much higher recovery ratios are possible, which makes energy recovery less critical. Also, with brackish water, electrodialysis becomes competitive. The reverse-osmosis system developed within this project is designed to be fed with seawater, including that taken from coastal wells. It is not intended to run from brackish feed water and will be less competitive in such situations.

Our system delivers around 3 m$^3$/day. It could readily be scaled in either direction to produce say 1 to 10 m$^3$/day, but would tend to be less competitive much outside of this range.

The potential market for the system developed in this project can be broadly divided as follows:

- Small communities in the developing world, funded by humanitarian aid organisations and governments;
- Luxury remote holiday resorts and private dwellings.

6.1 Developing-world market

Currently, rainwater collection, small-scale solar stills and the carrying of water for large distances are common in developing countries.

UNICEF believes that access to water should remain a basic human right. The true cost of water provision is often distorted by government subsidy at regional and national level. UNICEF are worried that privatisation and tradable profit rights may mean that access to water will no longer be regarded as a right, but merely as a function of economic markets.

The World Health Organisation and UN based organisations have comprehensive strategies and policies to halve the proportion of people who are unable to reach or to afford safe drinking water by 2015.
WaterAid, the World Health Organisation and UN based organisations recommend that, in semi-arid conditions, a person requires around 20 litres of fresh water per day for drinking, cooking, basic washing, hygiene and laundry. Thus, our 3 m³/day system could be expected to support a village of 150 people. A WaterAid representative in Madagascar suggested that requirements of livestock should also be considered 13.

The solar resource in arid developing countries is generally excellent and therefore solar-powered desalination is very well suited.

6.2 Luxury market

Currently, luxury remote holiday resorts and private dwellings tend to rely on imported water or desalination using imported diesel. If long-term running costs are considered, PV-powered reverse-osmosis is a very strong competitor.

Also, the growth of sustainable tourism and, more generally, the increased awareness of environmental impact creates a large market for renewable-energy solutions. Dulas, for example, are currently working on a remote Caribbean holiday complex powered from renewable-energy sources, including wind and PV.

6.3 SWOT Analysis

<table>
<thead>
<tr>
<th>Strengths:</th>
<th>Weaknesses:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Very low running and maintenance costs</td>
<td>• High capital cost</td>
</tr>
<tr>
<td>• No dependency on grid electricity or fossil fuel supplies</td>
<td>• High-tech (compared to solar stills)</td>
</tr>
<tr>
<td>• Environmentally benign</td>
<td></td>
</tr>
<tr>
<td>• Compact (compared to solar stills)</td>
<td></td>
</tr>
<tr>
<td>• Portable</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Opportunities:</th>
<th>Threats:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Water shortage in coastal regions and islands</td>
<td>• Fossil-fuelled alternatives</td>
</tr>
<tr>
<td>• Increased acceptance of RO as an appropriate technology</td>
<td>• Procurement agent buying patterns</td>
</tr>
<tr>
<td>• Increased environmental awareness</td>
<td></td>
</tr>
</tbody>
</table>
6.4 Comparative costs of desalination technologies

Assessments of commonly used desalination technologies were previously conducted by Dulas. The data from the current project has been calculated in a similar fashion and added to this to allow comparison.

To assess the real costs involved, cost comparisons are made for off-the-shelf, commercially available technology, standardised at 20 years of operation.

Basic assumptions are: feed is seawater, TDS of 40,000 mg/l. Units sized for 3 m$^3$/day. Insolation (Solar irradiation) on stationary panels, 5 kWh/m$^2$/day. The technologies considered are Simple Basin Solar Still (B.S.S), Multistage Flash Distillation (M.S.F.), Photovoltaic Reverse Osmosis (Solar PV-RO) with energy recovery and diesel Reverse Osmosis.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Expected lifetime</th>
<th>Spares, cons. £ / m$^3$</th>
<th>20-year cost, £ / m$^3$, inc. initial cost</th>
<th>20-year disc. cost @ 5%</th>
</tr>
</thead>
<tbody>
<tr>
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<td>5 years</td>
<td>1.0</td>
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<td>Diesel RO</td>
<td>20 years</td>
<td>11.0</td>
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</tbody>
</table>

