New Prospects for PV Powered Water Desalination Plants in Sunny and Arid Regions

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Summary: This paper summarizes a study of the economic and environmental performance of Reverse Osmosis (RO) desalination powered mainly with photovoltaics. It is based on up-to-date cost data for photovoltaic power plants and RO desalination plants. A case study is presented of a plant producing 6550 m^3 water per day on the coast of the Red Sea in Saudi Arabia powered by 3-MWdc PV or HCPV capacities. We used the HOMER Energy Modeling Software and the DEEP 5.0 desalination software to analyze the economic and environmental feasibility of these plants. Among other applications, solar electricity can produce affordable fresh water from sea water and pump it inland. Based on the results of this case study we infer the business prospects associated with large deployment of PV-RO plants in the greater Middle East and other sunny and arid regions.

Purpose of the work: As freshwater scarcity continues to increase with climate change and a growing population, desalinating seawater is becoming a necessity for meeting freshwater needs. Conventional desalination using fossil fuel-based power is not sustainable as fossil fuels are finite resources and their extraction and use pollutes the environment. The current global desalination capacity is more than 60 million cubic meters per day, with approximately two-thirds of this capacity in the sunny Middle East. It is estimated that only 0.8% of the global desalination capacity is supplemented by solar power generation. Furthermore, increased water demand and increased drought episodes in the Middle East and other regions, necessitate an expansion in desalination prospects, and create a great market opportunity for photovoltaics.

Approach/ Scientific Innovation and Relevance: We used technical data from a King Abdullah University for Science and Technology (KAUST) study proposing an HCPV-RO plant on the coast of the Red Sea in Saudi Arabia. The grid-connected 1-MW and 3-MW PV designs proposed by KAUST were used as base cases for comparison; we also studied system alterations, including non-concentrating cadmium telluride (CdTe) photovoltaics, and stand-alone power generation. We used the HOMER Energy Modeling Software and the DEEP 5.0 desalination software to analyze the economic and environmental feasibility of these plant configurations. We are investigating the potential for improving the environmental footprint of the plants by re-using membranes, recycling chemicals and managing waste flows.

Results and Conclusions: HOMER analysis shows that for producing the electricity to power a RO plant, using fixed-plane, CdTe PV at $1.75/W installed cost with grid-connection is the least expensive option for all considered cases; the LCOE for a 25-yr life is $0.075/kWh for a grid-connected 3 MW system (using 60% of the 8.9 GWh of required electricity from PV and the rest from the grid at $0.039/kWh. DEEP analysis showed the water production costs to be $0.87/$m^3$. Sensitivity analyses determined how panel efficiency, tracking, system costs, and discount rates affect the net present cost of the system. Based on these results we discuss the potential for large-scale global deployment of PV desalination.

SUPPORTING MATERIAL

The late Richard Small, Nobel Laureate in Chemistry, ranked the “top 10 problems of Humanity for the next 50 years”. Leading his list is Energy, followed in order of priority by Water, Food, Environment, Poverty, Terrorism & War, Disease, Education, Democracy and Population. He put Energy at the top because the other problems can either be resolved or alleviated with the availability of abundant and affordable clean energy. Had he lived eight years more, he would have been glad to see how affordable solar electricity has become in our days. Among other applications, solar electricity can produce affordable fresh water from sea water and pump it inland. Conventional desalination using fossil fuel-based power is not sustainable as fossil fuels are finite resources and their extraction and usage pollutes the environment. Photovoltaics provide a sustainable option for water desalination; in addition to being fuel-free and pollution-free during operation, photovoltaics do not require the large amount of water that thermoelectric power generation does.

1. Background on Reverse Osmosis Seawater Desalination

1.1. RO Module

Reverse Osmosis (RO) of saline water is a process that involves membrane separation, where the feedwater is pressurized to overcome the osmotic pressure, enabling the membrane to separate the feedwater into two flows: a flow that passes through the membrane (the desalinated or permeate water), containing 1% to 15% of its initial salt content, and the brine flow, which is rejected at high pressure. Electricity is needed for flow pressurization of saline water and water treatment processes (pre-treatment and post-treatment). Typical pressure values used in desalination processes ranges from 55 to 80 bars, depending on the salt concentration, the feed water temperature, and membrane types.

