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Economic Feasibility of Small Scale Solar Powered RO Desalination for Brackish/Saline Groundwater in Arid Regions

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Abstract: Fresh water supply in arid regions becomes an increasingly important issue. Desalination of brackish and saline groundwater could play an important role in water supply for remote areas where there are no access to both seawater and freshwater. The main challenge is saving the required power to operate the desalination plants in areas where there is no power grid. Using sustainable and renewable energy source such as solar for operating a groundwater desalination system include a high recovery ratio and high water output per unit of energy and land could be a solution. A small scale solar powered reverse osmosis (RO) desalination plants weredesigned constructed and operated in Abu Dhabi in 2010 to assess the feasibility of using solar powered desalinationfor the brackish and saline groundwater resources for water supply in remote areas. Using renewable energy such as solar can help to overcome desalinationenergy and environmentalrelated challenges due to the use of fossil fuels.The main objective of this study is to demonstrateand assess the feasibility of using of powering RO system with solar energy usingphotovoltaic cells (PVC)to desalinateeither brackish or saline groundwater pumped from the shallow groundwater aquifer systems located in the western region of Abu Dhabi Emirate, with salinity ranges between 5, 000 to 20, 000 ppm. The design capacity of the system is 5 m^3/hr with photovoltaic solar system of 45 kW hours. To minimize the cost, the system was operated during day time only to avoid using batteries for electricity storage. The produced fresh water stored in ground elevated tank to be used for 24 hrs. Also, a mathematical model was developed to calculate the required brackish groundwater and design of an RO system powered by photovoltaic energy (RO size and the number and configuration of the solar cells panels). The model was used as a tool for the design, optimization and costs.

Key words: Brackish Groundwater · Desalination · Solar power · ReverseOsmosis (RO)

INTRODUCTION

Fresh water supply in arid regions becomes an increasingly important issue. However, rapid industrial growth, worldwide population explosion and irregular distribution of water resources have resulted in a large escalation of demand of fresh water. It has been estimated that by year 2050 the problem of water scarcity will affect more than 66 countries all over the world with two third of the world population. Desalination of brackish groundwater and seawater could help to overcome this challenge. Thus, recent studies indicated that the production of desalination water volumes worldwide could be increased in the next decades. However, the increase in desalinated water supply will create a series of problems mainlyextensive energy use and environmental pollutions caused by the use of fossil fuels. Fortunately, there are nowadays various desalination systems that could be powered by renewable energy sources, but it is necessary to select a process suitable for a particular application or situation.

Groundwater deterioration due to long over abstraction is a widespread problem occurring across all arid continents [1]. Globally, there are a lot of unused brackish and saline groundwater reserves, especially in arid and semiarid regions. In the absence of rains and permanent surface freshwater bodies such as rivers, lakes and canals, brackish and salinegroundwater desalination could be the only solutionto supply remote areas in arid regions with fresh water. Recently, some countries within the Arab region started to test and assessbrackish and saline groundwater desalination systems such Egypt, Jordan, Morocco, UAE and KSA.

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Desalinatingbrackish andsaline groundwater requires less energy than seawater which is typically supplied from fossil fuel sources at present. The need to supply growing demand for freshwater, while reducing the environmental negative impactsdue to use of fossil fuel, makes it important to improve the efficiency of desalination processes and to take greater advantage of renewable energy sources such as solar or wind.At present many solar powered desalination technologies have been studied and several have been already implemented on testing scale [2] including Abu Dhabi Emirate [3, 4, 5] and KSA. These solar powered desalination technologies can be classified to two categories: (i) thermal distillation technology or (ii) membrane reverse osmosis (RO). In thermal distillation technology, single effect solar stills can provide only few liters of freshwater per square meter of captured sunlight per day, while multiple effect solar stills may provide tens of liters of freshwater per square meter [6].

Among available desalination technologies in the market, RO is rapidly growing and overtaking thermal desalination in terms of market shares [7] due to economic, energy and efficiency factors. RO ispressuredriven process that relies on the properties of semipermeable membranes to separate water from a saline feed water and the end result comprises the separate flows of freshwater permeate and concentrated brine. RO flow rate is proportional to the difference between the applied pressure and the osmotic pressure differential between brine and dilute compartments. At present, commercially available RO systems can retain about 98-99.5% of dissolved salts in the saline feed water [8] and typical operation pressures range from10 to 15 bar for brackish water and from 55 to 65 bar for seawater. The volumes of produced freshwater from RO is limited by membrane fouling and scaling. Overall freshwater recovery rates are typically ranges from 45 to 50% for seawater RO systems and increased up to80% in case of using brackish feed groundwater [9]. The coupling of RO desalination with solar energy is a promising to make the desalination sector more sustainable in the future, with the potential to (i) minimize or completely eliminate the dependence on fossil fuels and (ii) significantly reduce the operational and maintenance costs. Despite a growing reduction in the energy consumption of desalination technologies in recent decades, energy consumption is still a major cost component of RO desalination technology, accounting for 40 to 45% of total operation and maintenance costs [10, 11].

