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Economic feasibility of alternative designs of a PV-RO desalination unit for remote areas in the United Arab Emirates

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Abstract

Reverse osmosis (RO) is an electrically driven technology characterized by significantly low specific power requirements. In the meantime, coastal arid areas, as in the United Arab Emirates (UAE), are blessed with exceptionally high solar radiation most of the year. Normally, those areas have no access to municipal water network and the local power grid. In addition, primary fuel cost is soaring up while the need to maintain clean environment is becoming an increasingly important issue worldwide. In view of these facts, it is seen that a small seawater RO desalination unit powered by a photovoltaic array presents an ideal solution to provide small communities isolated at remote areas with freshwater.

This paper explores economic feasibility of three alternative configurations of an autonomous SWRO unit for remote areas in the UAE. Three different scenarios are proposed here for the powering system where the unit is driven either by a diesel generator, a PV-diesel hybrid system or solely driven by solar panels without battery backup.

Simple models are utilized to design the RO plant and produce a preliminary design of the PV array. Detailed cost calculations are performed for each one of the suggested configurations to assess their feasibility and cost effectiveness. These calculations are done in view of the environmental impact of each design and within the possible ranges of solar panels and primary fuel costs.

Keywords: Economic analysis; Design; PV-RO; Remote areas; Reverse osmosis; Diesel assisted; Solar desalination

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1. Introduction

1.1. Coupling photovoltaic cells with small RO plants: advantages and limitations

Small capacity desalination units utilizing the Reverse osmosis (RO) technology and powered by photovoltaic (PV) cells, represent an ideal solution for providing freshwater to small communities in isolated arid areas with high solar irradiation and having access to the sea or brackish water. Usually, such communities have no access, neither to the local power grid nor to the fresh water network.

The use of photovoltaic cells as a source of power is an excellent choice under such circumstances due to

- Modularity: this feature avails system enlargement whenever needed.
- Low maintenance, especially in the case of battery-less systems means reduced operation and maintenance cost.
- Low noise level: as a power generating system, solar panels have no rotating parts. The only noise would be from the pump. Without batteries, the system would only run in daytime and would not disturb people at night.
- Long life: currently, solar panels are guaranteed to stay in service up to 20 years, and withstand harsh environments.
- Well-matched to load as solar panels produce more energy in areas of higher solar irradiation where the people are likely to consume more drinking water.
- Environmentally friendly: CO_2 emissions normally accompanying burning of fossil fuels in conventional power plants do not exist. Nevertheless, we have to remember that considerable amounts of CO_2 are produced by the current silicon-based technologies applied for the production of photovoltaic cells. Such technologies are energy intensive and require large amounts of conventional fuels to be burnt.
- Possible use of single- or dual-axis trackers: this makes the array point directly at the sun throughout the day, which increases the amount of water produced by up to 30% [1].

Parallel to this, reverse osmosis technology is becoming more popular because of the following advantages:

- The specific energy requirement is significantly low 3–9.4 kW h/m^3 product [2].
- The process is electrically driven. As a result, it is readily adaptable to powering by solar panels.
- The RO plant is normally operated at ambient temperature, which reduces the headache of scale formation and corrosion problems, especially when the pretreatment system is properly designed and kept under control. Again this will reduce maintenance cost.
- The modular structure of the RO process increases flexibility in building desalination plants within a wide range of capacities.

The huge ground area normally required for solar panels, especially when the power demand is high, represents a limiting factor which negatively affects their widespread use.

An important consideration in using solar panels in hot environments is the performance deterioration of crystalline silicon solar cells with increasing temperature where panels performance drops by about 0.4% per °C. This factor should be taken into account when sizing a solar array to keep powering the connected system throughout its lifetime.

Amorphous silicon solar panels do not suffer from such performance deterioration and in fact their power output increases slightly at higher temperatures. However, stability of these devices is not satisfactory.

A more serious problem usually encountered when using solar panels for powering desalination units in remote areas is the need for a backup system to enable powering the desalination unit by night and during blackout hours (cloudy conditions may continue for days). This problem can be solved through the following paths:

(a) The use of an array of batteries as a backup system. However, batteries are expensive and are considered as a source of problems to power supplies in remote areas. Moreover, battery arrays require more solar panels for recharging during sunshine hours, which penalizes capital cost. The use of battery arrays thus reduces system reliability and increases maintenance cost.

(b) Power backup by night can be afforded through a hybrid diesel–solar powering system where the RO unit is driven by a diesel generator by night or during cloudy days.

(c) The third alternative solution is to design a larger capacity plant which is fully operated by solar cells. The plant will be able to produce the daily water requirements during sunshine hours or even during peak solar hours only. A 3-days water storage capacity can help such a battery-less plant in case of prolonged periods with no sunshine.

1.2. Economic aspects related to RO and photovoltaics

Cost effectiveness is essential for any device to be commercialized. In this contest we find that water cost from SWRO plants is affected by many design and economic factors including: feed seawater characteristics such as TDS, turbidity, temperature, heavy metals, product water quality, applied pressure, recovery ratio, whether or not an energy recovery devices is used within the system, stand-by equipment, cost of membranes, cost of equipments, cost of primary energy and type of power supplying system, consideration of interest on capital, labor cost, plant location, cost of land, disposal system, membrane performance etc.

