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Economics of Renewable Energy for Water Desalination in Developing Countries

Enas R Shouman[1]*, Sorour MH[2] and Abulnour AG[3]

[1]Department of Information Systems, National Research Center, Dokki, Giza, Egypt

[2]Chemical Engineering and Pilot Plant Department, National Research Center, Dokki, Giza, Egypt

Abstract

Freshwater shortage in many areas around the world presents a constraint to sustainable development. Desalination of saline water, especially seawater which accounts for more than 97% of the total water quantity on earth, represents a feasible option in many cases. The need for sustainable sources of energy to operate high energy - consumption desalination systems is mandatory. Future, in remote coastal and arid areas, the use of renewable energy for powering desalination plants could be a feasible option in view of several technical, economic and environmental considerations.

In this paper, the issue of integration of desalination technologies and renewable energy from specified sources is addressed. The features of Photovoltaic (PV) system combined with reverse osmosis desalination technology, which represents the most commonly applied integration between renewable energy and desalination technology, are analyzed. Further, a case study for conceptual seawater reverse osmosis (SW-RO) desalination plant with 1000 m3/d capacity is presented, based on PV and conventional generators powered with fossil fuel to be installed in a remote coastal area in Egypt, as a typical developing country.

The estimated water cost for desalination with PV/ SW-RO system is about \$1.21 m^3, while ranging between \$1.18-1.56 for SW-RO powered with conventional generator powered with fossil fuel.

Analysis of the economical, technical and environmental factors depicts the merits of using large scale integrated PV/RO system as an economically feasible water supply with an autonomous power supply.

Keywords: Renewable energy; Powered desalination-photovoltaic (PV); Desalination-reverse osmosis (RO); Economics; Developing countries

Introduction

There is a worldwide trend to intensify the use of desalination to reduce current or future water shortage. Over a billion people worldwide lack access to sufficient water of good quality [1]. Most of these people live in Asia and Africa. The growing population and steady increase in the living standards lead to increasing the specific water consumption per capita. A considerable increase in the world population (over the next decade) will be concentrated mainly in most of the developing countries and particularly in Africa, causing severe water shortages [2]. As a result, 40% of the world population is facing serious water shortage, mostly in remote rural areas and expanding urban areas [3]. According to a market research, a predicted average 3% increase in annual demand for fresh water would require an annual investment of about \$500 billion in water supply [4].

Renewable energies (RES) are expected to have a promising future and an important role in the domain of brackish and seawater desalination in developing countries. Recently, there are intensive endeavors to develop and install large-scale desalination plants, mainly powered by renewable energy sources, for low-density population areas deprived of electrical power grid connections. The cheap fresh water may be produced from brackish or seawater by using solar panels and other renewable energy technologies. The development of these technologies will be important for developing countries that are currently suffering from water shortage and do not have access to economical conventional energy resources to implement desalination systems. In addition, due to the fact that fossil fuel prices are characterized by high variability and a trend upwards, the use of renewable energies allows for saving fossil fuels and hence reducing risks related to energy price escalation along the whole desalination plants life cycle.

In this paper, the issue of technology integration is addressed. Special emphasis is focused upon PV system and SW-RO desalination. Further, a case study is presented for SW-RO desalination powered with PV system or conventional electricity-generator. Technical, economic and environmental merits are elucidated for applying desalination with relatively large scale PV/SW-RO.

Desalination-Renewable Energy (Re) Integration

Generally, integration with renewable energy sources can be achieved by direct use the heat or mechanical energy, or by generating electricity. Numerous efforts have been carried out throughout the world to find suitable coupling between desalination and RES. The suitability of a given renewable energy source for powering a specific desalting system depends on its type and magnitude of obtained energy. Different combinations between renewable energy sources and desalination technologies can be applied [5-8]. Renewable energy/ desalination options may be outlined as follows:

a. Solar energy options, including solar photovoltaic or solar thermal options. PV could be integrated with RO desalination. Solar thermal systems could be coupled with RO and mechanical vapor compression desalination systems.