Solar Powered RO Desalination Systems: The studies of using solar-powered RO desalination startedin late seventies [12], since that, the feasibility of this technology has been tested and assessed in a relatively large number of pilot experimental units. Most of these studies and researchesweredone in the countries where the freshwater demand is high and growing and intense solar radiation exists. These include Arid Arab countries, the southern part of Europe and Australia, where the average annual solar irradiance on a horizontal surface is higher than the worldwide average. At present, most systems in operation were designed in smallscale desalination plants located in remote areas where freshwater is scarce and connection to local power grid is unavailable. Some countries started fullscale plants such as Saudi Arabia [13], US Virgin Islands [14], Maldives [15], Australia [16], Mexico [17] and Tunisia [18], however worldwide most of thesesolar powered desalination systems are demonstration, pilot or prototype plants. Capacities of these systems range from less than 0.1 m^3/day for prototype units and up to 80 m^3/dayin some fullscaleunites. Recent several design studies investigated the technical and economical feasibilities of medium to largesize solar desalination units, but to the best of our knowledge, to date, no experimentaland feasibility studies of largescale solardriven RO desalination plants has been done.Depending on the type of solar technology used, three principal technological solutions were investigated for solarpowered RO desalination: (i) photovoltaic cells powered reverse osmosis (PV-RO), (ii) solar thermalpowered RO and (iii) hybrid solar desalination. The first two are standalone systems and hybrid system comprises combinations of solar with other one or more additional energy source(s), such as grid electricity, wind, or diesel generators.

The most common design option that has been used frequently in solar powered RO desalination plants is a combination of RO and arrays of photovoltaic cells (PVC) modules. The wide use of photovoltaics because they were the first widely commercialized technology for exploiting solar radiation to produce energy. Indeed, PVC panels still dominate the solar technology market and among all other available renewable energies, they constitute the fastest growing renewable energies market.In PV–RO desalination system, the direct current (DC) electrical energy generated fromPVCis used directly or after regulation to power the high pressure pumps required for the saline feed water to permeate the RO system. Despite the many recent technological improvements, however, the conversion efficiencies of PVC modules is stilllow, rarely exceed 17–18% with an average of 14% [19]. In addition to low efficiencies, the market retail prices for PVC modules are currently stands at 4.83 US$ per Watt peak (Wp) in USAmarkets [20], makesitscost an important key factor in the economic feasibility of PV–RO desalination system. The technical and economical feasibilities of PV–RO desalination systems were studiedwidely as shown in Table 1.PV–RO was implemented to desalinate both brackish groundwater and seawater. The production flow of experimental units still small and rangesfrom less than 0.1 m^3/day to 80 m^3/day.

Abu Dhabi Case Studies: The first Abu Dhabi solar powered desalination pilot project was started in September 1984 to sees using renewable energy in desalination. The plant was designed as a pilot unit toevaluate technical and economic feasibility of such technology to supply freshwater to remote arid areas of the United Arab Emirate using seawater as a feed resource. The main objective of this pilot project was to evaluate and assess the long-term performance and reliability of the system and determine the optimal operating strategy and future maintenance schedule. The unit consists of main three sub-unites:

- Solar collector field
- Heat accumulator
- Seawater evaporator.

The system design capacity was120 m^3/dand utilizes horizontal-tube, thin-film and multi-effect stack (MES) distillation concept [5]. The thermal energy required by the MES evaporator was provided by a bank of evacuated glass tube collectors. The system uses no auxiliary heat with solar energy representing the only source of thermal energy used by the system. The solar collectors have an effective area of about 1862 m^2. To provide he required thermal energy for the distiller, the system equipped with three thermally stratified, vertical thermal storage tanks with a total capacity of 300 m^3. The plant is designed to be stand alone and for continuous operation for 24hrs.

In 2010 Environment Agency – Abu Dhabi (EAD) started a project for using solar powered small scale desalination plants to desalinate brackish/saline groundwater as part from its mandate to explore and assess new environmental friendly technologies to provide remote protected areas with freshwater resources. The groundwater salinity ranges between 10, 000 ppm and 35, 000 ppm. The project considers the utmost reduction of negative environmental impacts by employment of latest technologies, innovative solutions and best management practices to produce freshwater with less cost. The total number of unites is 30 units constructed and distributed geographically allover Abu Dhabi Emirate. The main objective of these plants is to provide EAD managed natural habitat protected areaswith their demands of freshwater to sustain wildlife including labors and animals freshwater demands. Fig. 1 shows one of these solar powered desalination unites. The locations were selected when there is no connection to power grid and freshwater supply networks as shown in Fig. 2.