Hafez and El-Manharawy [3] presented a detailed cost analysis of grid connected small RO plants built at tourist resorts in Sinai and Hurgada on the Red Sea coasts in Egypt. Capacities of the studied plants varied between 250 and 4800 m^3/d. Production cost from the different plants showed inverse proportionality with plant capacity where it varied between 2.23 US\$/m^3 for the 250 m^3/d plant and 1.14 US\$/m^3 for the 4800 m^3/d plant.

High production cost has been recognized as the main barrier to successful diffusion of solar energy, in general, and seawater desalination in particular. In addition, the smaller the plant capacity is, the higher will be the product water cost. Another factor that plays an important role in determining the water cost from the solar driven desalination plant is the energy system configuration, i.e. whether the plant is grid connected or if it stands alone and whether it is diesel or battery assisted.

So far, water cost from very small PV-RO units remains to be much higher than the cost per cubic meter of freshwater produced by conventional [large capacity (>5000 m^3/d), grid connected] RO plants and the gap between the two costs has to be narrowed. Recent innovations in the solar panels manufacturing technology developed by HONDA-2005 [4] and the continual research efforts done to increase their energy conversion efficiency, see Table 1 [4], will result in significant reduction in solar panels cost. This

Table 1
Main goals regarding PV technology to be achieved during the period 2000–2005 [5]

Parameters	1995	2000	2005
PV modules efficiency (%)	7–17	8–18	10–20
PV modules cost ($/Wp)	7–15	5–12	2–8
System life (years)	10–20	>20	>25
Overall sales in USA (MW)	175	500	1000–1500

cost reduction will lead directly to reduction in water cost from solar driven small RO units since panels cost represents a major cost item in the plant investment.

It has been reported that using a thin film made from a compound of copper, indium, gallium and selenium (CIGS), Honda's next-generation solar cell achieved a major reduction in energy consumed during the manufacturing process to approximately 50% of the amount required by conventional crystal silicon solar cells. Thus, this new solar cell is more environmentally-friendly by reducing the amount of CO_2 even from the production stage. Further, this next-generation solar cell has achieved the highest level of photoelectric transfer efficiency for a thin film solar cell (almost equivalent to the conventional crystal silicon solar cell).

Fiorenza et al. [5] conducted a techno-economic study to explore the feasibility of utilizing solar energy for powering small to medium, grid-supported, desalination plants. In their study special attention has been paid to two main options, namely: PV-RO and ST-MEE (solar thermal multi-effect evaporation). They tried to single out the factors to be investigated to fill the gap between solar and conventional technology production cost and examine other critical aspects of the solar technologies, such as the required land area and amount of the initial investment.

They compared water cost from each one of the two options to that of its conventional counterpart (fully powered by electricity from the local grid).

They pointed out that results obtained, though purely indicative of the potentialities of the diverse technologies investigated, could vary significantly on an individual basis.

The data given in Table 2 are abstracted from Ref. [5] for the option of PV-RO grid-supported desalination plants. Based on these data, the authors predicted a water cost of about 2.8 US\$/m^3 for grid-supported (alternatively, solar-assisted) PV-RO plants of a capacity 500 m^3/d. They found that the cost goes down to a value close to 2 US\$/m^3 when the capacity is increased up to 5000 m^3/d.

Table 2
Values for the technical and economic parameters assumed in the analysis by Fiorenza et al. [5] for grid-connected PV-RO desalination plants with capacities 500–5000 m^3/d

Values for the technical parameters	
Utilization ratio	0.9
Annual solar energy (kW h/m^2)	2000
Peak radiation (W/m^2)	1000
PV modules efficiency	0.1
Electric energy need in RO (kW h/ m^3)	5
Values of the economic parameters adopted to calculate the water cost	
System life (years)	25
Interest rate (%)	8
Maintenance (% of plant cost)	2
Manpower (\$/m^3)	0.10
Pre-treatment (\$/m^3)	0.035
PV modules cost for a 10 MW size (\$/Wp)	3
PV modules cost for a 100 kW size (\$/Wp)	6
Battery supply (h)	12
Battery cost (% of modules cost)	15
Annual rate of batteries replacement (%)	12
Electronic device cost (% of PV plant cost)	5
RO plant cost for a 10,000 m^3/d size (\$/(m^3/d))	1000
Scale factor	0.9
Membranes cost (% of RO plant cost)	60
Annual rate of membranes replacement (%)	10

They found also that a PV-RO system of capacity 5000 m^3/d needs an initial investment of more than 22 million \$ compared to about 6 million \$ for an ordinary RO system.

In their study, they did not account for carbon emission taxes and assumed that charging this tax to conventional RO desalination facilities and giving 50% incentives to solar driven RO plants (such as tax reduction to encourage using solar panels) will cut water cost from PV-RO plants to about 1.5 US\$/m^3, a value which is close enough to the water cost obtained from conventional RO plants (around 1 US\$/m^3).

Al Suleimani and Nair [6] 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 Heelat ar Rakah camp, a remote location about 900 km south of Muscat, the capital of Oman. The authors claim that the demonstration PV-RO unit proved its adequacy for remote locations that have limited or no access to fresh water, power and fuel services.

In another study, Thomson and Infield [7] presented a cost effective battery-less photovoltaic powered RO desalination system with a water cost of two sterling pounds (3.64 US$) 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 (MPPT) 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. Full cost analysis of the demonstration unit is given by Dulas Ltd and Machyn-lleth, UK [8]. In this cost analysis, estimations were based on a 20-year lifetime of the system as a whole, with pump replacement at 5, 10 and 15 years. 8% discount rate was assumed and all membranes to be replaced every 12 months.

