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Development of mobile stand-alone solar-driven reverse osmosis groundwater/seawater desalination plants for sustainable development in Egypt

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ABSTRACT

Egypt is experiencing a fresh water crisis. Many large and small communities in Egypt are suffering an acute shortage of fresh water that complies with minimum health requirements. Water desalination projects based on reverse osmosis (RO) technology are being introduced in Egypt to combat drinking water shortage in remote areas. RO desalination is a pressure-driven process. This work focuses on the design of an integrated brackish water and seawater RO desalination and solar photovoltaic (PV) technology. Two small mobile PV-driven RO desalination plants prototypes were designed, deployed and applied into two areas in Egypt. Solar-driven RO desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. Moreover, the innovative features incorporated in the newly designed PV-RO plant prototype are focusing on improving the cost effectiveness of producing drinkable water in remote areas. This is achieved by maximizing energy yield through an integrated automatic single axis PV tracking system with programmed tilting angle adjustment. Mobility of the systems provides potable water to isolated villages and population as well as ability to provide good drinking water to different number of people from any source that is not drinkable. In the first project, a mobile battery-less photovoltaic powered groundwater reverse-osmosis (MSRO) desalinating unit was designed, manufactured and deployed in the Northwest coast of Egypt. This unit is capable of desalinating the brackish and saline groundwater as well as it was considered to produce 11 m^3/d of drinkable water for the Bedouins community. The second project focuses on designing, building and field-tested of an integrated mobile saline groundwater and seawater RO desalination and solar photovoltaic (PV) technology. The system was designed to produce 21 m^3/d of fresh water in Shalateen area, Southeast coast of Egypt.

Keywords: Design; Mobile; Reverse osmosis; Photovoltaic; Desalination; Northwest Coast; Shalateen; Egypt

1. Introduction

Desert regions in Egypt constitute more than 94% of the total area of the country. The other 6% of the area include mainly the cultivated lands in Nile valley and Delta. On the other hand, the majority of Egyptian population is concentrated within the area of the Nile valley and Delta whereas less than 5% of the population are scattered in all desert areas. Such situation resulted in serious economic, social and environmental problems. The current total water supply in Egypt is about 57.5 billion m^3/year, from which

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there is a fixed 55.5 billion m^3/year from the River Nile. The per capita water share was 771 m^3/year in 2005, which is below the international standards of water poverty line of 1,000 m^3/year. By the year 2025, this shortage will be severer, the total water demand will exceed 125 billion m^3/year that causes a shortage of more than 30%.

Desalination is a separation process that produces two streams, fresh water and saline solution (brine). Saline water is classified as brackish water when the salt concentration, mostly sodium chloride, is between 1,000 and 10,000 ppm, hard brackish water when the salinity is 10,000 to 35,000 ppm, and seawater when the salinity exceeds 35,000 ppm (Rizzuti et al. 2007). Seawater and brackish water desalination are attracting more and more interest and attention, as they are most important methods to solve the problem of water shortage (Matsuura 2001). The reverse osmosis (RO) process, which relies on the semi-permeable character of a polymeric membrane to achieve molecular separation under the driving force of hydraulic pressure, is one of the most popular technologies currently being used for brackish water and seawater desalination for the advantages such as saving energy, modularity, flexibility, ability to construct small size plants, high permeate quality and minimal chemical addition (Said et al. 2013, Shawky et al. 2011 and Shawky 2009).

Remote communities are often located in areas with access to seawater or brackish groundwater. For such communities, small-scale RO desalination can provide fresh water. Desalination is an energy-intensive process. Diesel generators or grid power are commonly used to power RO systems; however, diesel generators pollute the environment and their fuel is expensive. Grid power may not be available or may be expensive. Using photovoltaics to power RO desalination systems is a promising solution for such communities (Bilton et al. 2011). Solar energy coupled to desalination offers a promising prospect for covering the fundamental needs of power and water in remote regions, where connection to the public electrical grid is neither cost-effective nor feasible, and where water scarcity is severe. Moreover, the coupling of RO desalination with solar energy is a promising field of development in the desalination sector, with the potential to (i) improve its sustainability by minimizing or completely eliminating the dependence on fossil fuels, (ii) significantly reduce the operational costs of desalination plants (Ghermandi and Messalem 2009). Despite a steady reduction in the energy consumption of pressure-driven membrane processes in recent decades, energy consumption is still a major cost component of RO desalination plants, accounting for 40%–45% of total costs (Betts 2004).