System Design and Main Component: The system consists of the following main components as shown in Fig. 3:

Solar System (PVC Modules): Both mono-crystalline and multi-crystalline silicon modules were used to supply the 30 unitswith the required energy in Abu Dhabi Emirate. The PVC modulescan be constructedas fixed oradjustable arrays which is an important factor to improve the electrical power output from them and thus improve the overall performance of the desalination plants. The modules are with adjustable axes where can be manually repositioned based on seasonal changes.Recent studies by Alawaji and others[13]indicated that utilizing seasonal tilt angle variation increases the annual average permeate flow of a PV-RO desalination plant in Saudi Arabia from 15 to 17 m^3/day. Other researchers determined that tracking PVC arrays produced about 60% higher permeate flow than a fixed array in smallscale desalinationunites with a capacity of about 0.5 m^3/day. Due to its high initial capital costs of the tracking systems, have limited their use in PV-RO desalination units. Maximum Power Point Tracker (MPPT) circuits or similar optimizers are generally installed to maintain system operation at a voltage that achieves maximum power, while ensuring efficiency under conditions of low irradiance. In Abu Dhabi and due to the harsh desert conditions and to minimize both capital and operational costs, only fixed PVC arrays were used in all locations.

The advantages of using PVCmodules as a source of power can be summarized as follows:

- This feature allowsenlarging the number of modules for future extensions whenever needed.

Table 1: Overview of achievements in PV- RO membrane desalination systems

Location and country	Year	Feed Water TDS (mg/L)(*)	PV capacity (kW_p)	Battery storage	Pump drive	Production (m^3/day)	Cost, (US$/$m^3$)
Abu Dhabi, UAE	2008	45, 000	11.25	no	AC	20.0e	7.3
Athens, GRC	2006	30, 000	0.85	no	DC	0.35e	9.8
Aqaba, JOR	2005	4, 000	16.8	yes	AC	58.0	9.8
Baja California Sur, MEX	2005	4, 000f	25	yes	AC	11.5	9.8
Chbeika Centre, MARd	1998	40, 000	26.3	yes	AC	12.0e	35.9
Concepción del Oro, MEX	1978	3, 000	2.5	yes	DC	0.71	12.8
CREST, GBR	2001	32, 800	1.54	no	AC	1.45	3.0
Doha, QAT	1984	35, 000	11.2	no	AC	5.7e	3.0
El Hamrawein, EGY	1986	4, 400	19.84	yes	AC	53.0	11.6
Fredericksted, VIR	1986	4, 400h	19.84	yes	AC	75.7	11.6
Gillen Bore, AUS	1996	1, 600	4.16	yes	AC	1.2	11.6
Hammam Lif, TUN	2003	2, 800	0.59	no	DC	0.05e	11.6
Hassi-Khebi, DZA	1987	3, 500	2.59	yes	AC	0.85	10.0
HeelatArRakah, OMN	1999	1, 010	3.25	yes	AC	5.0e	6.5
Denver, ITN, USA	2003	1, 600	0.54	no	DC	1.5	6.5
Java, Cituis West, IDN	1981	1, 600h	24.5i	yes	DC	12.0e	6.5
Jeddah, SAU	1981	42, 800	8	yes	DC	3.22	6.5
KsarGhilène, TUN	2005	3, 500	10.5	yes	AC	7.0	6.5
Kulhudhuffushi, MDV	2005	2, 500	0.3	no	DC	1.0e	6.5
Kuwait, KWT	2005	8, 000	0.3	yes	DC	1.0	6.5
Lampedusa, ITA	1990	8, 000f	100	yes	AC	40	10.6
Lipari, ITA	1991	8, 000f	63	yes	AC	13.7	10.6
Lisbon, INETI, PRT	2000	2, 549	0.1	no	DC	0.02	10.6
Massawa, ERI	2002	40, 000	2.4	no	AC	3.9	10.6
Mesquite, ITN, USA	2003	3, 480	0.54	no	DC	1.28	3.6
Murdoch Univ., AUS	2003	3, 480	0.06	no	DC	0.05	3.6
Nicosia, CYP	2005	3, 480	10	yes	AC	50.4e	2.3
NRC, Cairo, EGY	2002	2, 000	1.1	yes	AC	1.0e	3.7
Pine Hill, AUS	2008	5, 300	0.6	no	DC	1.1	3.7
PozoIzquierdo, ESP	2000	35, 500	4.8	yes	AC	1.24	9.6
SERIWA, Perth, AUS	1982	5, 700h	1.2	yes	DC	0.55	9.6
Solarflow, AUS	1982	5, 000	0.12	no	DC	0.4e	9.3
Univ. of Almería, ESP	1988	3, 360	23.5	yes	DC	8.09	2.5
Univ. of Amman, JOR	1988	400	0.07	no	DC	0.1	2.5
Univ. of Bahrain, BHR	1994	35, 000	0.11	yes	DC	0.2	2.8
Various locations, JORd	2007	7, 000	1.1	yes	AC	3.6e	9.0
VARI-RO, USAd	1999	7, 000f	1.1	no	AC	3.6	9.0
Wanoo Roadhouse, AUS	1982	7, 000h	6	no	AC	3.6	9.0
White Cliffs, AUS	2003	3, 500	0.26	no	DC	0.06	9.0

(*) Notes: TDS = Total Dissolved Solids.