Another successful example is the Lampedusa autonomous PV-RO seawater desalination plant [9], which was commissioned in 1990. The plant was built and sized for demonstration purposes. It is capable of supplying 120 m^3/d of desalinated water for 8 h of operation at full load over three consecutive but not necessarily sunny days. The plant, powered by a system of 100 kW PV arrays, batteries and inverters, consists of an RO unit subdivided into two sections with respective product water capacities of 3 and 2 m^3/h. Spiral wound permeators are used in both sections. The power supply system is a 100 kW h PV array. Batteries with storage capacity of 2 × 2000 ampere-hours (Ah) at 220 volts (V) DC are used. The inverters, one for each section, are sized to allow the 22 kW motors to start easily.

2. Objectives of this study

In this work we present an economic feasibility study of a 20 m^3/d RO desalination plant with three alternative powering systems. The plant is designed for remote areas in Abu-Dhabi Emirate-UAE which falls in an area of very high insolation. The Emirate lies in the so called the solar belt with an annual average solar radiation of 6 kW h/m^2-day.

The three plant configurations include

(1) A diesel-assisted PV-RO plant with a diesel generator used to drive the RO plant by night or during blackout hours.
(2) An RO plant fully driven by a diesel generator (no photovoltaics used).
(3) An RO plant powered only by solar panels. Plant equipments are sized so that the water demand for the 24 h, 20 m^3, is produced during sunshine hours only, about 10.9 h.

Sensitivity of water cost from the three plants to variations in primary energy cost and cost of solar panels is presented where the cost of primary energy is varied between zero and 40$/GJ and cost of panels is varied between 1 and 20 US$/We. CO_2 emission tax, assumed as 31.75 US$/ton of CO_2 has been considered in water cost calculations.

2.1. RO plant design

A simplified flowsheet for the RO plant is shown in Fig. 1. The plant is a two-stage one where seawater is pumped to the pretreatment section by means of the intake pump. Pretreated seawater flows to the high pressure pump where its pressure is increased to a value between 55 and 60 bars before it is introduced to the permeators of the first stage. The relatively high pressure reject from stage 1 is directed to the energy

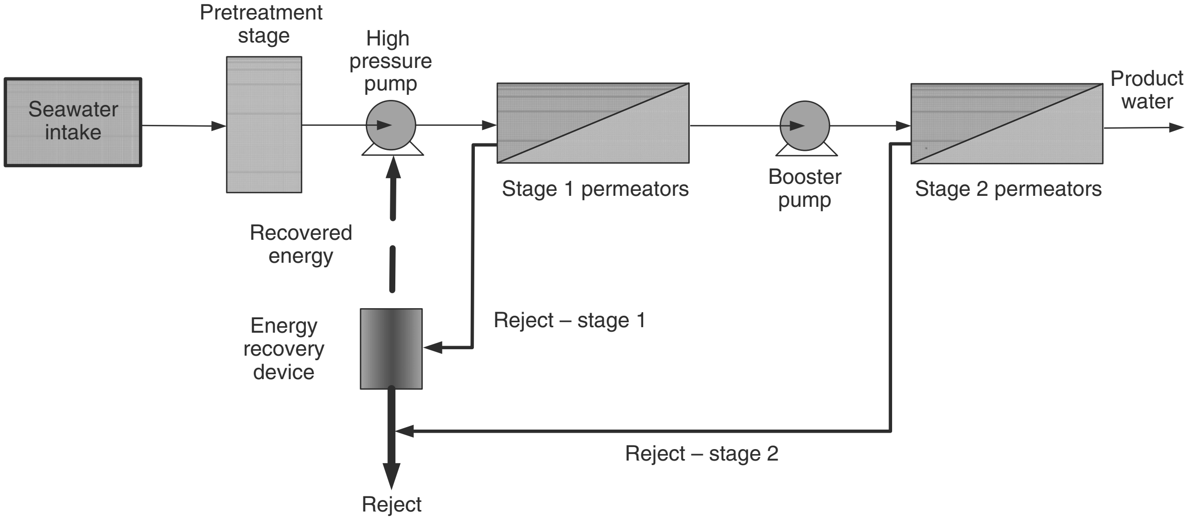

Fig. 1. Simplified RO desalination plant flowsheet.

recovery device and then discharged to the outfall. The permeate leaving stage 1 at atmospheric pressure is then pressurized, by a booster pump, to a pressure between 15 and 40 bars to be desalinated further in stage 2. Permeate leaving the second stage will have a level of TDS below 500 ppm and the reject is discharged into the outfall.

Filmtec FT30 SW 2.5 inch seawater membranes are used in stage 1 while brackish water Filmtec BW 2.5 inch membranes are used in stage 2. Two spiral wound membranes per pressure vessel have been selected for this study. Details of the pre and post-treatment stages will not be given here.

It is assumed that each one of the three plants will be equipped with three 20 m^3 storage tanks, a storage capacity which is believed to be enough for backing up the system and allow for unreliable weather conditions, unplanned system downtime and variability in consumption.

For the design purpose of the RO plant, the simplified model developed by S. Avlonitis et al. [10] has been used. In spite of the simplicity of the model's equations, geometric details of the spiral wound membrane have been taken into account. Such details include; number of leaves (in this work, one leaf membranes are used), membrane length and width and heights of brine and permeate channels. Other factors have been accounted for such as pressure drop in permeate and brine channel, concentration polarization and concentration gradient along the module.