Table 4 – Comparative costs of desalination technologies

This shows batteryless PV-RO in a very economically favourable light for small volume production.
7 CONCLUSIONS AND FUTURE WORK

The batteryless PV-RO system design developed in this project is really very good. The RO rig itself promises to be highly efficient, due to the Clark pump, the plumbing configuration, the quality of the other components and the control strategy adopted. The hardware is not over-complicated and will be straightforward to use and maintain. Its high efficiency, over a wide range of operating speed, enables it to be powered directly from a PV array of modest-size and without need of batteries. The system therefore requires no fuel and is non-polluting. The predicted total cost of drinking water is just £2.00 per m³, which makes the system very competitive with other small-scale seawater desalination systems. Given the large and increasing worldwide demand for drinking water, particularly in areas of medium and low population density, the system has enormous market potential.

Of course, other companies and researchers worldwide have also recognised this potential and are currently developing similar systems. However, to our knowledge, these systems all employ batteries and/or are for brackish water only.

We conclude that the system design developed in this project should be implemented immediately in a pilot demonstration scheme. Both Dulas and CREST are keen to participate in this. In the longer term, Dulas would hope to add batteryless PV-RO to their commercial range of renewable energy systems.

In the forthcoming months, CREST will commit its own funds to refine the system design. In particular, this will include purchase and assembly of further components for the test rig, the characterisation of these, the verification of the overall system model and the development of the recovery ratio control algorithm discussed in Section 5.8. Meanwhile, Dulas will seek partners and funding for a pilot demonstration project, which will aim to:

- Install a full prototype system in a hot arid coastal region (exact location to be guided by project partners/sponsors);
- Demonstrate its reliable operation in field conditions;
- Monitor its performance, especially that of the RO membranes themselves;
- Verify the Matlab-Simulink system model;
- Verify the cost predictions;
- Rectify any weaknesses in the design, for example due to corrosion;
- Develop the maintenance schedule and user interface, taking into account end-user skills and resources;
- Monitor the use of the system and assess its socio-economic effect;
- Promote the system to potential customers.
REFERENCES


4 Clark Pump, Spectra Watermakers, Sausalito, California, www.spectrawatermakers.com


8 ROSA, Version 4.2, Dow Filmtec Membrane Systems.


A HARDWARE TEST FACILITIES

The performance predictions presented earlier in this report are based, as far as possible, on in-house measurements of the major components.

Our hardware test facilities include:

- reverse-osmosis membranes;
- pumps, motors and inverters;
- energy recovery devices, including a Clark pump;
- a titanium-plate heat-exchanger, for feed water temperature control;
- a rooftop PV array;
- a PV-array simulator.

All of the above are fully instrumented using sensors including:

- oval-gear flow meters;
- in-line conductivity probes;
- silicon-diaphragm pressure sensors;
- a load-cell torque sensor.

These sensors are connected through National Instruments signal conditioning and data acquisition hardware into a LabView signal processing and data logging system.

We invested a lot of time and effort in configuring and calibrating all the above and this gives us good confidence in the data we have collected and hence in the software models built from it.
B  MATLAB-SIMULINK MODEL

B.1 Scope

For the purpose of overall system configuration and component sizing, our model performs an hour-by-hour simulation of a whole typical year.

The model includes everything from the solar radiation striking the photovoltaic panels through to the water in the product tank.

(For comparison, ROPRO $^7$ and ROSA $^8$ simulate only one constant operating point and cover only the membrane part of the system.)

B.2 Structure

Simulink is a graphical programming language in which blocks are structured hierarchically to represent the components of the system being modelled.