The solar-powered RO systems principally can be classified into three groups: (1) solar thermal driven or Rankine cycle driven RO systems; (2) PV-driven RO systems; (3) hybrid (particularly wind-PV) powered RO systems (Aybar et al. 2010). The Middle East and North African region has outstanding solar resources which can be captured for use either by (PV) devices or by direct absorption as thermal energy. The distribution of this resource is more evenly spread over the entire region than other renewable energy resources, which tend to be site specific. Huge areas are available for this resource to be utilized. Long-term development of this on a large scale will hinge on technical developments that will reduce the cost of electricity generated by PV or by solar thermal power plants.

The main goal of this paper is reducing the total cost (capital + operating) of desalinated water, designing and testing of two small mobile PV-driven batteries-less powered groundwater reverse-osmosis (PV-RO) desalinating units for sustainable development in different localities in Egypt. The first unit is capable of desalinating brackish and saline groundwater and produces 11 m^3/d of potable water per day that complies with international standards to be deployed in the northwest coast of Egypt, where, the second unit is producing 21 m^3/d of fresh water and deployed in Shalateen area, Southeastern Egypt.

2. Methodology

Development of hybrids of solar and conventional desalination requires careful analysis and innovative engineering solutions. Hybrids of RO and solar energy are relatively less complicated than hybrids of thermal desalination (Childs et al. 1999). A stand-alone RO desalination unit powered by solar is proposed. To predict the water production, 131 different water points are selected based on the available solar radiation data, sunshine hours and salinity of the feed water. The proposed system includes two main subunits—the energy production and the desalination subunits. The energy production subunit includes PV array without batteries, and DC/AC inverter. Because of the high humidity for the area under application, battery-less system was our favorable choice. The membrane separation section of the desalination subunit is fed via a high-pressure reciprocating pump, which is connected to energy production subunit for the recovery of energy by the brine stream leaving the process. The RO desalination unit consists of three 4 × 40 inch spiral wound seawater Filmtec membrane modules. The DC power is produced from a PV array that consists of six TOPSUN TS-S415 solar PV panels of total peak power of 2,490 W that is connected to the DC motor. Taking account of this fact, a preliminary design of small-scale PV-powered RO battery-less desalination system is proposed in this study. The system is battery-less as the low annual water storage cost in a tank (1%) compared with the electrical energy storage cost in batteries (12%) proves that it is more cost-effective to store fresh water rather than to store electrical energy (Mohamed and Papadakis 2004). The proposed system is supposed to be a promising option by its compactness, its transportability, and its technical and economic feasibility. More than 150 articles were collected by the research team covers the following topics; geology, hydrology and hydrogeochemistry of the study area, water desalination plants, PV/wind-driven RO desalination plants and design of PV/wind RO desalination plants. Field work for Matrouh project took place within 2012–2013, during which water samples were collected from the study area. The present research is based on the results of 131 water samples (5 fresh samples, 9 saline samples and 117 brackish water samples) corresponding to all available water sources in the area.

A complete technical report for the groundwater evaluation for the area between Shalateen and Haliab was prepared by the research team as a side activity from the project.

The unit contains three Filmtec spiral wound membranes (SW30-4040) in one pressure vessel, dosing pumps of 1.2 kW for the feed water pretreatment and a 0.25 kW washing pump. To operate the RO desalination plant, these items should be considered as following.