However, in their derivation, the authors assumed ideal conditions for the feed solution and the membrane performance. All the effects of fouling, scaling, chemical deterioration of membranes have been ignored. To counterbalance the last assumption, a fouling factor of 0.7 has been used here to augment the permeate flux equation.

The simple formulation of the model's equations enabled a straightforward solution procedure. However, the solution is iterative and requires a number of process variables to be given initial guess values as shown in Table 3D.

2.2. Solar array design model [11]

- The DC operating bus bar voltage, V_{DC}, is calculated by the following equation:

$$V_{\mathrm{DC}} = V_{\mathrm{m}} \cdot N_{\mathrm{s}} \tag{1}$$

where V_m = operating voltage of one module, should be taken as 12 V for a module of 36 cells. N_s = the number of modules in series

- Load current, I_L, can be calculated from the following equation:

$$I_L = DC_{power} / V_{DC} \qquad (2)$$

where $DC_{power} = P_{AC}/\eta_{inverter}$ and P_{AC} = output AC power from inverter and $\eta_{inverter}$ is the inverter efficiency to convert DC power to AC power.

- The number of parallel lines is calculated from the equation:

$$N_P = I_{PV}/I_{SC} \qquad (3)$$

where N_P should be an integer number and I_{SC} is the short circuit current supplied by an individual PV module when illuminated under standard conditions and I_{PV} represents the nominal current that can be obtained from the equation:

$$I_{PV} \cdot PSH = I_L \cdot H_{DL} \qquad (4)$$

where PSH = peak solar hours = number of hours of standard irradiance (1 kW/m^2) which would produce the same irradiation. PSH is numerically equal to the irradiation in kW h/m^2 day [12].

H_{DL} = number of daylight hours.

2.3. Carbon dioxide emission calculations

Calculation of CO_2 emissions is based on the following:

(1) Net calorific value of diesel oil: CV = 44 MJ/kg.
(2) Mass fraction of carbon in diesel fuel: $f_{carbon} = 0.84$.
(3) Life span of plant equipment: CRP = 20 years
(4) Load factor: $f_c = 0.9$

- Energy rating in MJ/d from diesel generator to the plant, E_{AC}:

$$E_{AC} = 3.6 P_{AC} \cdot H_{DL} \qquad \text{MJ/d} \qquad (5)$$

where P_{AC} = AC output power from diesel generator kW, H_{DL} = number of day-light hours, h

- Heat energy produced from burnt fuel, HF:

$$HF = E_{AC}/\eta_{Diesel} \qquad \text{MJ/d} \qquad (6)$$

- Fuel consumption rate, $\dot{m}_{fuel}$:

$$\dot{m}_{fuel} = HF / CV \qquad \text{kg/d} \qquad (7)$$

- Rate of carbon burning:

$$\dot{m}_{carbon} = \dot{m}_{fuel} \cdot f_{carbon} \qquad \text{kg/d} \qquad (8)$$

- Rate of CO_2 emission, $\dot{m}_{CO_2}$:

$$\dot{m}_{CO_2} = \dot{m}_{carbon} \,.\, (44/12) \qquad \text{kg/d} \qquad (9)$$

- Total CO_2 emissions saving over the life span of the plant, ε_{CO_2}:

$$\varepsilon_{CO_2} = \dot{m}_{CO_2} \,.\, f_c \cdot 365 \cdot CRP/1000 \text{ Metric ton} \qquad (10)$$

$$O_2 \text{ consumption} = \varepsilon_{CO_2}\ 32/44 \quad \text{Metric ton} \qquad (11)$$

2.4. Cost model

The basic equations of the cost model used in this work are taken from Marcoveccio et al. [12]. Definitions and units of the different cost items included in this model are given in the symbol list at the end of this paper. The model's equations are expressed as follows:

$$cc_{swip} \geq 996 \left(Q_f\right)^{0.8} \qquad (12)$$

$$\mathrm{cc}_{\mathrm{hpp}} = \frac{Q_{\mathrm{f}}}{24 \cdot 450}\,(393{,}000 + 10{,}710 \cdot P_{\mathrm{f1}} 1.01325) \tag{13}$$

$$\mathrm{cc}_{\mathrm{ers}} = \frac{\left(Q_{\mathrm{f}} - Q_{\mathrm{prod}}\right)}{24 \cdot 450}\,(393{,}000 + 10{,}710 \cdot P_{\mathrm{b1}} 1.01325) \tag{14}$$

$$\mathrm{cc}_{\mathrm{eq}} = (\mathrm{cc}_{\mathrm{hpp}} + \mathrm{cc}_{\mathrm{ees}} + \mathrm{cc}_{\mathrm{prm}} + \mathrm{cc}_{\mathrm{st}}) \tag{15}$$

$$\mathrm{cc}_{\mathrm{install}} = 0.2 \cdot \mathrm{cc}_{\mathrm{eq}} \tag{16}$$

where
$\mathrm{cc}_{\mathrm{st}}$ = storage tanks cost

$$\mathrm{cc}_{\mathrm{prm}} = N_{\mathrm{ml}} \cdot c_{\mathrm{ml}} + N_{\mathrm{m2}} \cdot c_{\mathrm{m2}} \tag{17}$$

$$\mathrm{DCC} = \begin{pmatrix} \mathrm{cc}_{\mathrm{swip}} + \mathrm{cc}_{\mathrm{hpp}} + \mathrm{cc}_{\mathrm{ers}} \\ + \mathrm{cc}_{\mathrm{prm}} + \mathrm{cc}_{\mathrm{l}} + \mathrm{cc}_{\mathrm{st}} + \mathrm{cc}_{\mathrm{sd}} \end{pmatrix} \tag{18}$$

where cc_{l} = land cost, and $\mathrm{cc}_{\mathrm{sd}}$ = site development cost = 0.25 · DCC

