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ABSTRACT

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 paper focuses on the design of an integrated brackish water and seawater RO desalination and solar photovoltaic (PV) technology. A small Mobile PV-driven RO desalination plant prototype without batteries is designed and tested. 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. An autonomous cleaning system for PV modules is adopted for maximizing energy generation efficiency. RO plant components are selected so as to produce 4–5 m^3/d of potable water. A basic criterion in the design of this PV-RO prototype is to produce a minimum amount of fresh water by running the plant during peak sun hours. Mobility of the system will provide 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.

Keywords: Design; Reverse osmosis; Photovoltaic; Energy; Desalination; 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 there is a fixed 55.5 billion m^3/year from the River Nile. The per

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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 resulting in 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 10,000–35,000 ppm, and seawater when the salinity exceeds 35,000 ppm [1]. 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 [2]. The reverse osmosis (RO) process, which relies on the semipermeable 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 [3–5].

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 (PVs) to power RO desalination systems is a promising solution for such communities [6]. 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 either not cost-effective or not 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 and (ii) significantly reduce the operational costs of desalination plants [7]. 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 [8].

The solar-powered RO systems are 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 [9]. 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 (RE) 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.

Present time for both brackish and seawater desalination the RO constitutes a more realistic choice. Considering the energy supply, RO presents lower energy consumption comparing to other methods of desalination, especially in countries where the conditions for solar-driven desalination are the most favorable, i.e. intense solar radiation and severe water scarcity exist. Several RO desalination systems driven by PV have been installed throughout the world in the last decades, most of them being built as experimental or demonstration plants. Some authors present experimental or simulation results [10,11], while some others concentrate on cost analysis [12,13]. Taking into account of the need and requirement of rural areas at present time it seems to be the development of small, autonomous, modular, flexible and reliable units, offering operation, and maintenance at reasonable cost, in order to serve the segment of isolated users [14]. On that level, the development of battery-less systems, as well as the use of recovery devices, is of special importance. For this reason, intermittent operation of direct connected PV–RO system may be a promising option. This requires modification of common design rules for the electronics and the water processing part of the plant. The battery-less option has been discussed by some authors in PV desalination applications [15]. Advantages of battery-less systems with electronic power converters are simplified configuration, compact design, improved robustness, and long life of all components of the power supply subsystem [16]. Battery less PV–RO systems are based on the idea that water storage is often more efficient and cost-effective than energy storage [17].

The main goal of this paper is to design and testing of a small mobile PV-driven battery-less-powered groundwater reverse-osmosis (PV–RO) desalinating unit. This unit is capable of desalinating brackish and saline groundwater points with salinity up to 25,000 ppm and produces 4–5 m^3/d of potable water per day that complies with international standards.

2. Design 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 [18]. 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 of two main subunits—the energy production and the desalination subunits. The energy production subunit includes of PV array without batteries, and DC/AC inverter. 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 to 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 [19]. The proposed system is supposed to be a promising option by its compactness, its transportability, and its technical, and economical feasibility (Fig. 1).

2.1. *Design inputs*

Tracking system should carry six PV modules each of dimension 1.96 m × 1.308 m × 40 mm and weight 35.5 kg and maximum allowable mechanical pressure = 5,400 Pa, with four mounting points at 653 mm distance from the mid points of the two long sides of the module. The overall dimensions of the RO unit are: L × W × H = 145 cm × 45 cm × 115 cm.

The tracking PV panel rotates automatically about the normal axis to the ground within an angle of about 220 deg and tilts manually from the fully horizontal position to a tilted position making an angle of 60 deg with the ground. All the system components should be carried on a trailer; considerations should be taken for transportation and operation.