2.1. Pre-treatment

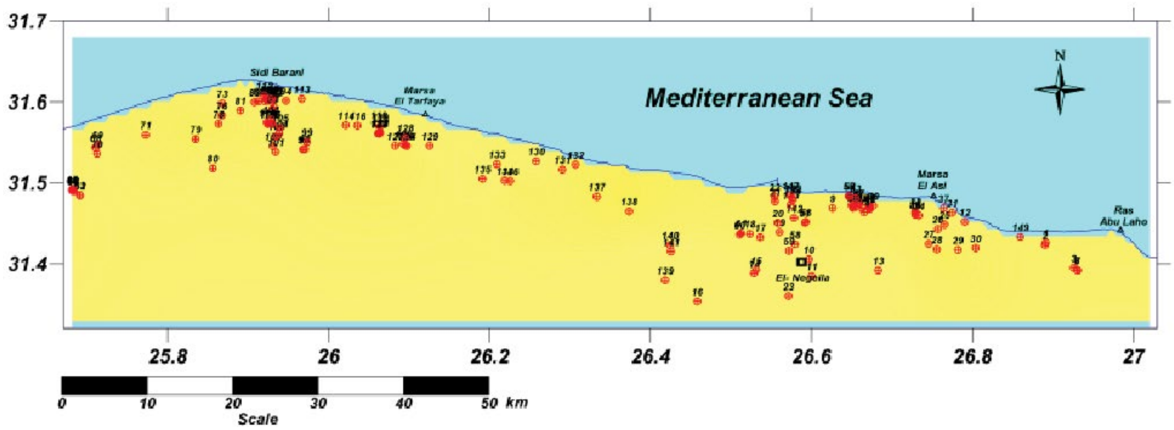
The incoming feed-water is pretreated to be compatible with the membranes by removing suspended solids, adjusting the pH, and adding a threshold inhibitor to control scaling caused by constituents such as calcium sulphate.

2.2. Pressurization

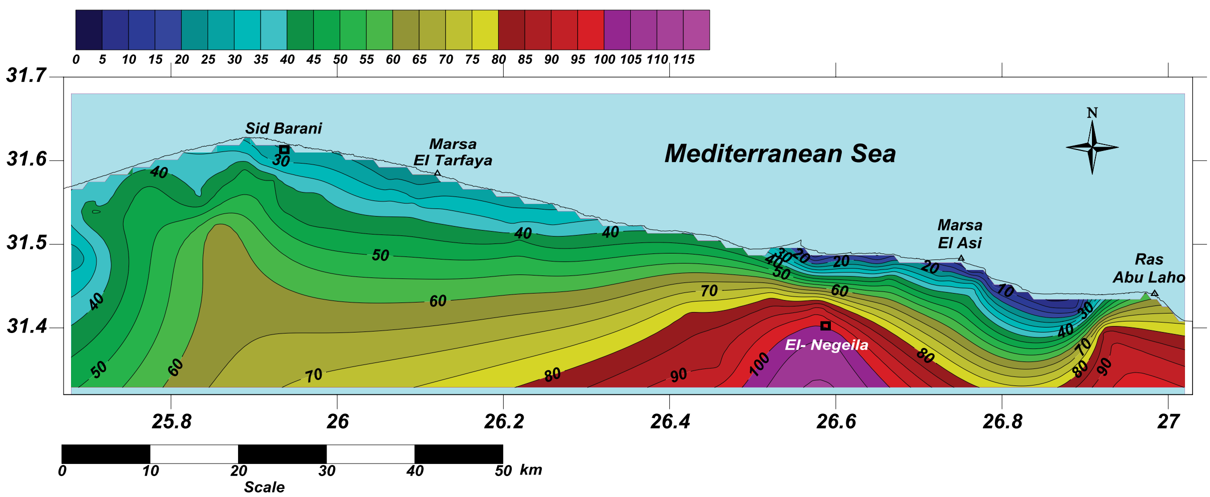
The pump raises the pressure of the pretreated feed water to an operating pressure appropriate for the membrane and the salinity of the feed water.