Installed capital cost, ICC, and the total capital cost TCC are then given by Eqs. (19) and (20) as follows:

$$\mathrm{ICC} = \mathrm{DCC} + \mathrm{cc}_{\mathrm{install}} \tag{19}$$

$$\mathrm{TCC} = \mathrm{ICC} + \mathrm{cc}_{\mathrm{i}} \tag{20}$$

where cc_{i} is the indirect capital cost (contingencies) given by

$$\mathrm{cc}_{\mathrm{i}} = 0.1 \cdot \mathrm{DCC} \tag{21}$$

$$\mathrm{co}_{\mathrm{rp}} = 0.2 \cdot \mathrm{cc}_{\mathrm{prm}} \tag{22}$$

$$\mathrm{co}_{\mathrm{s}} = Q_{\mathrm{prod}} \cdot 365 \cdot f_{\mathrm{c}} \cdot 0.033 \tag{23}$$

$$\mathrm{co}_{\mathrm{ch}} = Q_{\mathrm{f}} \cdot 365 \cdot f_{\mathrm{c}} \cdot 0.018 \tag{24}$$

For large capacity RO plants, a value of about 0.03\$/m^3 is normally assumed for labor cost estimation. This value will not be realistic for the case of small RO plants operated at remote areas. An annual labor cost of \$18,000 has been assumed in this work which we consider is the minimum to be considered for such a case.

$$\mathrm{co}_{\mathrm{labor}} = 18{,}000 \tag{25}$$

$$\mathrm{AOC} = \mathrm{co}_{\mathrm{rp}} + \mathrm{co}_{\mathrm{s}} + \mathrm{co}_{\mathrm{ch}} + \mathrm{co}_{\mathrm{labor}} + \mathrm{co}_{\mathrm{e}} \tag{26}$$

where co_{e} is the annual energy operational cost including cost of primary energy, diesel generators and solar panels, depending on the powering system of the RO plant.

$$\mathrm{AP} = \mathrm{TCC}/\mathrm{CRP}$$

Here, we have taken the capital recovery period, CRP = physical equipment lifetime = 20 years.

Now, if i represent the interest rate on capital, then the future value of capital, FV, is given by the equation:

$$\mathrm{FV} = \mathrm{AP} \cdot \sum_{n=1}^{\mathrm{CRP}} (1 + i)^{n} \tag{27}$$

$$\cos t = \frac{\mathrm{AOC} + (\mathrm{FV}/\mathrm{CRP})}{Q_{\mathrm{prod}} \cdot 365 \cdot f_{\mathrm{c}}} \tag{28}$$

3. Results and discussions

Discussions in this section are based on the input data set given in Tables 3A–3D. The different plant configurations will be referred to as

- Scenario-1: for the diesel assisted PV-RO plant having a daily capacity of 20 m^3/d.
- Scenario-2: for the fully diesel-driven RO plant having a daily capacity of 20 m^3/d.
- Scenario-3: for the fully solar-driven PV-RO plant having a daily capacity of 44 m^3/d. where the required 20 m^3 for consumption over 24 h will be produced during the sunshine hours (10.92 h).

Table 3A
Input data: general, geometric and physical data

Plant capacity	20	m^3/d
RO plant configuration	2 stage	
No. permeators per pressure vessel in each stage	2	
Feed concentration	45,000	ppm
Fouling correction factor	0.7	
Atmospheric pressure	100,000	Pa
Modular length (without glue)	0.867	m
Modular width (without glue)	1.17	m
Membrane surface area	2.02878	m^2
Channel height — permeate	0.00043	m
Channel height — brine	0.00077	m
Dissociation factor	0.9	
Number of ions resulting on dissociation	2	
Universal gas constant	0.00008206	m^3 atm/g mol K
Molar density of water	55.6	$kmol/m^3$
Feed temperature	25	°C
Salt molecular weight	58.5	kg/kg mol
Friction parameter (permeate)	1.10E+09	m^{-2}
Solution viscosity	0.00089	kg/m s
Solution density	1100	kg/m^3
Diffusivity	1.6E-09	m^2/s
Mass transport characteristics of membranes		
Stage 1		
Water permeability coefficient	3.31E–12	$m\ S^{-1}\ Pa^{-1}$
Salt permeability coefficient	3.34E–07	m/s
Mass transfer coefficient	3.76E–05	m/s
Stage 2		
Water permeability coefficient	4.70E–12	$m\ S^{-1}\ Pa^{-1}$
Salt permeability coefficient	2.52E–07	m/s
Mass transfer coefficient	3.76E–05	m/s

Tables 4A–C present details of the output data for the three plant configurations. Referring to Table 4C it is seen that the three scenarios give water cost values greater than 7$/m^3. The three values are close to each other with the fully diesel-powered plant being the highest, 7.64$/m^3. Water cost from the fully solar-powered one comes second with a value of 7.34$/m^3. These costs are much higher than the water cost obtained from large scale conventional SWRO plants, around 1$/m^3.