Fig. 1: General layout for RO solar powered desalination unit

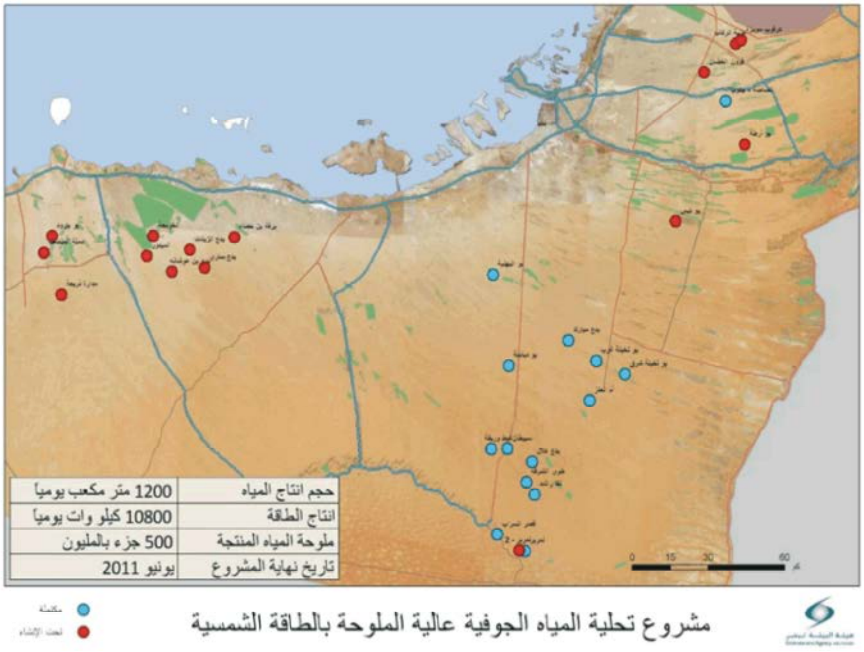

Fig. 2: Location map for the selected sites

- Low maintenance cost, especially if battery-less systems usedwhich reduce operation and maintenance cost.
- As a power generating system, PVC panels have no rotating parts which will lead tolow noise levels. The only noise would be from the pumps. In battery-less systems, it would only run in daytime which not disturb people at night.
- Currently, PVC panels with 25 years life time are guaranteed and withstand in harsh environments.
- Well-matched to load as PVC panels produce more energy in areas of higher solar irradiation where the people are likely to consume more drinking water.
- No CO_2 emissions compared with what normally produced from using fossil fuels in conventional power plants. However, considerable amounts of CO_2 are produced by the current silicon-based technologies applied for the production of PVC. Silicon-based technologies are energy intensive and require large amounts of fossil fuels to be used.
- Possible use of single- or dual-axis trackers which makes the arrays pointed directly to the sun throughout the day, which increases the permeate flowby up to 30%.

Groundwater Well(s) and Feed Pump(s): It is electrical submersible pump with a capacity of 15 m^3/hr and 50 m head that convey the feed water from the groundwater well to the pretreatment system. It is powered by the arrays of the PV modules. The groundwater wells depths ranges from 50 m to more than 100 m and the depth to groundwater ranges between 5 m to 20 m from the ground surface.

Pretreatment Unit: To improve the efficiency of RO unites, pretreatment systemsare generally implemented. This pretreatment system consists of two layers of filters. The main filter typically has a pore size of 5 µm and is preceded by a coarser filter with pore sizes of 20-25 µm or larger. Additional active carbon filterscan be used to removethe free chlorine, which can damage the RO membranes. In case of the feed water bacterial counts are high, disinfection by chlorination or ozonation are used to protect the membranes from biofouling [22]. In some cases ultrafiltration (UF) as a pretreatment systemwere used on limited scale in experimental tests in Australia using brackish groundwater as feed water [23, 24]. However, UF pretreatment system costs are higher than conventional pretreatment systems. However, because it removes significant numbers of microorganisms and generally delivers higher quality RO feed water, which eliminates the need for membrane disinfection. UF pretreatment system may reduce RO membrane cleaning and replacement (operational) costs. Chemical pretreatment system with antiscalantsshould be used to reduce the risk of membrane surface scaling [25].