2.2. *Design step 1. Water salinity map in the area of study*

2.2.1. *Site description*

The area under investigation is located in the North Western Mediterranean Sea coastal zone of Egypt. It located between latitudes 30° 50′ and 31° 40′ N, and longitudes 25° 00′ and 29° 40′ E (Fig. 2). The area stretches westwards about 104 km length and 20 km average width. It is bounded on the north by the Mediterranean Sea. The selected area is considered as one of the most promising regions for development. It can possess a good agricultural expansion, due to its

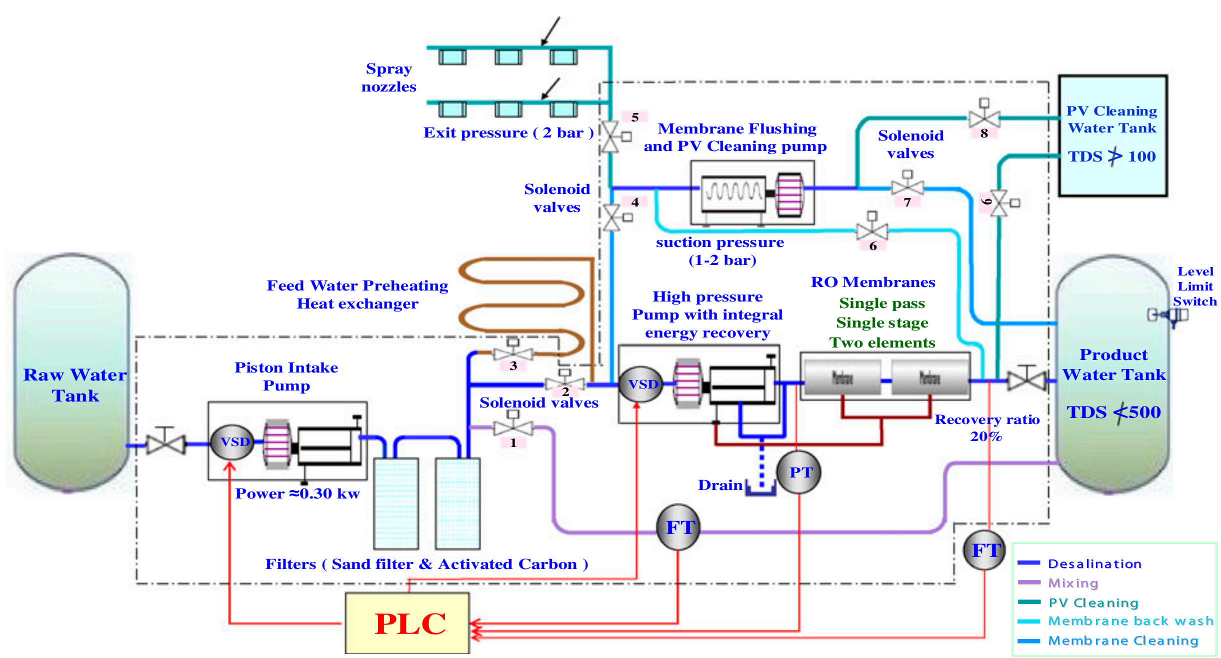

Fig. 1. Schematic diagram for the integrated PV/RO system.

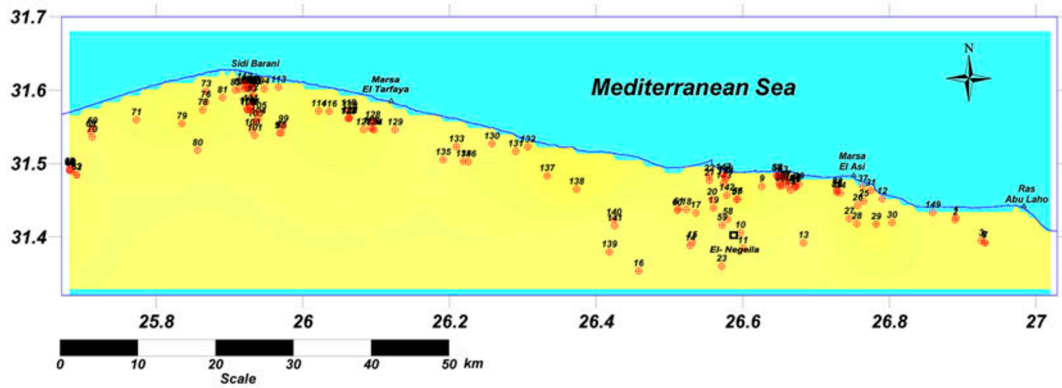

Fig. 2. Groundwater well location map for the study area.