The typical lifespan of an RO membrane is estimated to range from 3-5 years depending on the operating conditions of the desalination unit. Membrane cleaning via chemical treatment is required and the cleaning frequency depends on feed water quality and other operating conditions. Furthermore, membrane sterilization is required if the desalination unit is shut down for 2 days or more. The predominant RO membrane materials (with spiral wound or hollow fiber configurations) consist of aramids, polyamides, or cellulose acetate. At a membrane’s end-of-life, membranes are typically disposed of. However, these membranes can be treated and reused as secondary micro or nanofiltration membranes, allowing for potential improvement of environmental sustainability. For example, reused membranes could be incorporated further upstream in the desalination plant for pretreatment; they can also be reused in other less-intensive applications, such as brackish water desalination.

1.2. Pre-Treatment & Post-treatment

The quality of feed water greatly affects the performance of a desalination unit. Pre-treatment requires filtration for the removal of suspended solids, and chemical treatment is needed to reduce scaling of the RO membrane. Acid feeding and antiscalants (e.g., polyphosphates, polycarboxylates, or sodium hexametaphosphate) are used to control calcium carbonate scaling, while silica scaling is typically controlled by temperature. Biofouling can also reduce RO performance, but it can be mitigated with biocide (e.g., chlorine) treatment; however, while biocides will inhibit growth of existing and new biofilms, they will not eliminate dead cells that stay within the system and persist to reduce RO performance. Post-treatment may include mineralization and conditioning with carbon dioxide and sodium hydroxide in order to reduce the corrosiveness of the purified product water. In summary, pre- and post-treatment processes will vary by case depending on feedwater quality and product water requirements; the types and quantities of treatment chemicals will be discussed in the complete paper. In terms of energy usage, the pre- and post-treatment processes use about 1 kWh per cubic meter of permeate water, versus 2 kWh required for the RO process itself.

As desalination capacity increases over time, waste flows, which consist of brine, heavy metals, and chemicals used during treatment processes, and that are typically released into the ocean, may pose considerable adverse impacts on ocean water quality and local ecosystems. Therefore, increasing the sustainability of this technology must involve the appropriate management of waste flow disposal.

2. The KAUST Case Study

In April 2013, KAUST prepared a report titled "Combined Concentrated Photovoltaic and Seawater Reverse Osmosis Facilities." The report has three parts: a) a HCPV-RO business case analysis, b) an economic evaluation of a HCPV-RO demonstration-scale plant, and c) design of the plant. The demonstration-scale evaluation considered a plant in Saudi Arabia, producing 3,120 m^3 of fresh water per day. The business-case analysis considered capital and operating expenses for six scenarios; three with grid connection and gradually increasing solar electricity penetration (from no penetration in the first case to all PV electricity in the third case), and three with diesel generation and gradually increasing solar electricity penetration. The net present costs (NPC) of each system were added up and estimated water selling prices that would satisfy the return on investment expected by investors were calculated for each scenario. Due to highly subsidized fuel prices, the water selling prices for systems without PV, were always lower than the prices of systems powered by unsubsidized photovoltaic systems (The price of diesel fuel in Saudi Arabia is $0.30/gallon instead of the world market value of $2.60/gallon.) If the fuel prices were not subsidized, the trend would be inversed and PV powered systems would become cheaper than plants powered solely by diesel fuel. We used the HOMER and DEEP software to redo the performance and economic analysis of on the KAUST demonstration-scale design plant. Then we updated and expanded this study using more recent cost data and various scenarios of a two-axis HCPV power system, a latitude-tilt CdTe PV system, and a one-axis tracking CdTe PV system.

3. Methodology

The Hybrid Optimization Model for Electric Renewables (HOMER), and the Desalination Economic Evaluation Program 5.0 (DEEP), were used in tandem to model capital expenses and energy inputs of grid-connected PV-RO plants. The RO plant for each scenario was assumed to have a constant 1 MW load throughout the year. PV system scenarios were created for 1 MW and 3 MW sizes, where the 1 MW system would account for the RO load during most days day, while the 3 MW system would generate excess power to partially compensate for 24-hour operation of the RO plant, selling electricity at the grid at the same price as the purchased power (i.e., $0.039/kWh).

3.1. HOMER Analysis

HOMER, developed at the National Renewable Energy Laboratory, is a tool for designing and analyzing hybrid energy systems, allowing users to select from both conventional and renewable energy technologies. Users can design both grid-connected and stand-alone systems and can analyze performance based on technological feasibility and resource availability. The software takes into account the configuration of a particular system, the capital and O&M costs of the different system components, and the sizing of each component so that the NPC of the whole system is optimized while the load needs are met.