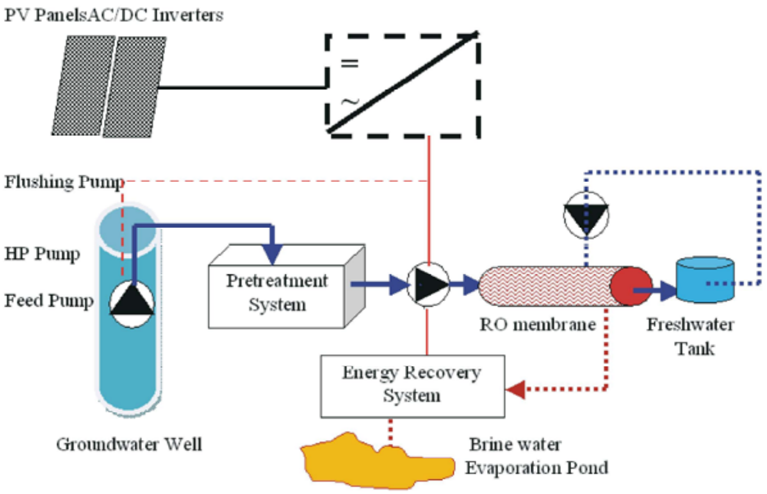

Fig. 3: Solar powered RO desalination system for brackish/saline groundwater

High-Pressure Pump: Positive displacement pumps are used as high pressure pump due to their higher energy efficiencies with respect to centrifugal pumps at low flows. Both rotary positive displacement pumps (e.g., rotary vane [23] and progressive cavity pumps) and reciprocating pumps (e.g., piston [26] and diaphragm pumps) were used. The Clark pump, a reciprocating pump that was specifically developed for energy recovery in small desalination systems and that was used in several PV–RO applications in combination with reciprocating plunger pumps [27] and rotary vane pumpsfor seawater desalination, was shown to significantly reduce energy consumption. For the desalination of brackish water, systems using rotary pumps have the lowest energy consumption. Specific energy consumptions (SEC) as low as 1.4 kWh/m^3 were reported both for rotary vane pumps (influent TDS = 3, 480 mg/L; Dank off Solar Slow pump) and for progressive cavity pumps (influent TDS = 5, 300 mg/L; custom-designed Mono-Pumps). SEC values for systems using reciprocating pumps, however, were only available for outdated units (SEC = 6.9 kWh/m^3; influent TDS = 3, 000 mg/L) and small prototypes (SEC = 29.1 kWh/m^3; influent TDS = 2, 137 mg/L). Pump motors are powered with either direct current (DC) or alternating current (AC). In the latter case, since both PV arrays and batteries produce DC, a current inverter is required [28].

RO Membranes: Many recent studies indicated that spiral-wound thin-film composite membranes have been developed to desalinate either seawater or brackish groundwater by RO [29]. Among the most promising spiral-wound, thin-film composite membranes developed are an expanding family of aromatic polyamides, polyureas, poly(ether/amides) and poly(ether/ureas). Membranes of these types exhibit outstanding transport, mechanical, thermal, biological and chemical properties. So that, spiral-wound thin film composite RO membrane systems are the most suitable choice for PV-PV-RO systems. The most common PV-RO configuration is the single pass, in which the RO membranes are organized in series within single or more pressure vessels in one row. Concentrate recirculation configuration was used in some brackish groundwater PV-RO unitesto increase the overall efficiency, recovery ratio and reduce brine discharge to environment. Single pass PV-RO desalination unitesoften designed with generous membrane areas which can be operated at lower pressures atfixed recovery rate and increase the energy use efficiencies. However, large membranes areas introduce a trade-off with permeate quality which decreases when operating pressure increases. Some recent studies indicated that Nano-filtration membranes can be used as a cost-effective alternative to PV-RO in brackish groundwater due to their lower operating pressures and energy requirements. However, using nano-filtration will not remove all sales from feed water and the TDS will mostly remain as it is.Also, so far no studies monitored the continuous operation of solar powered nano-filtration desalination system and analyze the difference in cost between it and RO. In Abu Dhabi project single pass spiral-wound thin film composite RO membranes were used.

The advantages of using spiral-wound, thin film composite RO membranes can be summarized as follows:

- The energy use requirement is significantly low ranges between 3kWh/m^3 for brackish groundwater to about9kWh/m^{3}for seawater [30].

- The process is electrically driven so, it is readily adaptable to powering by PVC.
- The RO plant is normally operated at ambient temperature, which reduces the challenges of scale formation as well as corrosion problems, especially when a pretreatment system is properly designed, installed and operated and maintained in proper way which will reduce O&M cost.
- The modular structure of the RO processeseither single passor multi-pass increases the flexibility in building desalination plants with wide range of capacities.

One of the most limiting factors for PV-RO which negatively affects their widespread use and capital cost is the large land area normally required for PVC panels, especially when the energy demandis high. Also, an important consideration in using PVC panels in hot environments such as Abu Dhabi is the performance deterioration of crystalline silicon solar cells with increasing temperature where PVC panels performance drops by about 0.4% per 1°C. This factor should be taken into considerationduring the design and sizing the PVC array to power the connected system throughout its lifetime [31].