favorable soil and water potentials in addition to its mild weather. So, at present, great efforts are directed to develop this zone which is mainly given a special priority in land reclamation. The water resources in study area are represented by groundwater. Moreover, the rainy season begins from October till January. The annual rainfall ranged from 100 mm/year to 181 mm/year with mean of about 139.2 mm/year. The area is characterized by moderate to low temperature and heavy short rainfall storms in winter and high temperature and high rate of evaporation in summer. It attains its maximum temperature values during May, June, July, and August. The rainy season begins from October till January. The rainfall occurs in the form of heavy short storms; hence the chance of surface water runoff and groundwater recharge is possible.

2.2.2. Water sampling

Fieldwork 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. Two kinds of analyzed water samples were taken from each of the above water points for different measurements. The first kind is for the measurement of major cations, anions, and minor elements. The second kind includes supra-pure nitric acid acidified samples for the measurements of trace elements and soluble heavy metals.

2.2.3. Site measurements

In situ measurements of water samples location together with some physical and chemical characteristics of the collected water were determined in the field using GPS model (Magellan Nave 5000 pro.) for the determination of latitudes and longitudes and Electrical Conductivity (EC) meter (Jenway, model 470) for the determination of water salinity (EC in μS/cm) and temperature of the collected water samples. pH and dissolved oxygen were measured using pH meter (Jenway, model 3150) and DO meter (WTW, model oxi 315i), respectively. Depth to water was measured using water level sounder Heron model dipper-T water level meter. Moreover, water level was measured by water level sounder with referring to ground elevation from the sea level (Figs. 2 and 3).

2.2.4. Laboratory analyses

The analyses include the determination of EC, total dissolved salts (TDS), pH, concentration of major ions Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, CO_3^{2-}, HCO_3^{-}, SO_4^{2-}, and Cl^{-}. The minor, trace, and soluble heavy metals and non metals are, NH_4^{+}, NO_2^{-}, NO_3^{-}, PO_4^{3-}, B^{3+}, Al^{3+}, Fe^{3+}, Mn^{2+}, Co^{2+}, Cu^{2+}, Ni^{2+}, Cr^{3+}, Cd^{2+}, Pb^{2+}, Sr^{2+}, V^{2+}, and Zn^{2+} in addition to BOD and COD. Measurements were carried out by EC meter model Orion (150 A^{+}), pH meter (Jenway 3510), Flame photometer (Jenway PFP 7), Ion selectivity meter (Orion model 940 with 960 titration plus), UV/Visible spectrophotometer (Thermo-Spectronic 300), and ICAP (thermo 6500). The obtained chemical data are expressed in milligram per liter (mg/l) or part per million (ppm).

2.2.5. Physical characteristics of the groundwater

The physical properties of the water samples were discussed through the measurement of EC (Table 1). The conductivity of an aqueous solution is its ability to carry an electric current. The current is conducted

Fig. 3. Site measurements for water quality and quantity.