Similarly, the specific energy requirements are more or less the same ranging between 7.33 for the fully solar driven design and 7.74 for the other two designs. In all cases the specific power consumption lies within the range of values known for RO technology, i.e., 3.0 to 9.4 kW h/m^3.

The solar-driven plant is characterized by the highest specific capital cost, 18,278$/m^3/d, compared to the other two scenarios which have a specific capital cost of 14,875$/m^3/d. This is because of the higher rates of flow within the solar-driven plant, the larger number of membranes and larger equipment sizes.

Table 3B
Input data: solar powering system and diesel generators

	Diesel assisted	Fully diesel driven	Fully solar driven	
Solar power system				
Number of peak solar hour in plant location, PSH	16.40	_	16.40	h
Daylight hours, H_{DL}	10.92	_	10.92	h
Inverter efficiency	0.75	_	0.75	
Nominal voltage at standard conditions, V_m	12	_	12	V
Nominal current (short circuit current), I_{SC}	5.20	_	5.20	A
Area of module (a_p)	0.56	_	0.56	m^2
Efficiency deterioration	0.20	_	0.20	
Nominal DC voltage V_{DC}	360	–	360	V
Solar panels model	TOTAL ENERGIE-TE850A2	–	TOTAL ENERGIE-TE850A2	
Installed cost of solar panels including auxiliaries	7.65	–	7.65	$/W
Diesel generator and diesel fuel				
Model: 10 kW (12.5 kVA)	Model: Kohler-10ROZ	Model: Kohler-10ROZ	–	
Load factor	0.90	0.90	0.90	
kW	10	10	_	
Prime power	9	9	_	kW
No of generators	2	4	_	One stand by
Overall generator efficiency (heat to electricity)	0.22	0.22	_	
Cost of generators	18,480 (2 generators)	36,292 (4 generators)	0.00	$
Rating	0.75	0.75	–	of the prime power
Fuel	Diesel	Diesel	–	
Fuel density (0.9 kg/L)	3.41	3.41	–	kg/US gal
Calorific value of diesel fuel	0.04	0.04	–	GJ/kg
Mass fraction carbon in fuel	0.84	0.84	0.84	
Cost of primary energy (1.98$/US gal)	14.70	14.70	–	$/GJ

To study the sensitivity of water cost of the three designs to changes in primary energy cost and cost of panels the fuel cost was varied over a range of 0–40$/GJ and the panels cost was varied between 1 and 20$/W.

Fig. 2 shows the water cost from each plant as a function of primary energy cost. It is seen that the solar-driven plant scenario will be the most feasible option with a water cost of about 7.2$/m^3 at any cost of primary energy greater than 14$/GJ. Meanwhile, panels cost has to go down to a value below 8$/W for this scenario to be the most favorable as could be seen in Fig. 3. However the water cost will stay high at a value about 7$/m^3.

Table 3C
Input data pumps: energy recovery, membrane and economic cost data

	Diesel assisted	Fully diesel driven	Fully solar driven	
Pumps and energy recovery				
Pump motor efficiency	0.8	0.8	0.8	
Mechanical efficiency of pumps	0.8	0.8	0.8	
Intake pump — assumed exit pressure	4	4	4	bar
Product pump — assumed exit pressure	4	4	4	bar
Energy recovery efficiency	0.85	0.85	0.85	
Membrane elements				
Membrane type — Stage 1 [for the three plants]	Filmtec FT30 SW2.5 inch			
Membrane type —Stage 2 [for the three plants]	Filmtec BW 2.5"			
Stage 1: Membrane element cost	194	194	194	$
Stage 2: Membrane element cost	172	172	172	$
Economic data				
Cost of land	50	50	50	$\$/m^2$
Site development	25% of DCC	25% of DCC	25% of DCC	
Indirect CC contingency	10% of DCC	10% of DCC	10% of DCC	
Capital recovery period	20	20	20	years
Interest rate	5%	5%	5%	
Installation cost	20% of equip. cost	20% of equip. cost	20% of equip. cost	
Area of land for plants of capacities up to 200 m^3/day	500	500	500	m^2
CO_2 tax	31.75	31.75	31.75	$/ton

Table 3D
Input data: initial guesses and process constraints

Initial guesses
Feed pressure to stage 1
Feed pressure to stage 2
Overall plant recovery
Brine concentration leaving each membrane in each stage
Permeate concentration off each membrane in each stage
Brine velocity in brine channels
Number of pressure vessels in stage 2

Process constraints
55 < feed pressure to stage 1 < 60 bar
15 < feed pressure to stage 2 < 40 bar
Brine velocity in brine channels > 0.1 m/s
Recovery at stage 1 < 30%
Recovery at stage 2 < 85%
Convergence criteria: for unused models equations

Intersections of the lines drawn on Fig. 2 define the range of primary energy cost over which each design becomes the most favorable. Based on this, we find that the diesel-assisted plant design becomes most favorable for a primary energy cost between 7.8 and 14$/GJ while the fully diesel-driven RO plant design becomes the most favorable only at a primary energy cost below 7.8$/GJ where the water cost reaches a value of about 6.6$/m^3 at that limit.

Similarly, from Fig. 3, we find that increasing the panels cost beyond a value of 8$/W makes the diesel-assisted PV-RO design most favorable until panels cost reaches a value of 13$/W when the fully diesel-driven takes the lead.

It is important to notice that in all cases, water cost will not go below 6$/m^3.