In addition to the main components of PV–RO desalination system, another additional series of elements should be alsousedto improve these systems. These include the followings:

AC/DC Inverter: In most of the RO desalination plants an AC induction motors are used as a high pressure pumps which require inverters to transform the DC current generated in the PVC modules or stored in AC batteries. The use of DC motors however they eliminate the need for inverters but generally their retail cost is higher which increase the initial capital investments. In general DC motors do not experience energetic losses inherent in inverters, so PV–RO desalination with DC motors mostly functionedwith higher energy efficiencies [32]. However, a studyof 6 m^3/day brackish groundwater PV–RO desalination system, experienced steadier operation and significantly lower energy use (3.1 kWh/m^3vs.4.7 kWh/m^3) after replacing DC motor with an AC induction motor. Systems with DC motors are also more reliable compared to systems with inverters, as failures are frequently related to the inverter overheating during plant operation or overloading when the motors in systems with more than one pump in the PV-RO unit and no softstart features are installed.

Electrical Storage: Storage batteries can be included in PV-RO either to balance the electrical output of the PVCarrays during day-time operation or to provide required operation energy during night-time or overcast days. Batteries storage enables steady PV-RO units operation and may increase overall productivity however there are many disadvantages: (i) Installation and replacement of these batteries add significant capital and operational cost the plant which in some cases estimated to be 35% more in capital cost; (ii) These storage batteries imply additional losses of electricity and reduce the allover system efficiency; (iii) Adding all auxiliary components of the storage batteries such as charge controller and wiring, the inclusion of the system will be more complex; (iv) Absence of systems careful maintenance especially in remoteareas may dramatically reduce the lifetime of these batteries, which add significant cost due to the replacement of these batteries. Battery-less PV–RO systems are based on the idea that water storage is often more efficient and more cost-effective than energy storage. These systems are operated either at fixed or variable capacity. In the former, all radiation below the threshold value for start-up of the high pressure pump is dropped and the desalination plant works only during peak radiation hours (generally 5–8 h, depending on the local meteorological conditions). Systems operating at variable capacity achieve higher performance and flexibility by including speed control systems on the pumps and electronic power converters [33]. The technical feasibility and short-term operation of variable speed, battery-less PV–RO systems was tested in a series of studies, but long-term performance has not been monitored[34]. RO membrane biofouling can prevent the long-term operation of such systems. The hot climate typical of the regions where PV-RO systems are implemented promotes biofouling when the plant is not operating. Automatic shut-down devices and membrane cleaning systems are usually installed in such systems so that during periods of low solar radiation, the pump is shut off, thereby reducing the potential for membrane biofouling. The recirculation process used for membrane cleaning can be gravity-driven, rely on the high pressure pump, or on a dedicated flushing pump. Timing of membrane flushing is crucial: recirculation should be activated while there is still enough radiation to power the flushing pump, but limiting to a minimum the waste of radiation that could be used for the desalination process. In Abu Dhabi battery-less PV–RO systems were selected and the units were equipped with water storage tanks for night use.

Energy Recovery System: Due to the high investment in PVC modules, energy efficiency is a key factor required during the design of PV-RO desalination system. Brackish/saline groundwater desalination requires minimal energy consumption equal to osmotic pressure times the volume of fresh produced water. The osmotic pressure is proportional to the total dissolved salts concentration in the feed groundwater. For seawater which normally has salinity of about 35, 000 ppm, the osmotic pressure of 27 bar needs minimal energy of about 0.75 kWh/m^3 and it varies according to the water salinity concentrations. This minimal energy, derived by thermodynamic considerations, is general and true to all desalination technologies and not only RO. In general the energy use requirement for brackish groundwater is significantly low which is about 3-4 kWh/m^3. However recent studies indicating that advanced RO systems apply energy recovery or pressure conversion systemsare reported to lower energy consumption of 2 kWh/m^3. With the development of suitable devices for implementation in small-scale units, the use of energy recovery devices either in seawater or brackish groundwater PV–RO desalination is rapidly becoming standard practice. More recently devices that are more efficient at low flows were developed, such as Clark pumps, hydraulic motors, energy recovery pumps and pressure exchangers. Studies comparing different recovery mechanisms applied to the same PV-RO system reached different conclusions, possibly indicating that the choice of the most efficient energy recovery device is system-specific. Only limited number of studies [35] investigated the use of energy recovery devices in brackish water desalination since low concentrate pressure and high water recovery rates make energy recovery less critical in such systems.

