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Economic evaluation of a small RO unit powered by PV installed in the village of Hartha, Jordan

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ABSTRACT

A PV-powered desalination system has been successfully designed, installed and tested at the Hartha Charitable Society in northern Jordan as part of Autonomous Desalination In Rural Areas (ADIRA) with renewable energies—Potentials, technologies, field experience, socio-technical and socioeconomic impact) project installations, partially supported by the European Commission. The system is composed of photovoltaic (PV) panels (433 Wp), a commercially available small RO compact unit with a typical daily production of 428 L, and a softener. The system produced clean drinking water from a variety of feed waters, including brackish water (1700 mg/L). The amount of energy required to produce 1 m^3 of high quality water (30 mg/L) is about 13 kWh, depending on the salinity of feed water and the system operating conditions. The cost per cubic meter of water produced is US$ 15.6. The price is not competitive with the price of water produced by conventional desalination processes, but in some cases, for instance small rural sites or during catastrophes where drinkable water is not available, such systems are indispensable. This paper presents the cost calculations of the PV–RO system and the possible scenarios to reduce the production cost.

Keywords: PV; RO; Solar; Clean energy; Cost; Brackish water; Desalination; Jordan

1. Introduction

Desalination inherently consumes much energy, the theoretical minimum for seawater being around 0.8 kWh/m^3. As the price of fossil fuels is high and continues to rise, fuel-poor countries like Jordan are finding it costly to desalinate water. The problem becomes more acute in remote areas and islands where it is difficult to obtain fossil fuels.

Some of the potential methods of minimizing energy usage and cost include the utilization of renewable energy (wind, solar, geothermal). Renewable energy sources constitute a clean supply of energy for desalination and provide a reliable tool for rural applications. In view of global energy needs and concern for environmental degradation, solar energy as a clean energy source is receiving greater attention for various applications including desalination [1].

A cost analysis for a given desalination technology is site-specific and is one of the most important steps in solar-powered desalination system planning as it is strongly related to the sustainability of the unit. The

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product cost is observed to be affected by unit capacity, quality of feed water, cost of energy, type of technology, site conditions, costs of land and labor and additional costs such as taxes, permits, fees, brine disposal, etc.

Although solar energy is essentially free, the equipment required to convert it to a useful form, thermal or electrical, is not free. Economic factors are the main barriers to the diffusion of solar energy to the desalination processes. However, solar energy could be competitive economically (even at the actual costs) at places where the price of fossil fuels used to run a desalination unit is notably higher than their standard value [1].

From this point of view, cost of water produced from a solar-powered desalination system can only be competitive in remote areas, far from conventional energy sources compared to water produced from plants that run on grid electricity or oil. However, it is expected that desalinated water will soon become economically viable as the number of solar-powered desalination systems increases, allowing some economies of scale.

Many researchers have reported cost estimates for the RO plant driven by photovoltaic cells. For example, Herold et al. [2] studied the feasibility of PV–RO plants for the supply of domestic drinking water in the arid/rural regions of the Canary Islands. The plant was supplied with a stand-alone 4.8 kWp PV system with additional battery storage of 60 kWh. The nominal production was 1 m^3/d. The specific energy consumption of this system was considered high, with a \$16/m^3 production cost.

Carvalho et al. [3] estimated the cost of a PV–RO desalination plant with batteries. This plant was installed in the community of Ceara, Brazil. The specific energy consumption of produced water was around 3.03 kWh/m^3 with cost a of \$12.76 m^3.

Al Suleimani and Nair [4] reported an average water cost of 6.52 US\$/m^3 for a demonstration PV–RO desalination unit with a battery backup and freshwater capacity of 5–7.5 m^3/d which is produced during peak solar hours (5 h). The unit was built to desalinate brackish water at the Heelatar Rakah camp, a remote location about 900 km south of Muscat, the capital of Oman.

Thomson and Infield [5] presented a cost-effective battery-less PV-powered RO desalination system with a water cost of £2 Sterling (US \$3.64) per cubic meter. The plant capacity is 3 m^3/d and the system has a modest 2.4 kWp PV array. The simple control system of the unit provides maximum power point tracking for the PV array. The system is equipped with a large storage tank to allow for erratic weather conditions, unplanned system downtime and variability in consumption. The objective of this paper is to present an economical analysis of a small PV–RO unit installed in the village of Hartha in Jordan as part of the ADIRA project that was co-funded by the European Union.

2. System description

The system is composed of a softener, RO unit, PV panels (432 Wp) and storage batteries. A residential type Osmonics membrane (TFM-100) was utilized in the RO unit. Field tests were performed on municipality (350 mg/L TDS) and brackish water (1700 mg/L TDS). A block diagram of the Hartha PV–RO system is shown in Fig. 1.