Table 1
Chemical characteristics of 131 groundwater samples collected from the study area

	Concentration (mg/L)				Concentration (mg/L)		
	Minimum	Maximum	Median		Minimum	Maximum	Median
EC ηm/cm	393	36,700	8,840	B	0	4.72	1.11
TDS	337	22,114	5,106	Cu	0	0.09	0.0037
Na	30	7,300	1,500	Fe	0.05	13.96	1.365
K	7	316	51	Li	0	0.55	0.093
Ca	40.1	527.6	147.9	Mn	0	1.72	0.053
Mg	8.3	615	164.2	Mo	0	0.05	0.0015
CO_3	0	112.8	50.8	Ni	0	0.27	0.0058
HCO_3	160.6	779.8	292.4	P	0.01	1.36	0.2127
Cl	33.5	12,592	2589.7	Pb	0	0.07	0.0054
SO_4	11	1,536	318	Si	3.61	40.18	8.04
Br	1.1	219.2	39.5	Sr	0.74	29.37	8.96
I	0.01	1.36	0.066	V	0	0.32	0.0133
Al	0	18.97	0.73	Zn	0	0.39	0.0505

in the solution by the movement of ions, and the greater the number of ions, and the higher their mobility, the higher the level of conductivity. Conductivity is expressed in units of microsiemens/cm (μS/cm). For this reason, the measurement of conductivity gives a good indication of the concentration of dissolved salts in water. The EC of the groundwater samples in the area of study is varied from 393 μS/cm (well No. 131) to 36,700 μS/cm (well No. 47) with median value of 8,840 μS/cm.

2.2.6. *Chemical characteristics of the groundwater*

Water salinity is the sum of all minerals substances detected from the chemical analyses. Different methods are used for water classification according to its salinity values. Natural water is classified into three main categories of total salinity; fresh water, brackish water, and saline water. In the area of study, the salinity of the groundwater is ranged between 337 ppm at (well No. 131) to 22,114 ppm (well No. 47) with median value of 5,106 ppm. According to this salinity classification, 10 samples representing 7.6% of total samples are fresh, 53 samples representing 40.5% are brackish, and 68 sample representing 51.9% of the total samples are saline.

Moreover, major constituents (Ca^{2+}, Mg^{2+}, Na^{+}, HCO_3^-, SO_4^{2-}, Cl^-, and SiO_2), as well as, minor and trace constitutes (K, CO_3, Ag, Al, B, Ba, Bi, Cd, Co, Cr, Cu, Fe, Li, Mn, Mo, Ni, P, Pb, Sr, V, and Zn) of the groundwater sample are also analyzed to study their effect on the PV/RO conceptual design (Table 1).

Therefore, the data revealed from this part is very important for the conceptual design of our PV/RO stand-alone system due to the following:

(1) 93.13 % of the groundwater samples in the area of study are not suitable for drinking due to higher contents of soluble salts which reflects the importance of our PV/RO to this area.
(2) 51.9% of the groundwater samples are saline meaning that SeaWater (SW) membrane element will be preferred in our RO plant.
(3) The higher contents of calcium, magnesium, and silicate need antiscalent addition in the plant.
(4) Studying depth to water levels is very important for the calculation of the power for the pump.

2.3. Design step 3. Saline water RO unit sizing

Assuming that the daily operation time of the system is 6 h, seawater RO unit was chosen to cover the daily water needs of the population. The technical characteristics of the unit are:

(1) The RO plant is operated at constant recovery ratio of 30%.
(2) Operating feed temperature is 25˚C.
(3) High pressure pump efficiency is 70%.
(4) Single pass-single stage three-element membrane unit.
(5) Membrane element (Filmtech SW30-4040).
(6) Average daily working duration is 6 h.
(7) Feed water concentration 1,000–25,000 ppm TDS.
(8) Product water concentration <500 ppm TDS.
(9) Fixed feed water flow rate.
(10) Fixed permeate quantity.

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.

2.3.1. 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 sulfate.

2.3.2. 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.

2.3.3. 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 (69 bar/1,000 psi is typical), firstly, to force the water through the mechanical constriction presented by the membrane and, secondly, 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. Unfortunately brine turbines cannot be engineered for small RO plants due to the low-brine flow rate [20]. In the last few years, much research is being done to develop energy recovery systems compatible with small RO plants. Some companies have developed systems to directly recover the hydraulic energy contained in the high-pressure brine [1].