2.3. Energy recovery

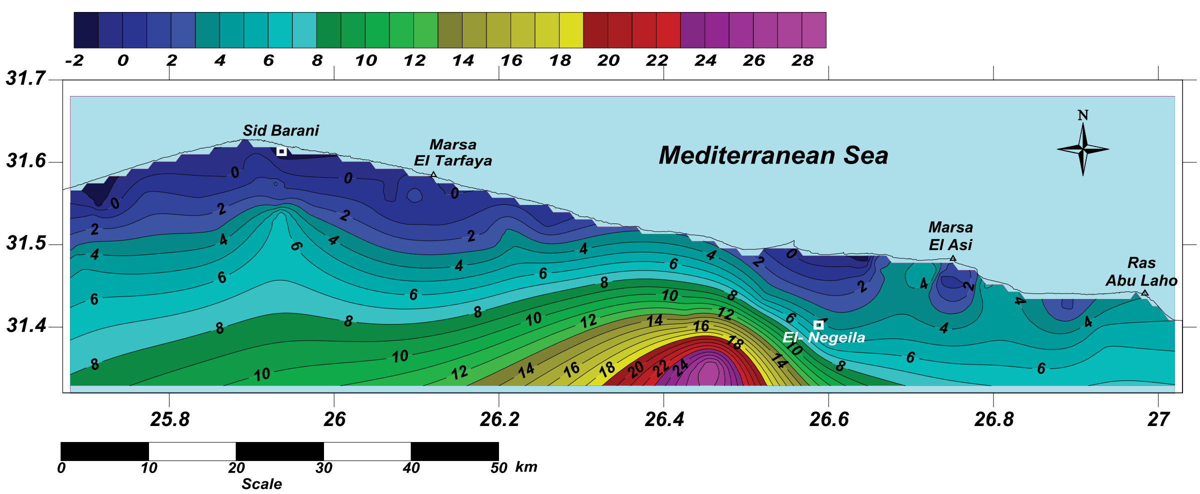
Seawater RO uses a very fine membrane that allows pure water to pass through, while mostly rejecting the relatively large salt molecules. The seawater feed must be pressurized (may be up to 69 bar/1,000 psi), first, to force the water through the mechanical constriction presented by the membrane and, second, against the natural osmotic pressure. Not all of the feed water can be forced through the membrane; some, typically more than half, must be allowed to pass over the membrane (cross-flow) in order to remove the salt. This water, known as the concentrate or brine, comes out of the RO module at a pressure only slightly below that of the feed pressure. In large RO plants, it is economically viable to recover the rejected brine energy with a suitable brine turbine. Such systems are called energy recovery RO systems.



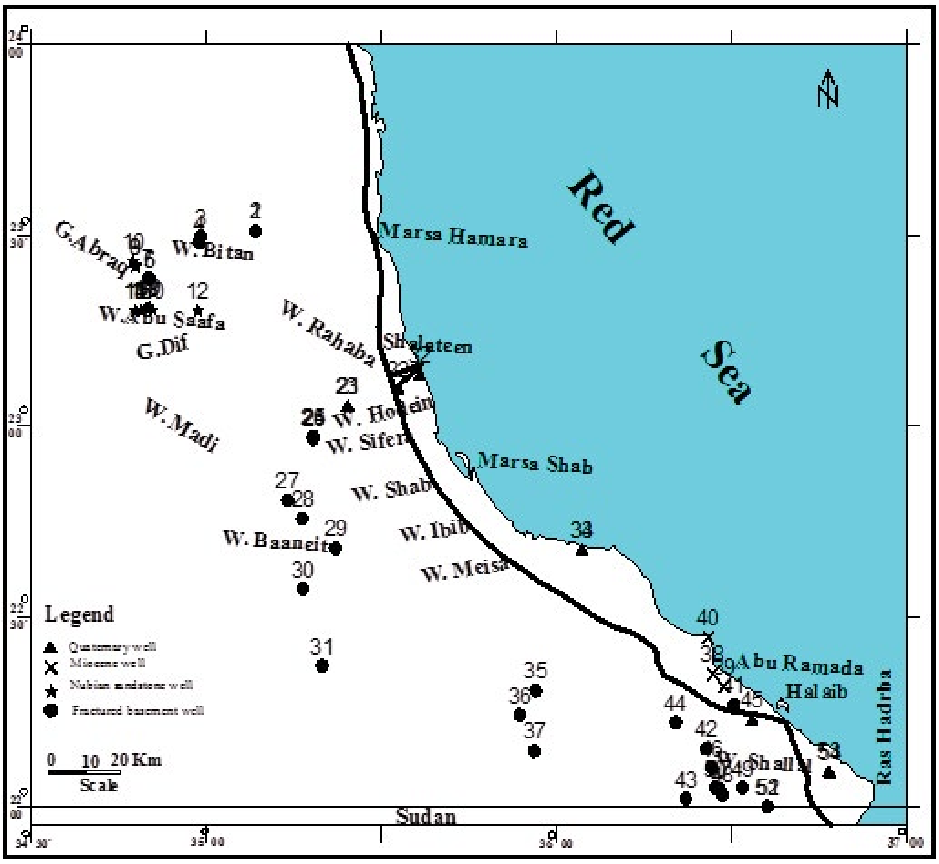
Well location map of the ground water in Matrouh area, Northwest coast of Egypt, May (2004 and repeated in May 2015).