3.2. DEEP Analysis

DEEP was developed by the International Atomic Energy Agency (IAEA). It enables side-by-side comparisons of various energy sources and desalination technology configurations, yielding an estimated water production cost based on site specific and design parameters (e.g., desalination capacity, total dissolved solids (TDS), maximum membrane pressure, and power plant characteristics). DEEP yields the levelized costs of water, a breakdown of cost components, and energy consumption.

4. Preliminary Results

Preliminary results show that the levelized (over 25 yr life) water production costs for 3 MW HCPV with dual-axis tracking, and CdTe PV at either fixed latitude-tilt or single-axis tracking are 0.96, 0.87, and 0.89 $/m^3, respectively. (Figure 1). The costs for 1 MW PV systems connected to the same load are lower, due to much greater purchases (~80% of total electricity) of subsidized grid electricity at $0.039/kWh). Figure 2 shows the breakdown of the annualized cost of the 3 MW-RO seawater desalination plant. The breakdown includes capital costs of the RO plant, power costs, material costs, labor and management costs, and insurance costs. In this scenario power accounts for 32% of the water production cost.

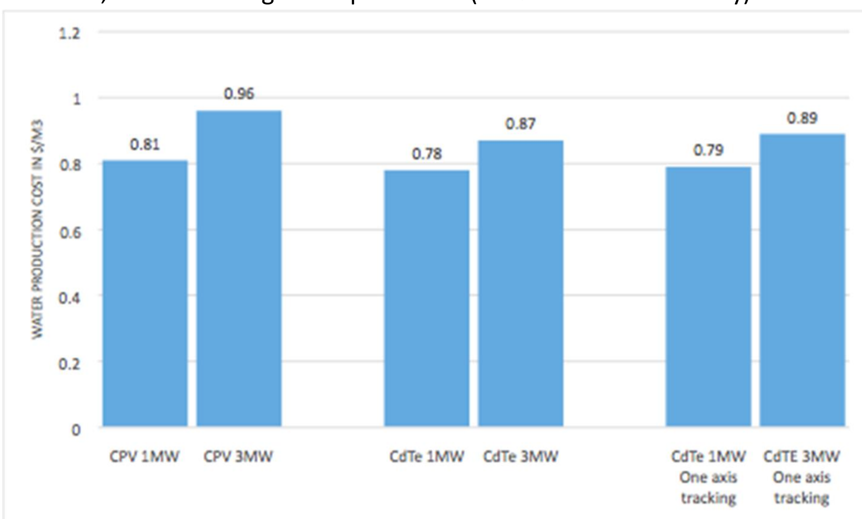

Figure 1. Water production cost estimates for a 6550 m3 per day RO seawater desalination from HOMER-DEEP analysis for different power generation scenarios

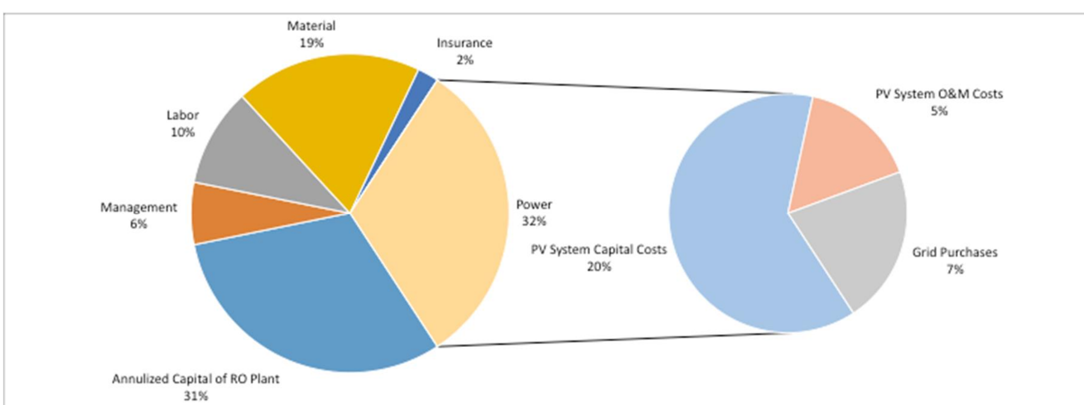

Figure2. Annualized cost breakdown of a 3 MW CdTe PV System (total water production cost is 0.87 $/m3)