***Corresponding author:** Enas R Shouman, Department of Information Systems, National Research Center, Dokki, Giza, Egypt, Tel: +20 2 33371211; E-mail: Shouman28@hotmail.com

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b. Wind energy, through direct use of mechanical shaft power or electricity generation could be integrated with RO, mechanical vapor compression and electrodialysis.

c. Geothermal energy, through direct use of thermal energy could be used with multistage flash, multiple effect distillation and thermo vapor compression. Electricity generation could be applied with RO, electrodialysis and mechanical vapor compression.

d. Combined wind, with solar or geothermal energy could be also integrated with thermal and membrane desalination.

The current dominant renewable energy source for desalination is solar photovoltaic (PV), which represent about 43% of the existing capacity, followed by solar thermal and wind energy [9]. The right combination of a renewable energy source with a desalination technology can be the key to match both power and water demand economically, efficiently and in an environmentally friendly way.

In addition renewable energy could represent the best energy supply option for autonomous desalination systems, especially in remote areas.

In conclusion, desalination based on the use of renewable energy sources can provide a sustainable technology to produce fresh water. It is expected to become economically attractive as the costs of renewable technologies continue to decrease and the prices of fossil fuels continue to increase. Applying locally available renewable energy resources for desalination is likely to be feasible, particularly in remote regions deprived of efficient electricity supply. Although, the present deployment of renewable-based desalination is less than 1% of desalination capacity based on conventional fossil fuels [10], it is anticipated that much higher contribution of the desalination/ RES in the near future will be achieved.

Economics of Desalination/Renewable Energy Systems

The cost of desalination is largely dominated by the energy cost. Therefore, the economic feasibility of desalination depends strongly on local availability, cost of energy and other site specific factors. The technologies most commonly used commercially are reverse osmosis (RO), multistage flash (MSF) and multi-effect distillation (MED). The global desalination capacity is reported to be about 62 million m^3/d. The percentages of the global capacity according to technology are 60%, 27%, 9%, and 4% for RO, MSF, MED and electrodialysis, respectively [11]. Low capacity, solar still is reported to produce water at cost ranging from \$2.4 to \$20/ m^3 [12-14]. Recent improvements in solar distillation technology make it the ideal technology for some remote isolated areas with water demand up to 200 m^3/d [15].

The dominant competing technology is reverse osmosis (RO), having investment costs ranging from \$600 to 2000 m^3/d production capacity [16]. The reported production cost range for large scale conventional desalination is \$1 - \$2/m^3 [17].

SW-RO desalination requires only electricity, while thermal desalination (MSF, MED) requires both electricity and thermal energy. RO has lower energy consumption when compared to MSF and MED [13].

Costs breakdown for SW-RO desalination showed that energy represents about 43% of the total water production cost, compared to 59% for large-scale thermal desalination plant [12].

Typical reported capacities applied and costs of desalted fresh water from most common desalination processes based on renewable energy are shown in Table 1 [18]. Most of such technologies demonstrated rapid decrease of renewable energy costs and technical advances.

he future expected electricity costs beyond year 2020 for the most common solar systems have been reported to be \$0.04-0.1/kwh and about 0.04/kwh for solar thermal and Photovoltaic systems, respectively for an annual energy isolation of 2500 kw/ m^3.

The optimistic forecast of electricity cost of photovoltaic system, especially in countries with high irradiance solar energy (isolation), as in the case of Egypt and many other developing countries, will lead to better economics of PV-RO desalination.

Case Study: Seawater Reverse Osmosis (Sw-Ro) Desalination Plant (1000 M³/D) Powered with Photovoltaic (Pv) or Conventional Diesel Electricity Generation System (Dg)

In this section, a conceptual case study for desalination plant based on RO technology, powered with renewable energy PV system is presented. The choice of RO and PV technology is based on dominant application and promising future of such technology. The plant is designed for Egypt, as a typical developing country, with excellent high average annual irradiance solar energy isolation of 2500 kwh/m^2 [19]. The present state of the art in both RO and PV-systems and cost indicators are applied based on international up-dated published data and national experience.