Discharge of Brine Water: One of the main challenges facing the inland brackish/saline groundwater desalination is the efficient dischargeof brine water to environment. Some options forinland brine disposalinclude deep groundwater well injection back to aquifer systems, evaporation ponds and or reusing the brine for irrigation of salt tolerant species.In Abu Dhabi case study, using the deep injection groundwater wells has been rejected because these wells are difficult to permit, regulate and control. Also, they are very costly; their injection capacities are very limited and affect the deep aquifers groundwater quality. Also, since reject brine is corrosive, many safeguards must be added to the well. The costs associated with implementing these safety measures can make the deep wells disposal option prohibitively very expensive and its life time is very short and needs consequence replacement and maintenance. In some areas where the deep aquifer systems are confined and under pressure, additional pumps may be need for injection. An evaporation pond is merely an excavated protected and ceiled depression in the land which acts as a reservoir for brine and help evaporating it. Once the brine evaporates, the residual solids may be landfilled in situ or collected and disposed of elsewhere. To design the evaporation pond, the evaporation in each location was calculated according to the volumes of the brine disposal and the evaporation rate in the same site. This option is cheaper than deep wells; however about 40% of the brine water is lost by evaporation. Other option is to use the brine for irrigation of salt tolerant species however also the faced with many challenges such as the blocking and salt accumulation of irrigation systems and on the top of the soil. The last two options were selected and applied in different locations in Abu Dhabi Emirate project.

Cost Analysis: Costeffectiveness analysisisvery essentialpart from assessing anydevice or system tobecommercialized. The constructed PV-RO unites in Abu Dhabi were assessed technically and financially. It has been found that cost of produced freshwater from SPV-RO plants is affected by manytechnicalandeconomic factors including:

- Feedbrackish groundwaterquality and characteristics suchassalinity, turbidity, temperature and heavy metals concentration.
- Product waterquality and its salinity concentration
- Appliedpressure which is affected the quality of the feed water
- Recoveryratio also it is affected by both feed and produced water quality
- Energyrecoverydevices
- Stand-byequipment required for the system
- Costof RO membranes which is improved and become less year after year
- Costofequipment
- Costofprimary energyandtypeof powersupplyingsystemwhich in the case of PV-Ro affected by the retail cost of PVC matrixes
- Interestoncapital, labor cost
- Plant location which is affected by the land cost
- Implemented disposalsystem
- RO membrane performance
- Cost of any mitigation measured or cautions required by regulators.

Table 2: PV technology improvement (1995–2010)

Parmer	1995	2000	2005	2010
PV modules efficiency (%)	7-17	8-18	10-20	12-22
PV modules cost ($/W$_p$)	7-15	5-12	2-8	2-5
System life (years)	10-20	>20	>25	>25

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

Plantcapacity	40	m^3/d
RO plant configuration	1 stage	
Feedconcentration	15, 000	ppm
Foulingcorrectionfactor	0.7	
Atmosphericpressure	100, 000	Pa
Feedtemperature	25	°C
Saltmolecularweight	58.5	kg/kg mol
Friction parameter (permeate) 1.10E+09m^{-2}		
Solutionviscosity	0.00089	kg/m s
Solutiondensity	1100	kg/m^3
Diffusivity	1.6E-09	m^2/s
Masstransportcharacteristicsof membranes		
Stage 1		
Water permeability coefficient 3.31E-12m S^{-1} Pa^{-1}		
Saltpermeabilitycoefficient	3.34E-07	m/s
Masstransfercoefficient	3.76E-05	m/s

Table 4: Output data: capital cost and CO_2 emission

Parameter	Fullydieseldriven	Fullysolardriven	Unit
Capital Cost Estimation(*)			
Numberof20m^3tanks(4500imp.gal)	3	3	
Pre-treatmentcost	30000	30000	$
Highpressurepumpcost	7242	7242	$
Energyrecoverydevicecost	5395.67	11731.71	$
Membranecost	3704	9172	$
Waterstoragetank, cost	36, 000	36, 000	$
Costofland	0	0	$
Capitallesssitedevelopmentcost, CMSD	109989.77	134001.90	$
Sitedevelopment, cc_{sd}	36296.62	44220.63	$
Directcapitalcost, DCC	146286.40	178222.52	$
Indirectcapitalcost:contingencies, cc_i	14628.64	17822.25	$
Installationcost, $cc_{install}$	10468.44	14531.09	$
Installedcapitalcost, ICC	171383.47	210575.87	$
Annualpayment(withoutinterestoncapital)	8569.17	10528.79	$/y
Annualcapitalcost	14875.76	18277.59	$/y
CO_2Emission Cost Estimation			
Thermalpowerrequired	29.31	-	kWthermal
Thermalpowerrequired	0.11	_	GJ/h
Kgoffuelrequired	2.36	_	kg/h
Fuelconsumptionrate	0.69	_	USgal/h
Fuelconsumptionperyear	5451.19	_	USgal/y
Dieselfueldensity	0.90	_	kg/L
Massoffuelburnt	18569.48	_	kg/y
Massofcarbonburnt/y	15598.36	_	kg/y
MassofCO_2produced/y	97.19	_	Metricton/year

(*) This case study was done under specific condition where the water table of the well is rather near and the cost of pumping of groundwater will increase in different areas when application such pilot model

- Cost of transmission and distribution networks for both feed and produced water

Recentinnovations in the PVC panelsmanufacturing technology developed by different manufactures [4] andcontinuousresearcheffortsdoneall over the world toincreasetheirenergy conversion efficiency, resultedinsignificantreductioninPVCpanelcosts are shown in Table 2 [36]. This also will resulted in land uses and the its cost. In some cases where the PV-Ro near the cost the land price is very important factor affecting the allover capital cost.