Depth to water contour map in Matrouh area, Northwest coast of Egypt, May (2004 and repeated in May 2015).



Water level contour map of Matrouh area, Northwest coast of Egypt, May (2004 and repeated in May 2015).



Well location map of the ground water in Haliab and Shalateen area, May (2004 and repeated in May 2015).

3. Prediction of power consumption in the presence of energy recovery device

The use of a pressure exchanger to recover the hydraulic energy in the brine line plays a dominant role in the reduction of the size of the high-pressure pump and resulted in the reduction of the energy consumption power for the seawater which finally reduced the size of the hybrid energy system and the water production cost.

4. Survey on PV panels to choose the suitable type of panels

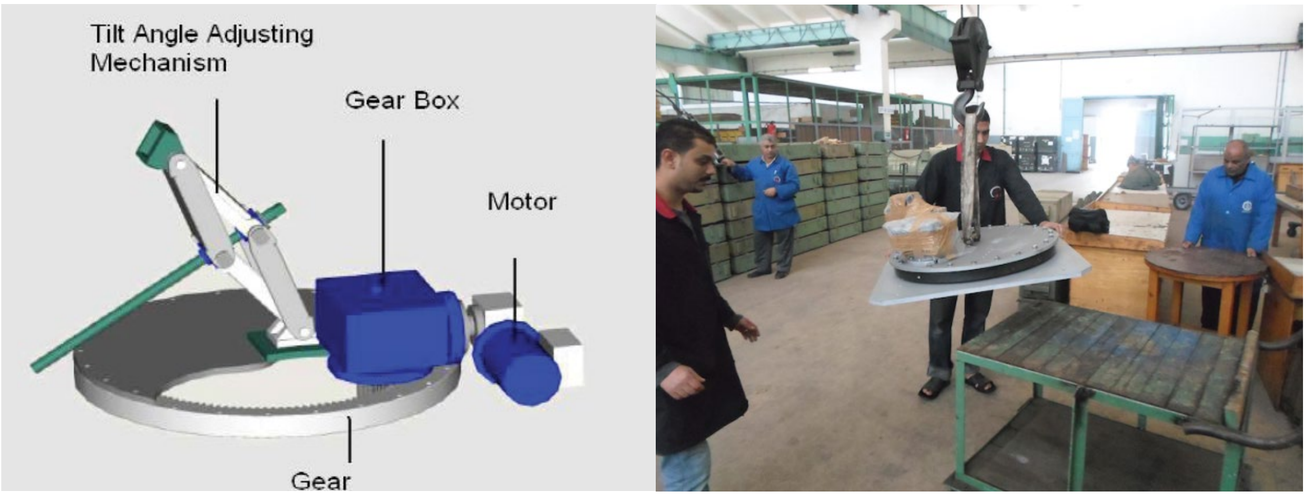
Selecting PV modules to satisfy total peak power requirements of the system. The PV generator will comprise efficient mono crystalline PV modules, a relatively high output power module will be selected to minimize the number of modules for better mobility considerations. The interconnection of the selected PV modules will be configured so that