Table 4A
Output data: RO plant, pumping power and solar arrays

	Diesel assisted	Fully diesel driven	Fully solar driven	
Plant capacity	20	20	44	m^3/day
Plant recovery	0.26	0.25	0.26	
Stage 1 recovery	0.30	0.30	0.30	
Stage 2 recovery	0.85	0.85	0.85	
Number of pressure vessel in stage 1 NPV1	6	6	13	
Number of pressure vessel in stage 2 NPV2	4	4	12	
Total membrane area	36.03	35.97	97.69	m^2
Average flux stage 1	1.03	1.03	1.01	m^3/m^2 day
Average flux stage 2	0.74	0.75	0.47	m^3/m^2 day
Final product concentration	93.59	93.34	140.46	ppm
Pumping power requirements				
High pressure pump — exit pressure	56.35	56.42	55.36	bar
Booster pump (permeate to stage 2) — exit pressure	23.32	23.38	15	bar
Total AC power requirements (before energy recovery)	9.70	9.71	20.25	kW
Energy recovery	3.25	3.26	6.79	kW
Net pumping power requirements (after energy recovery)	6.45	6.45	13.45	kW
Solar arrays				
Actual DC power DC_{power}	8.59	_	17.9	kW
Number of series module N_s	30	_	30	
Actual load current per line I_L	23.87	_	49.82	A
Nominal load current I_{PV}	15.89	_	33.17	A
Actual number of parallel lines N_P	4	_	7	
Actual number of panels for the RO plant powering	120	_	240	
Maximum DC power available from solar array	11.25	_	22.49	kW
Total cost of solar arrays including auxiliaries	86059.47	_	172119	$
Ground area req. for the solar array	68	_	136	m^2

For small capacity RO plants operated at remote areas, such as the ones described here, water cost will be strongly dependent on labor cost. In this work we have assumed an annual labor cost of 18,000$. This item alone will charge water cost by 2.74$/$m^3$ for a plant capacity of 20 m^3/d. The labor cost normally assumed for water cost estimation from conventional RO plants, 0.03$/$m^3$, will not be realistic for very small capacity plant calculations.

As expected, we can see from the figures related to CO_2 emissions, Table 4B, that the fully diesel-driven option is the most environmentally hazardous with a yearly mass of 57.2 metric ton of CO_2 discharged into the air. However, fuel consumption rate and consequently the amount of CO_2 emitted are direct functions of the generator efficiency for converting heat to electricity. Emission tax charges the cubic meter of product water from this scenario with 0.28$ based on an emission tax of 31.75$/ton of gas as given in Table 3C.

Encouraging the use of solar panels by reducing taxes, interest on capital and cost of land for

Table 4B
Output data: capital cost and CO_2 emission

	Diesel assisted	Fully diesel driven	Fully solar driven	
Capital cost				
Number of 20 m^3 tanks (4500 imp.gal)	3	3	3	
Seawater intake and pre-treatment cost, cc_{swip}	32647.59	32647.59	61346.42	$
High pressure pump cost, cc_{hpp}	7236.66	7242.51	15751.76	$
Energy recovery device cost, cc_{ers}	5391.31	5395.67	11731.71	$
Membrane cost, cc_{pern}	3704	3704	9172	$
Water storage tank, cost, cc_{st}	36,000	36,000	36,000	$
Cost of land, cc_l	25,000	25,000	25,000	$
Capital less site development cost, CMSD	109979.57	109989.77	134001.90	$
Site development, cc_{sd}	36293.26	36296.62	44220.63	$
Direct capital cost, DCC	146272.83	146286.40	178222.52	$
Indirect capital cost: contingencies, cc_i	14627.28	14628.64	17822.25	$
Installation cost, $cc_{install}$	10466.39	10468.44	14531.09	$
Installed capital cost, ICC	171366.50	171383.47	210575.87	$
annual payment(without interest on capital)	8568.33	8569.17	10528.79	$/y
Annual capital cost (annual to be paid back to the bank)	14874.29	14875.76	18277.59	$/y
CO_2 emission cost				
Thermal power required	29.30	29.31	_	kW thermal
Thermal power required	0.11	0.11	_	GJ/h
kg of fuel required	2.35	2.36	_	kg/h
Fuel consumption rate	0.69	0.69	_	US gal/h
Fuel consumption per year	3437.42	5451.19	_	US gal/y
Diesel fuel density	0.90	0.90	_	kg/L
Mass of fuel burnt	11709.58	18569.48	_	kg/y
Mass of carbon burnt/y	9836.05	15598.36	_	kg/y
Mass of CO_2 produced/y	36.07	57.19	_	metric ton/y

solar driven industrial facilities such as the RO plant under study, helps to sustain the environment and reduces water cost. From the data given in Table 5 and based on the water cost corresponding to an interest rate of 8%, an incentive of 4% reduction in interest on capital will result in a reduction in water cost between 14% and 17% depending on the design configuration.

Total exemption from interest, especially for very small plants as the RO plants considered here, will result in a water cost reduction between 22% and 27%, depending on the initial capital cost.

4. Conclusion

(1) A techno economic study has been conducted to study the economic feasibility of three alternative designs for a 20 m^3/day RO plants for remote areas in Abu Dhabi, UAE. Design options included a diesel-assisted PV-RO plant, a fully diesel driven RO plant and a fully solar-driven PV-RO plant.