3. Cost analysis

The cost of desalination is usually a function of plant capacity, feed water quality, pretreatment, process technology, energy cost, plant life and investments amortization. The major cost elements for desalination plants are capital cost and annual operating costs. Capital cost covers purchasing cost of equipment, auxiliary equipment, land, installation charges and pretreatment of water. Annual operating costs are the total yearly costs of owing and operating a desalting plant. These include amortization or fixed charges, operating and maintenance (O&M) costs and membrane replacement costs.

3.1. Capital cost

Calculation of the capital cost depends on the process capacity and design features. Table 1 lists the technical values used to estimate the water production cost for the Hartha PV–RO system.

The following cost basis was used in the estimation of the capital investment of the PV-RO desalination system:

- Membrane price for the Osmonics residential type is about \$50–\$75 [6].
- PV module price is about \$4.85/Wp [7] and \$6.5/Wp [8]. The cost of solar panels including the auxiliaries is about \$7.65 Wp [9].

Table 1
Summary of the technical values used in the cost estimation for Hartha PV-RO system

Item	Value
Plant capacity (design), L/h	62.5
Plant capacity (operation), L/h	9.3–53 (depends on recovery)
Membrane type	Osmonics, Residential
Number of membranes	4 elements
PV modules, Wp	433
Solar regulator, V (A)	12/24 (20)
Softener unit, L (bar)	64 L (8 bar max pressure)
Number of batteries, Ah–V	2 (230 Ah, 12 V each)
Battery capacity, Wh	5520

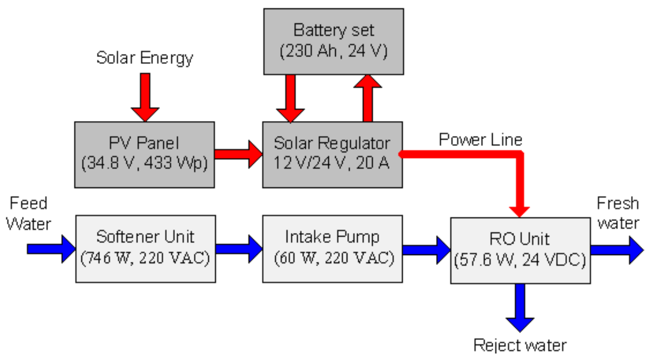

Fig.1. Block diagram of the Hartha PV–RO system.

- Battery price can account for around 15% of the cost of an installed solar energy system ($300/kWh output for a small battery while it is around $150/kWh for a large battery) [10].
- The battery regulator cost typically represents around 10% of the total installed cost of an off-grid complete solar system ($5.80/amp) [7].
- The installation cost is 25% of the purchased equipment costs [9].
- Zero land cost.

Table 2 shows the total estimated investment cost for the Hartha PV–RO system based on the market prices and the recommended percentages in the literature. The actual costs for the PV–RO system are $23,200 in addition to $1429 as installation cost and $2671 for piping and tanks. The softener unit cost is $1614. This totals an actual investment cost of $28,914. It should be mentioned here that these costs are based on real purchase prices and the assumptions given above but may change as these assumptions change.

It can be seen that solar-energy-based plants are capital intensive; however, market prices for renewable energy sources could gradually become lower in the future and would be competitive with conventional energy sources. If the selection of a desalination system (solar vs. non-solar) were made on the basis of initial cost alone, the solar desalination system would rarely be selected. Non-solar desalination systems usually have relatively small initial costs and relatively large annual operating costs, reflecting raw energy purchases. Solar desalination systems, however, are relatively expensive initially but have a negligible non-solar energy cost during their lifetime [11].

It can also be noticed that the total investment cost for the Hartha system was higher than expected due to a lack of experience in the local market. The RO unit (designed for solar application), PV modules, gel batteries and the solar regulator had been brought by a local provider from Germany. Taxes, transportation fees, expert technician and trader profit were part of the high total investment cost for the Hartha system.

Table 2
Capital investment cost for Hartha PV-RO system (depending on prices of the market and the percentages present in the literature)

Item	Value, US$
RO unit	4,500
PV module	2,100
Solar regulator	386
Batteries	1,656
Piping and tanks	2,671
Racks	300
Electrical wiring	100
Softener unit	1,000
Feed pump	150
Total equipment cost	**12,863**
Installation cost	3,216
Total investment cost	**16,079**

3.2. Annual operating costs

Annual operating cost covers all expenditures incurred after plant commissioning and during actual operation. These include the following.

3.2.1. Amortization or fixed charges

The capital cost for construction of desalination plants is usually amortized over the term of repayment of the capital used to build the desalination plant (typically a period of 5–30 years). To determine the amortized value of the capital costs, these costs are multiplied by an amortization factor (a). The amortization factor is a function of the interest rate of the capital and the numbers of years over which the investment is recovered. The amortization factor can be calculated using the following relationship [12]:

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (1)$$

where i is the interest rate of the amortized investment (%) and n is the period of repayment of capital expenditures (life time).