The objective of this case study is to elucidate the technical, economic and environmental merits of applying SW-RO with relatively high capacity powered with PV system, as compared to conventional powering with diesel generator (DG), conventionally used in remote coastal areas for supplying electrical power. Figure 1

Option	Capacity m^3/d	Energy Consumption (kWh/m^3)	Water Cost (\$/m^3)
Solar stills	<0.1	-	1.3-6.5
Solar-Multiple Effect	1-100	Thermal: 100	2.6-6.5
Humidification		Electrical: 1.5	
Solar/CSP*- Multiple Effect	>5,000	Thermal: 60-70	2.3-2.9
Distillation		Electrical: 1.5-2	
Photovoltaic -Reverse Osmosis	<100	Electrical: 4-5	11.7-15.6
Wind-Reverse Osmosis	50-2,000	Electrical 4-5	6.5-9.5(capacity <100 m^3/d) 6.5-9.1 2-5.2 (capacity 1000 m^3/d)
Wind-Mechanical Vapor Compression	<100	Electrical 11-14	5.2-7.8

Note: cost calculated at the exchange rate of 1.3 from euro to \$ *(CSP) refers to concentrating solar power

Table 1: Typical capacities and costs for most common options of solar and wind seawater desalination [18].

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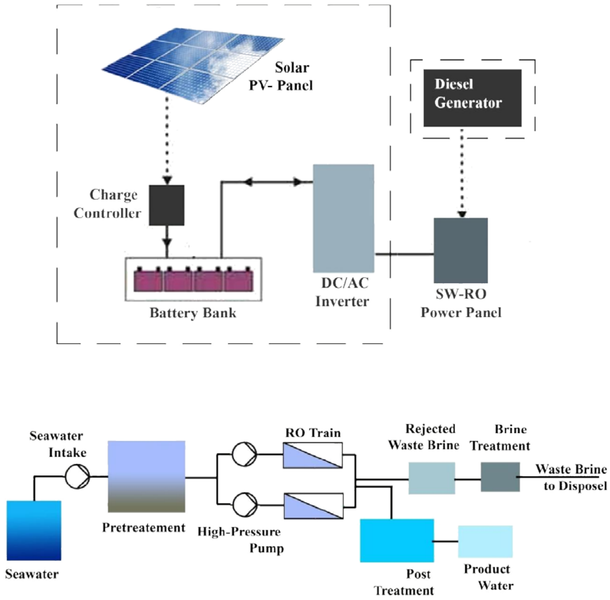

Figure 1: A Schematic for the SW-RO desalination plant with PV and diesel power options.

Item	SW-RO system	DG system	PV- Power system
System components	o Raw seawater intake/ rejected brine outfall o Seawater pretreatment, including chlorination for algae removal, dechlorination to remove excess active chlorine, pH- adjustment, dual media filters and fine filters o RO system comprising 2 trains each 500m³/d including high press pumps with energy recovery system, membrane modules arranged on skid, piping fittings and valves, instrumentation and measurements	o 2 diesel generator, each 300 KVA- capacity o Diesel fuel storage and handling system o Power supply, o Operation and control panel	o PV- panels, for average power/24 hrs of 250 kW o Storage system including batteries, charge controller and accessories. o DC/ AC inverter o Operation and control panel
Basic Process design	o Post treatment including o Operation and control panels o Building and site infrastructure o Seawater salinity: 35000 mg/l o Production water salinity : 300-400mg/l o Modules: spiral wound SW/RO membrane o Operating pressure:65 o Recovery: 40 % o Average daily production hours 20 hr, o Average yearly working days 300d/yr o Average power consumption :5 kWh/m³	o Fuel, Diesel Fuel o Fuel consumption: 0.3 l/ kWh o Power output: AC, 3 phase, 380V, 50H2	Average annual solar irradiation 2500 kWh/m²
Cost estimate basis			
1. Capital cost	average market price of $1500 m³/d capacity	Based on average market prices	Average marketprice of $8000/kW
2. Depreciation	Plant life time of 15years	System life time of 10 years	System life time of 20 years
3. Operating cost (O&M)	Membrane replacement $ 0.1/m³	Fuel cost variable according to oil price (range $0.2- 0.5/l)	-
	Maintenance 3% of capital cost	Maintenance 5% of capital cost	Maintenance 3% of capital cost
	Labor $ 0.05/m³	Labor $ 15000/yr	Labor $ 15000/yr
	Chemical $ 0.03/m³	Diesel fuel price $ 0.2-0.5/l	-