(2) Optimal design selection depends primarily on the cost of primary energy and cost of solar panels where the solar-driven plant

Table 4C
Operating and specific costs

	Diesel assisted	Fully diesel driven	Fully solar driven	
Operating cost				
Annual emission cost	1145.09	1815.93	0.00	\$/y
Annual cost of panels	4302.97	0.00	8605.95	\$/y
Membrane replacement cost, co_{rp}	740.80	740.80	1834.40	\$/y
Annual energy (fuel) operating cost, co_e	6676.02	12257.34	0.00	\$/y
Annual spares operational cost, co_s	216.81	216.81	476.98	\$/y
Annual chemicals cost, co_{ch}	463.76	463.76	1020.28	\$/y
Annual labor cost (one technician \$1500/month)	18,000	18,000	18,000	\$/y
Total operating cost	32469.46	35309.25	29,938	\$/y
Specific costs				
Water cost	7.21	7.64	7.34	\$/m^3
Specific power consumption	7.73	7.74	7.33	kW h/m^3
Specific Energy cost [including fuel + generators + panels cost]	1.81	2.14	1.31	\$/m^3
Specific capital cost	14874.29	14875.76	18277.59	\$/m^3/d

configuration becomes most favorable at panels cost below 8\$/W and a primary cost of energy greater than 14\$/GJ.

(3) For such small capacity RO plants in remote areas, the labor cost becomes a significant cost item when estimating water cost. This contributes to a very high water cost relative to that obtained from conventional plants, around 1\$/m^3.

(4) For the input data used in this study, results showed that the fully solar-driven alternative is very competitive, having a specific water cost of 7.34\$/m^3. Nevertheless, this cost can be reduced through incentives to encourage the use of solar panels such as reduction in interest on capital, exemption from taxes and reduction of land cost.

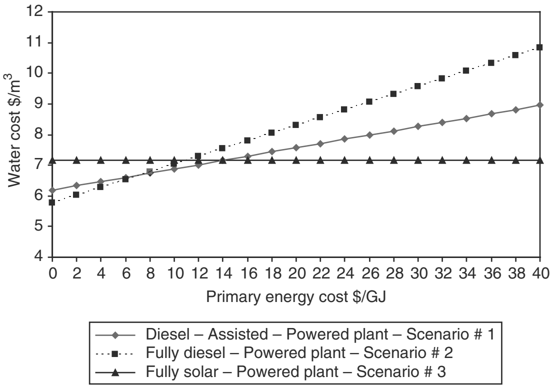

Fig. 2. Water cost as a function of primary energy cost.

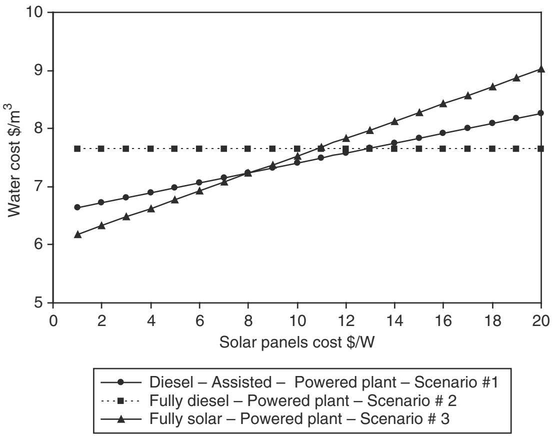

Fig. 3. Water cost as a function of solar panels cost.

Table 5
Effect of interest on capital on water cost

Plant configuration	Interest rate	Water cost $/m^3	% reduction in water cost
Diesel assisted PV-RO plant	8%	8.14	0.0%
	4%	6.94	15%
	0%	6.22	24%
Fully diesel-driven RO plant	8%	8.60	0.0
	4%	7.39	14%
	0%	6.68	22%
Fully solar-driven PV-RO plant	8%	8.35	0.0
	4%	6.87	17%
	0%	6.00	27%

Symbols

A_m	membrane area, m^2
AOC	annual operating cost, $/y
AP	payment, $/y
c_{mi}	membrane element cost at stage *i*, $
cc_{eq}	total equipment cost, $
cc_{ers}	cost of energy recovery system, $
cc_i	indirect capital cost, $
cc_{hpp}	high pressure pumps capital cost, $
$cc_{install}$	installation cost, $
cc_l	cost of land, $
cc_{prm}	permeator capital cost, $
cc_{sd}	site development cost, $
cc_{st}	cost of water storage tanks, $
cc_{swip}	seawater intake and pre-treatment capital cost, $
co_{ch}	chemical treatment operational cost, $/y
co_e	energy operational cost, $/y
co_{labor}	annual labor cost, $/y
co_{rp}	permeator replacement operational cost, $/y
co_s	spares operational cost, $/y
cost	cost of freshwater, $/m^3
CRP	capital recovery period, y
DCC	direct capital cost, $
f_c	load factor
FV	Future value of capital, $
i	interest rate
ICC	installed capital cost, $
J	average volumetric water flux, m/s
J_2	average solute mass flux, kg/m^2 s
N_{m1}	number of membrane elements in stage 1
N_{m2}	number of membrane elements in stage 2
$P°$	atmospheric pressure = 10^5 Pa
P_{bl}	reject brine pressure from stage 1 permeators
P_{fl}	feed pressure off the high pressure pump
Q_f	volumetric flow rate, m^3/d
Q_{prod}	daily water production, m^3/d
TCC	total capital cost

Subscripts

b	brine
ef	effective
f	feed
m	membrane
p	permeate

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