3.2.2. Operating and maintenance (O&M) costs

This includes the operation and maintenance staff cost, cost of spares, etc. This cost shall be expressed on a yearly basis for each item for all the commercial operation period [13]. The annual O&M costs are estimated at 20% of the plant annual payment [9].

3.2.3. Membrane replacement

For RO and ED processes, the membrane replacement rate depends largely on raw water quality. Replacement rate may vary between 5%–20% per year. The lower figure applies to low salinity brackish water and the upper reflects high salinity seawater [12].

The average annual cost of a desalination system depends on the expected lifetime, interest rate, and total initial investment. The values of the common economic parameters are listed below:

- Plant life expectancy is 25 years.
- Operating days per year are 300 days (assumes 300 days per year without clouds).
- Feed water TDS is 1500 mg/L (normal case).
- O&M costs are 20% of the plant annual payment.
- Annual rate of membrane replacement is 20%.
- Interest rate is 5%.
- Plant availability (f) is 90% [12].

This calculation method implies that the salvage value of the units will be zero at the end of the amortization period.

The Hartha system produced about 428 L/day (fully autonomous) with a low concentration of dissolved solids (less than 30 mg/L). This water can be blended with feed water to prepare potable water with a salinity of 500 mg/L.

4. Results

The Hartha PV–RO system cost data include the following:

- Capital cost (CC) = $28,914 from vendor (real price) and $16,078 estimated from market price.
- Membrane cost (MC) = $300
- Capacity (M) = 62.5 L/h (428 L/d)
- Specific consumption of electrical power (W) = 13.82 kWh/m^3.
- Plant availability (f) = 90%
- Lifetime = 25 years

The calculations proceed as follows:

- Amortization factor (a):

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{0.05(1+0.05)^{25}}{(1+0.05)^{25} - 1} = 0.070952\ \text{y}^{-1}$$

- Annual fixed charges (A_{fixed}):

$$A_{fixed} = (a) \times (CC) \quad (2)$$

- Annual membrane replacement costs ($A_{replacement}$):

$$A_{replacement} = (20\%) \times (MC) \quad (3)$$

$$A_{replacement} = (20\%) \times (\$300) = \$60/\text{y}$$

- Annual operating and maintenance costs ($A_{O\&M}$)

$$A_{O\&M} = (20\%) \times \left(A_{fixed}\right)$$

$$A_{O\&M} = (20\%) \times (\$2052/\text{y}) = \$410/\text{y} \quad (4)$$

- Total annual cost (A_{total})

$$A_{total} = A_{fixed} + A_{replacement} + A_{O\&M}$$

$$A_{total} = \$2052/\text{y} + \$60/\text{y} + \$410/\text{y} \quad (5)$$

$$A_{total} = \$2522/\text{y}$$

- Unit production cost (A_{unit})

$$A_{unit} = (\$2522/\text{y}) / (90\%)(0.428\ \text{m}^3/\text{d})(300\ \text{d}/\text{y})$$

$$A_{unit} = \$21.8/\text{m}^3$$

$$A_{unit} = \left(A_{total}\right) / (f)(M)(300) \quad (6)$$

The RO unit produces water with high quality (less than 30 mg/L). If we blend the 128 m^3/y (30 mg/L) with feed water of 1500 mg/L, we will need 51.4 m^3/y (40% blending), and hence we will get 179.8 m^3/y of potable water (less than 500 mg/L) production with a cost of $15.6/m^3.

A summary of the water production cost results for the Hartha system is presented in Table 3. The previous cost analysis for all systems is done without considering the cost of instrumentation and control (digital online sensors and data acquisition system). Table 4 illustrates the cost of water production for the Hartha system including the costs of instrumentation and control. The cost increased by 18%. The unit water cost of a R&D pilot unit is not indicative since in most cases extra instruments are included for R&D purposes. In this case the total capital investment will be $34,251.

In its simplest form, neglecting interest charges on capital, one could calculate the cost of produced water. The unit cost of produced water is equal to the total capital investment, membrane replacement and O&M costs divided by the total amount of produced water during the lifetime of the desalination unit. The cost per m^3 desalinated water without amortization is shown in Table 5.