In Abu Dhabi the installed PV-RO units are typical unites with a capacityofa40m^3/dayusing brackish/saline groundwater in remote areas.All unites are standalone (self-sufficient) with no other alternative sources for power. Abu DhabiEmirateliesinthesocalledthesolar beltwithanannualaveragesolarradiationof 6kh/m^2/day. Theplantsare poweredonlybyPVCpanels. All plantsequipmentaresizedsothatthewater demandforthe24h, 20 m^3/day, isproduced duringsunshinehoursonly (in average isabout10hrs/day).CO_2 emissiontax, assumedas30US$/tonof produced CO_2hasbeenconsideredinwatercostcalculations.The input data is shown in Table 3. In suchsmallscale PV-ROsystemsoperatedat remoteareas, produced freshwatercoststronglydependent onlabor costs.In this financialanalysisit has beenassumed that the annual laborcostis of10, 000$.This item alone will charge water cost by about 1.0$/m^{3}based on plant capacity of 40 m^3/d. Inconventional RO seawater desalination plants, labor costnormallyis of only0.03$/m^3 of the total watercostwhich is not realistic forsmallscale PV-RO plant. As expected also, the figures related to CO_2 emissions comparing the PV-RO with diesel generator powered unit as shown in Table 4, indicated that the fully diesel-driven option is the most environmentally hazardous with an annual mission of 97.2 tons of CO_2 discharged into the air. However, fuel consumption rate and consequently the amount ofCO_2 emitted in tons are direct functions of the used generator efficiency.Another important factor that land cost here in this analysis was considered as zero, as all of these areas are remote areas given for free by the government with no cost and it was very difficult to give an estimation for these remote areas. Fortheinputdatausedinthisstudy from Abu Dhabi PV-RO unites, results showedthatthefullysolar-driven alternativeisverycompetitive, havingaspecific produced freshwatercostof4.2 $/m^3 from brackish/saline groundwater with feed water sanity up to 15, 000 ppm.

Conclusions and Recommendations

Solar Unit Technologies: Recently level of technological development in PV–RO desalination systemis promising and allows their commercialization;however their implementation and market presentation still far beensmall, mainly due to very high capital investmentsand costs especially for the PVC modules. Research in the field of PVC modules, however, is developing rapidly to increase their efficiency which is about 15% in average to more than 33% in the near future and their retail price. This seems to offer a hope that significant cost and land use reductions can be expected in short to medium term. Promising field of research are the exploration of the properties of both crystalline and amorphous silicon and of other semi-conductors such as cadmium telluride and copper indium gallium diselenide for application in thin film cells and the development of Concentrating Solar Power (CSP). The rapid development in CSP technologies will be crucial in determining whether solar powered desalination will become economically feasible for largescale commercial RO or thermal desalination systems. Recent research studiesresults indicating that the very large CSP thermal desalination units with a capacity up to 100, 000 m^3/day have the mediumterm potential to achieve a freshwater production cost below 0.55 US$/ m^3 and to become very cheapoption for desalination ofseawaterin the MENA region [37]the near future.

RO Unit Design and Operation: Using advanced pretreatment systems by ultra-filtration or nano-filtration membranescan potentially reduce fouling and scaling of the RO unites and decreasesthe energy consumption which will have an impact on the overall desalination costs. Some studies also recommended that Nano-filtration membranes could be applicable in the solar powered desalination of brackish groundwater due to their lower operating pressures and energy requirements. However, these could be used only for low saline groundwater as both ultra-filtration andnano-filtration membranescould not remove the total dissolved salts. Also, developingmechanisms to automatically control the water recovery ratio in PV-RO desalination systems can help to promote the development of energy efficient systems that will require only minimal maintenance which will affect the overall O&M cost for the system [38].

Solar and RO Unit Integration: First, to date, the full potential of dual-purpose designs for the co-generation of power and water has not been sufficiently explored.

Such designs have a potential to operate at low water generating costs and levelized electricity costs. Second, an operation strategy with the potential to increase both energy efficiency andpermeate water production comprises preheating the RO feed by cooling the PV panels or absorbing rejected thermal energy in solar thermal power systems [39]. Third, improvements in the durability of batteries may eliminate the current maintenance and replacement issues and make energy storage attractive for long daily operation.

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