2.3.4. 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 from 7.63 kWh/m^3 (3.16 kW) before recovery to 4.68kwh/m^3 (1.94 kW), which finally reduced the size of the hybrid energy system and the water production cost.

2.4. Design step 4. Modeling saline Water RO

2.4.1. Model description

ROSA 6.0.1 software is the latest version, used in the analysis in order to determine the performance of a membrane and energy requirements for desalination. The use of the model is influenced by the need to design a technically feasible RO system. The main inputs of the model include the amount of feed water and its chemical characteristics, feed water flow rate, feed water and concentrate feed pressures, temperature, and pH. Then a configuration of the number of membranes, pressure vessels, and type of membrane, and feed, and booster pumps is determined. After performing calculations, the model provides the

Table 2
Modeling brackish/saline RO unit

Feed flow rate	1.38 m^3/h
Feed pressure	9.83–33.9 bar
Power consumption	0.17–1.14 kw/h
Permeate TDS	8.7–160 ppm
Permeate product	0.43 m^3/h
Mixing	52–1,162 L

Table 3
The power and energy needs of the system

Type of load	Power (kW)	Duration (Hours)
High-pressure pump	1.2	6
Feed pump	0.250	6
Cleaning pump	0.1	0.1
Dosing pumps	0.25	4

amount of water produced and energy required. Booster pumps and an energy recovery turbine are applied (Table 2).

2.5. Design step 5. Calculation of the energy needs of the system

To calculate the energy needs of the system, first we calculated the total power requirements for the different parts of the system, given the maximum operation hours of the SWRO system, which is 6 h, the energy needs are shown in Table 3.

2.6. Design step 6. PV system sizing to cover 100% of energy needs

2.6.1. Step 6.1. PV module tracking and tilting angle manipulation 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 sunrise and ending at the azimuth angle at sunset. 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.

Table 4
Actual tilt angles measured during the whole year for AOI PV power plant together with the average values for each month

Month	Average bet. 7:30−2:30	Average bet. 10:30–11:30	Average
Jan.	55	50	53
	55	53	
Dec.	55	53	53
	55	50	
Nov.	55	50	49
	53	41	
Oct.	53	40	43
	52	30	
Sep.	52	28	38
	53	18	
Aug.	53	18	32
	52	9	
Jul.	52	9	30
	52	7	
Jun.	51	7	29
	51	9	
May	51	9	30
	46	18	
Apr.	53	19	38
	52	28	
Mar.	52	28	43
	53	41	
Feb.	53	41	49
	55	50	

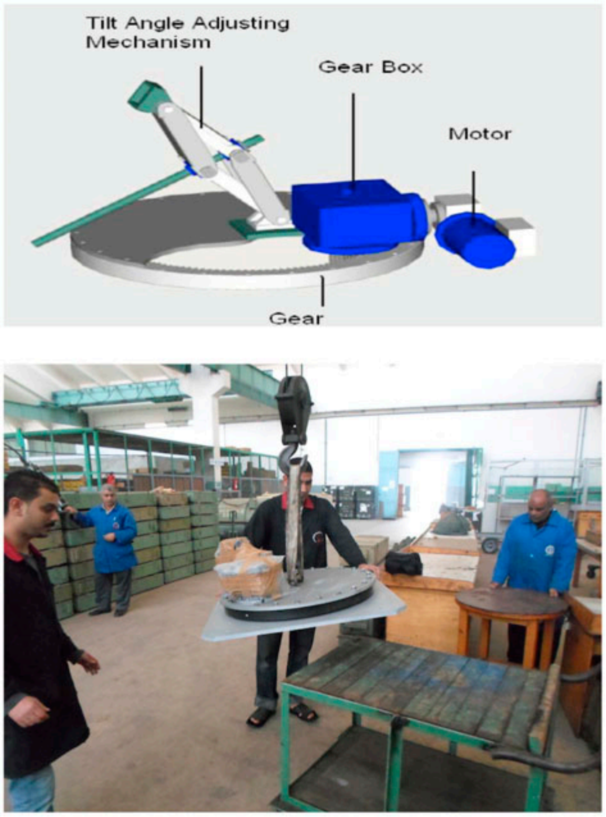

Fig. 4. Tracking mechanical drive.