Based on the previous analysis of the PV–RO system, it can be seen that the final water production costs still remain high compared to those of conventional systems. The economic penalty is mainly due to the high initial capital investment. It is therefore necessary to evaluate

Table 3
Summary of the cost results for the Hartha PV–RO system

Item	Vendor price		Estimated price
	Without instrumentation	With instrumentation	
Annual fixed charges ($/y)	2052	2430	1141
Annual membrane replacement ($/y)	60	60	60
O&M annual payment ($/y)	410	486	228
Total annual payment ($/y)	2522	2976	1520
Unit product cost ($/m^3)	21.8	25.7	12.4
Unit product cost with blending ($/m^3)	15.6	18.4	8.8

Table 4
Desalinated water cost per m^3, based on the running cost

Item	Value
Annual fixed charges ($/y)	—
Annual membrane replacement ($/y)	60
O&M annual payment ($/y)	410
Total annual payment ($/y)	470
Unit product cost ($/m^3)	4.1
Unit product cost with blending ($/m^3)	2.9

Table 5
Desalinated water cost per m^3, without amortization

Item	Value
Total capital investment ($/m^3)	9.0
Membrane replacement ($/m^3)	0.5
O&M ($/m^3)	3.2
Total ($/m^3)	12.7
Total with blending ($/m^3)	9

carefully those factors that could be helpful to reduce this cost.

Table 5 presents the cost per m^3 desalinated water based on the running cost only. As shown in the table, the costs are very competitive, especially with blending. In a solar-powered water purification system, the running costs tend to be far lower because no money is spent for fuel or electricity. If the system is subsidized from external funds (governments) the production cost for such a small unit will not exceed 3 US$/m^3.

Table 6 presents a cursory survey of different desalination units; the table reveals the significant higher costs from small-scale desalination plants.

Although solar-powered small-scale systems tend to have high costs per unit fresh water output, this option is sometimes less costly than transporting water by trucks to small villages or isolated communities. In many remote areas, the reliability of delivered fuel is low, and the cost, due to fuel transportation over long distances and poor roads, is very high [14].

Table 6
Unit product cost of selected desalination units

Process	Capacity (m^3/d)	Power	Cost ($/m^3)	Reference
BW (PV–RO)	3	PV+wind	9.7	[15]
BW (PV–RO)	6	PV	12.76	[3]
BW (PV–RO)	0.02–0.05	PV	80	[16]
SW (PV–RO)	4	PV	9.05	[3]
SW (PV–RO)	120	PV	8.36	[15]
SW (PV–RO)	0.8–3.0	PV	16	[17]
BW (PV–RO)	0.6	PV	15.6	This work

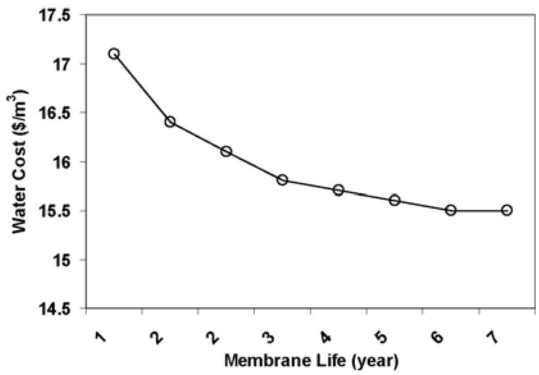

Fig. 2. Membrane lifetime on the cost of produced water.

Briefly, in isolated areas having no access to the electrical grid as well as suffering from a critical water supply shortage, the cost and the profit will have a low priority, and desalination with solar energy remains one of the most favorable processes for small capacity water desalting.

4.1. Influence of membrane life on water cost

The effect of increasing the membrane lifetime on the product water cost is shown in Fig. 2. It can be clearly seen that by increasing the membrane lifetime the cost of water decreases significantly. When the membrane lifetime is

Table 7
Effect of interest on capital on water cost

Unit configuration	Interest rate (%)	Cost ($\$/m^3$)	% reduction in water cost
Hartha system	5	15.6	0.0
	3	12.7	18.6
	0[a]	9.0	42.3

[a]Neglecting interest charges on capital (without amortization).

about 1 year, the cost of permeate for the Hartha system is close to 17 $\$/m^3$. However, when the membrane lifetime is assumed to be 5 years (economical value), the cost of permeate production drops to 15.6 $\$/m^3$ (8% reduction). Based on the above results, it is concluded that to reduce the water production cost, it is necessary to increase the reliability of the RO membranes.

4.2. *Influence of interest rate on water cost*

Table 7 shows the water cost as a function of interest rate. Reducing the interest rate from 5% to 3% decreases the cost by 18%. Exempting such renewable energy-driven units from interest, i.e. 0%, reduces the cost by 42%.

5. Conclusions

An economic study of the PV–RO unit installed in the Hartha village in the northern part of Jordan has been conducted. It was found that although the energy is free (solar energy), water production by such systems is still expensive compared to other desalination processes. The potable water production cost from the PV–RO unit is $15.6/m^3$. If the capital cost of the unit is subsidized by governments, the running cost will be about $ 3/m^3$. Increasing the membrane lifetime and/or reducing the interest rate will lower the cost of produced water.

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