Table 2: Technical and economic features of SW-RO desalination plant 1000 m³/d.

represents a schematic for the SW-RO desalination plant with PV and diesel powering options.

Table 2 illustrates the main technical features of the system, including SW- RO and power generation systems (PV or DG), as well as basis of cost estimates

Table 3 represents the estimated capital, annual operation and maintenance (O&M), depreciation, annual operation cost of the sub-system and the integrated system as well as unit cost of water produced and electricity generated. As indicated from Table 4, the capital cost of the integrated RO- PV system is 1.75 times than of RO-DG. The cost of water for RO- PV system is about $1.247/m³, while for RO-DG, it ranges between $1.212- 1.589/m³ depending on fuel price.

Table 4 depicts a qualitative comparison of the economical, technical and environmental factors of the two applied options.

Capital Investment ($ 1000)	1500	2000	500	3500	2000
Annual O&M ($1000)					
1. Membrane replacement	30	-	-	30	30
2. Maintenance	45	60	25	105	70
3. Labor	15	15	15	30	30
4. Chemicals	9	-	-	9	9
5. Fuel price $0.2 - $0.5/l	-	-	75- 187.5		75-187.5
Total annual (O&M)	89	75	115- 227.5	164	204- 316.5
Annual Depreciation	100	100	50	200	150
Total Annual cost	189	175	165- 277.5	364	354- 466.5
Unit Cost	0.63	0.117	0.11- 0.185	1.213	1.18- 1.555
	$\$/m^3$	$/ kWh	$/kWh	$\$/m^3$	$\$/m^3$

Table 3: Summary of cost estimates for RO-PV & diesel powered desalination plant (1000 m^3/d).

Item	RO + PV	Reason	RO + DG	Reason
1. Capital Investment	High	High PV- system cost	Moderate	DG is much cheaper than PV system
2. O&M	Low	No fuel is used	Moderate	Fuel price is dependent on oil price fluctuations.
3. Improvement Opportunity	High	Improvement of PV system cost reduction. Potential improvement in SW-RO membrane and power consumption	Moderate	Potential improvement in SW-RO membrane and power consumption
1. Operability & Maintainability	High	PV- with little mechanical system.	Moderate	Fuel supply and common trouble with DG mechanical system.
2. Reliability	High	Self standing.	Moderate	Stand by generator is used.
3. Foot-Print	High	PV arrays, require large area	Low	Require small area
4. Improvement opportunity	High	PV-system efficiency improvement and RO-system energy consumption advance	Moderate	Membrane efficiency, RO- system energy consumption advance

Table 4: Qualitative comparison of economic, technical and environmental factors for SW-RO desalination powered with PV & DG options.

Conclusion

Desalination represents a potential alternative technology for the efficient production of water from saline water sources at remote causal and desert areas. The continuous development in improving energy consumption reduction and the improvement in PV-power system efficiency and cost will lead eventually to wide-spread application of the combined RO-PV system as a reliable and sustainable source of fresh water supply in remote areas, deprived from potable water and electricity. The merits of application of the RO-PV system in arid areas in developing countries is much favored by the high irradiation which is double that in many developed countries. According to the presented case study, the cost of producing water for is $\$1.213\ m^3$, compared with variable cost of $\$1.118\text{-}1.555/m^3$ (according to the fuel price variation). The prospective for cost reduction in RO-PV system is promising in view of progressive development of PV and RO systems, and it is expected with scaling up to high capacities, the economics of water production will improve.

Besides, the technical and economical features, the RO-PV system are characterized by being friend to the environment (with no gaseous emission).

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