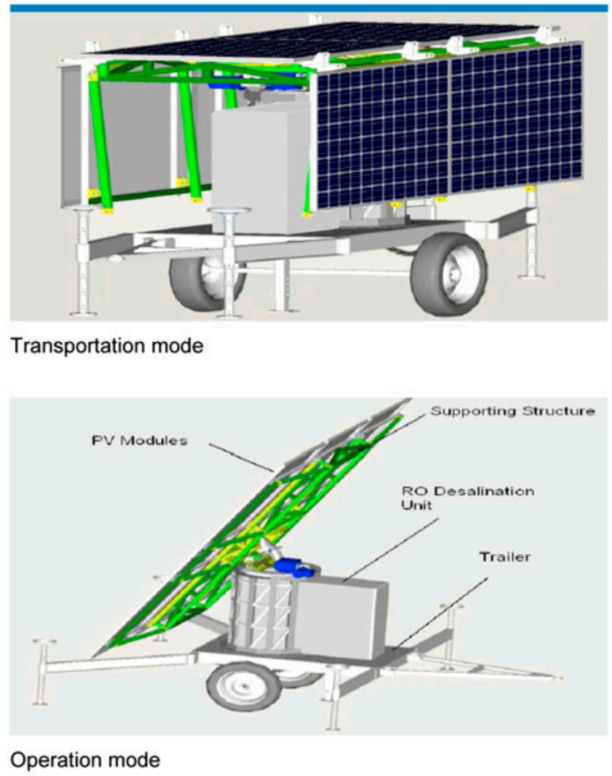

Fig. 5. Main structure design.

Thirty-six azimuth adjustment programs have been developed such that three programs for each month thus covering the whole calendar year. Actuation of the PV panel tilt for azimuth tracking and rotation of the PV panel for solar tracking are operated with a gear motor-based control system for adjusting the PV mounts system's position so as to collect maximum solar radiation. The gear motor controller module is built with low-cost microcontroller with built-in flexibility to accommodate seasonal position adjustments of the PV mounts. The system is configured for a solar radiation condition specific to the location of the system at the northwest coast. Tracking system will operate with PLC that will command the electric AC motor to rotate the PV panels at specific timings; a gearing system reduces motor speed to 22.5 deg/min. A proximity sensor detects that the correct azimuth incremental change is performed. The above-described steps are executed daily starting at sunrise time minus 30 min. The last command is to rotate the system to the standby position which is detected by the limit switch.

Moreover, adjusting the tilting angle of the PV modules will result in a power increase in 7–8%. A simple design is proposed for our PV tracking system. Twelve tilting angles for the whole calendar year are calculated. Actual tilt angles measured during the whole year for AOI PV power plant are used to determine with the average values for each month. A PLC is programmed to command an AC motor engaged to a liner screw actuator to adjust the tilt angles according to the calculated average values. Using the local meteorological data from the area of suggested application, the daily solar radiation at different tilt angles was recorded (Table 4).

Two DC gear motors with selected gear ratio, control the rotation of a dual-axis PV array along and the azimuth (tilt) tracking axis X, and the solar tracking axis Y as shown in Fig. 4.

2.6.2. Step 6.2. Peak PV power needs

When the temperature of a PV module is increased, the efficiency drops due to thermal loses in the PV system. Therefore, using a proper PV cooling system is a must to keep the temperature at ambient. Moreover, cleaning the PV panels from dust and dirt will also result in higher performance.