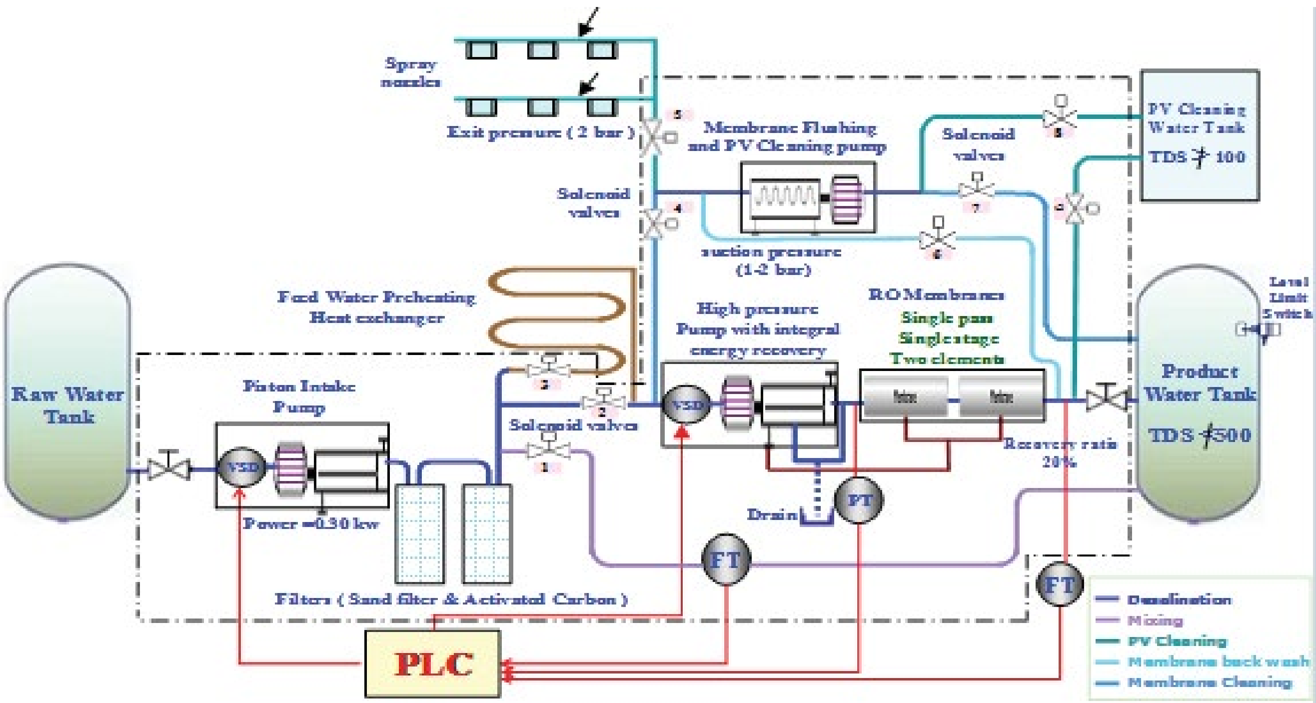
Mono-crystalline PV panels

the output voltage of the PV generator will fit with the input voltage of the inverter. Fourteen PV mono crystalline Si modules (each of 420 Wp with total peak power 5,880 Wp) were delivered by AOI.

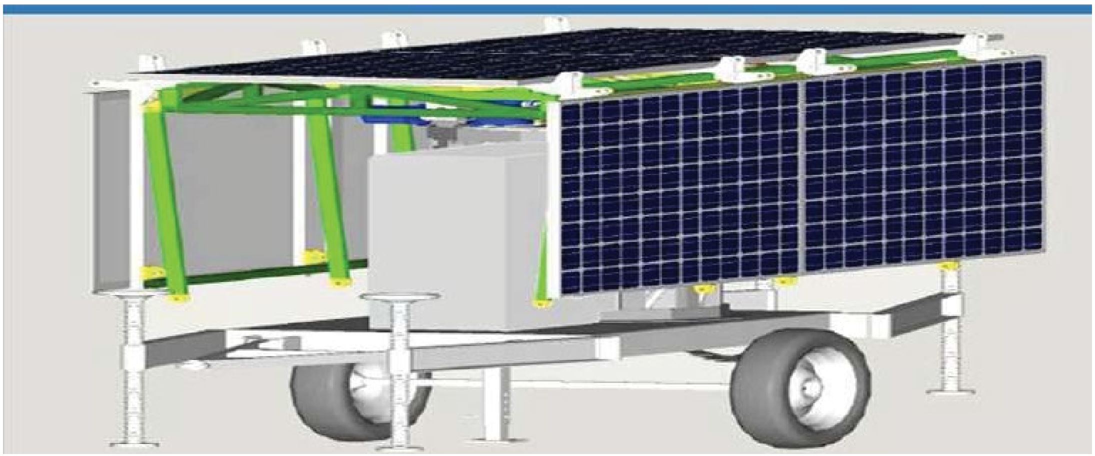
4.1. Assigning the structure, tracker system

To maximize the total solar radiation collected, PV tracking system is realized. For a simple tracking system, the daily solar tracking is achieved by rotating the PV array about the solar tracking axis staring at the azimuth angle at sun rise and ending at the azimuth angle at sun set. This rotation is achieved by incremental azimuth angular movements based upon the location of the system. The azimuth angle range is determined for each month and set in the PLC.