![Simulink model of overall system](image)

The blocks on the left provide the solar irradiation and ambient temperature data. From this, the PV Array block calculates the available electrical power and, when this exceeds the threshold, the RO Rig block is run, which fills the Product tank.

Figure 11 – Simulink model of overall system
Figure 12 – Simulink model of RO rig

This diagram shows the contents of the RO Rig block in the previous diagram. The components are immediately recognisable.

It also shows that many of quantities are fed backwards (from right to left), implying that the model must know the answer before it can work it out. These circular references are a necessary feature of this type of system model. In Simulink, they are known as algebraic loops and are solved by Newton-Raphson iteration.

The above paragraphs indicate just two reasons that we chose to build the model in Simulink, rather than in Excel for example. The remainder of this section indicates the basis of each of the main system components and is intended to substantiate the performance predictions already presented.

B.3 Solar irradiance

The hour-by-hour solar irradiance data originated from Meteonorm 4.0. Adjustment to include single-axis solar trajectory tracking was performed using PVsyst. Both of these packages are well proven.

B.4 PV modules

The individual PV cells are modelled with the standard two-diode model using parameters from the manufacturer. The module models were then checked against the manufacturer’s performance curves. Ambient temperature data, again from Meteonorm, is used along with the Normal Operating Cell Temperature (NOCT) to provide correction for module temperature as per Markvart.

B.5 **Maximum power point tracking**

The model determines the genuine maximum power point \( (\frac{dP}{dV} = 0) \) under all conditions. Our performance predictions assume that the controller can achieve this in practice.

B.6 **Inverters**

The inverter models used in our performance predictions are based on manufacturer’s data. This compared well with our measured data from a competing manufacturer’s inverter.

B.7 **Motor**

Our early models of the induction motors were based on a full equivalent circuit. However, it proved difficult to obtain parameters from the manufacturers and to match them with measured efficiencies. The induction motor models now use simple direct and quadrature current models based on standard three-point (100%, 75% and 50% load) manufacturer’s data.

B.8 **Plunger pump**

The plunger pump model uses mechanical and volumetric efficiencies measured in-house from a similar (slightly larger) pump.

B.9 **Moineau pump**

The Moineau pump model includes curves for both mechanical and volumetric efficiencies. However, these are based entirely on manufacturer’s data and we have no experience against which to check this.

B.10 **Clark pump**

The Clark pump model is based on comprehensive in-house measurements. We are fully confident of its accuracy.
B.11 Reverse osmosis membrane modules

The practical performance of reverse-osmosis membrane modules is not easily predicted with satisfactory accuracy. The product flow and concentration are affected, firstly, by pressure, flow, temperature, concentration and composition of the feed water. Secondly, the performance can vary significantly from one module to the next, even when new. Thirdly, the performance degrades significantly during the life of the membrane due to the combined effects of fouling, scaling, compaction and general fatigue.

Membrane manufacturers generally provide proprietary performance-prediction software. Dow offer ROSA; Koch offer ROPRO; etc. The software comes with the usual disclaimers and industry accepts that practical results will vary from the predicted. Certainly, the performance we measured of both Dow and Koch membranes differed significantly from that predicted by ROSA and ROPRO respectively. The differences were most marked in the unusual regions of operation: regions of low flow that would not be of interest to the designer of a constant-flow system.

Our membrane model covers the very wide operational range that is of interest for a variable-flow system. It is based on thorough in-house characterisation of 2.5” modules, but scaled up to 4” modules according to ratios determined from ROPRO 7.

If anything, we believe our model is pessimistic.

Fortunately, the performance of the membranes themselves becomes less significant in systems with efficient energy recovery mechanisms, such as the Clark pump.
### C. CHEMICAL ANALYSIS OF WATER FROM A SEAWATER WELL IN MASSAWA

Date 16/09/98  
Description: Sea Water Min. of Fisheries  
P.O.Box 1455  
Well Ident. MS002D05  
Lab No. 888  
Sub Zone Massawa  
Village Massawa

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