2.6.2.1. PV Cleaning system. Experts agree that power losses due to dust and dirt may range as high as 15% in some areas. According to the actual measurements at AOI, PV power plant 10% losses were found. The present task deals with the design of a simple solar panel cleaning system to automatically wash the PV modules. The solar panel cleaning subsystem will be controlled by a simple PLC to activate the PV cleaning process. The system can be programmed to wash PV modules at a frequency determined by dust and dirt conditions at the location of system deployment. A single nozzle will be attached to each PV solar panel. Water from the clean water tank is pumped to feed the cleaning nozzles with a copper or plastic line. A small DC pump is required to operate the system. Power requirements of the PV cleaning subsystem can be calculated as follow:

(1) Required fresh water for cleaning PV module = 1.5 L/m^2.
(2) Total cleaning time for all modules = 5 min.
(3) The required volume of fresh water for cleaning a single PV module is (1.3 × 2) × 1.5 = 4 L.
(4) For six PV modules the total required volume of fresh water is 24 L.
(5) The required flow rate of the cleaning fresh water is 0.3 m^3/h.
(6) To perform proper PV cleaning, experience has shown that the exit pressure of the cleaning nozzles should be 2–3 bars. Consequently, power requirement for the PV cleaning subsystem is 67 watt.

2.6.3. Step 6.3: Selecting PV modules and number

To satisfy total peak power requirements of the system, the PV generator will comprise efficient poly crystalline PV modules, a relatively high output power modules is selected to minimize the number of modules for better mobility considerations. The chosen PV panels are TOPSUN TS-S415 with a peak power of 415 W/module and an MPP voltage of 49.53 V/module. The interconnection of the selected PV modules (series/parallel) is configured so that the output voltage of the PV generator will fit with the input voltage of the inverter. A 5 kW off grid DC/AC inverter was selected (Table 5).

2.7. Design step 6. Design of mixing water system

ROSA data show that some water point, because of their low salinity after the desalination process, will be resulted in water product of very low

Table 5
Technical specification of the 5 kW off grid inverter

Model	PVES-005
I Input	
Maximum voltage	DC550 V
Voltage range (MPPT range)	DC200–510 V
II Output	
Nominal output power (kW)	5
Nominal AC voltage	AC220 V ± 10%
Nominal frequency range	50 Hz ± 5%
System specification	
MPPT efficiency	+99%
Conversion efficiency	+95%
Constant	Single phase
Control function	Auto start and stop/ MPPT/auto voltage regulation

Fig. 6. Main structure.

Fig. 7. Mobile PV/RO water desalination plant.

Table 6
Testing the efficiency of the PV/RO unit

Feed salinity (NaCl, mg/l)	Permeate salinity (mg/l)	Power (W)	SEC (Kwh/m^3)
5,000	32	866.4	1.9
6,200	32	1050.9	2.3
8,300	32	1162.8	2.6
10,500	65	1,143	2.5

salinity (less than 500 ppm). Low salinity water products are harmful for human body, but at the same time a good chance for water mixing. Mixing is a process to mix the low-salinity water product with feed water under controlled and calculated process to reach the target value of salinity (500 ppm). Thus, resulting in an increasing in the amount of permeate product. Mixing calculation shows that we will be able to increase the permeate product by 52–1,162 L.

2.8. Structural design and materials

The configuration of a foldable PV panel is selected for transportation considerations. The arrangement of PV panel is made as compact as possible such that the middle array is built of two PV modules, and two foldable modules are attached at each side of the middle array. The rotation about the normal axis to the ground is made by means of a slewing internally geared bearing that carries all the tracking system and is supported with a semicircular cage structure of suitable height to allow partial containment of the RO unit for compactness considerations. The pane-tilting requirement is realized using a scissor jack that is designed with single joint connections to avoid the complexity of the traditional design of the geared links (Fig. 5).