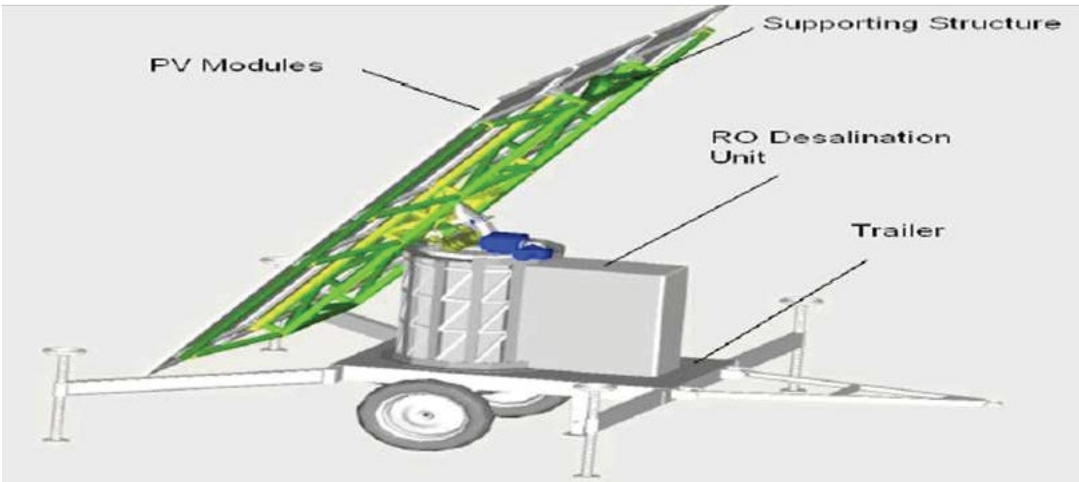




Schematic diagram for the integrated PV/RO system



Transportation mode



Operating mode

Structure of North coast unit

Structure of Shalateen unit

Structure of North coast unit

Structure of Shalateen unit

Transportation of North coast unit

Transportation of Shalateen unit

Factory testing of North coast unit

Factory testing of Shalateen unit

Matrouh unit in the final destination

Shalateen unit in the final destination

5. Conclusion

This work focuses on the improvement of mobile standalone solar driven RO groundwater desalination plants for maintainable expansion in different areas in Egypt. The aim of this study was working with the design of an integrated brackish water and seawater RO desalination and solar photovoltaic (PV) technology. Two small mobile PV-driven RO desalination plants prototype were designed, organized and applied into two areas in Egypt. Solar-driven RO desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. Moreover, the innovative features incorporated in the newly designed PV-RO plant prototype are focusing on improving the cost efficiency of generating drinkable water in remote areas. A small mobile PV-driven RO desalination plant prototype without batteries was designed. Solar-driven RO desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. This was achieved by maximizing energy yield through an integrated automatic single axis PV tracking system with programmed tilting angle adjustment.

Mobility of the systems delivers drinkable water to remote villages and population as well as aptitude to provide good drinking water to diverse number of people from any source that is not drinkable. First, a mobile battery-less photovoltaic powered groundwater reverse-osmosis (MSRO) desalinating unit was intended, contrived and organized in the Northwest coast of Egypt. This unit is able to desalinate the brackish and saline groundwater as well as it was deliberated to produce 11 m^3/d of drinkable water for the Bedouins community. Second, the designing, building and field-testing of an integrated mobile saline groundwater and seawater RO desalination and solar photovoltaic (PV) technology was achieved. The system was designed to produce 21 m^3/d of fresh water in Shalateen area, Southeast coast of Egypt.

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