The structure carrying the PV modules is made by welding using standard square tubes 2´´ × 2´´ with various thicknesses (2.1, 3.2, 4.8, and 6.4) all are made of commercial steel grade 37 (with yield stress 210–235 N/mm2). Stress analysis was made for the panel carrying structure using software ANSYS 12.0,

Table 7
Complete analysis of groundwater sample (Raw), fresh water product (permeate), and reject of the PV/RO desalination unit

1. *Analysis of major cations and anions*

No.	pH	EC µs/cm		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Total cation (epm)	CO_3^-	HCO_3^-	SO_4^-	Cl^-	Total anion (epm)
Raw	7.6	10,930	ppm	168	280.7	1,600	65.0	102.69	9.0	271.45	550	3,200	106.43
			epm	8.38	23.08	69.57	1.66		0.30	4.449	11.44	90.24	
			%	8.16	22.48	67.74	1.61		0.282	4.180	10.75	84.79	
Reject	7.2	12,960	ppm	180.6	362.31	1980	90.0	127.19	21.0	289.75	1,100	3,720	133.23
			epm	9.01	29.8	86.09	2.29		0.70	4.749	22.88	104.90	
			%	7.08	23.43	67.68	1.80		0.525	3.564	17.17	78.74	
Permeate	7.5	53.7	ppm	3.0	2.9	11.0	1.0	0.892	0	7.32	9.0	21.50	0.913
			epm	0.15	0.24	0.478	0.026		0	0.12	0.19	0.61	
			%	16.78	26.74	53.62	2.86		0	13.13	20.49	66.37	

2. *Analysis of heavy metals (mg/l)*

Parameter	Raw	Reject	Permeate
Al	<0.04	<0.04	<0.04
B	2.094	2.375	0.8495
Cu	0.0071	<0.006	<0.006
Fe	0.0341	0.04	<0.01
Mn	0.0501	0.064	0.0038
Sr	10.58	12.81	0.0214
Zn	<0.07	<0.07	<0.07
SiO_2	8.939	10.57	Nil

the structure was modeled using frame and shell elements and solved under the above mentioned pressure loads on the PV modules (Fig. 6).

2.9. Complete system

The system is equipped with motorized valves for automatic operation as well as conductivity, pH, temperature, flow, and pressure meters. Alarm controls for these variables and pressure drop at the membrane automatically monitor a secure plant operation. The PV power generation unit is equipped with power meter as well as temperature sensor for monitoring electrical yield and PV cell temperature. The inverter converts variable DC level to fixed amplitude AC output with fixed frequency to actuate variable speed drive of the high-pressure pump (Fig. 7).

2.10. Testing for PV/RO water desalination plant

Factory testing for the PV power generator system with variable loads shows maximum power of 6.9 Amp. that can cover the power needed for the RO unit to desalinate all kind of water samples (brackish, saline, and sea). Meanwhile, testing of the PV/RO desalination plant using synthetic saline feed water contains NaCl with concentration (5,000–10,500 mg/l) shows permeate salinity ranged from 32 to 65 mg/l with specific energy consumption (SEC) from 1.0 to 2.6 kwh/m^3 (Table 6). Finally, Table 7 shows the complete analysis of feed, raw, and permeate water related to field working of the PV/RO unit. Results show that feed groundwater of salinity 10,930 μs/cm desalinated to be 53.7 μs/cm permeate water with SEC 1.7 kwh/m^3.

3. Summery and conclusion

This work focuses on the integration of brackish water and seawater RO desalination and solar PV technology. 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. 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 was achieved by maximizing energy yield through an integrated automatic single axis PV tracking system with programmed tilting angle adjustment. An autonomous cleaning system for PV modules was adopted for maximizing energy generation efficiency. RO plant components were selected so as to produce 4–5 m^3/d of potable water. A basic criterion in the design of this PV-RO prototype was to produce a minimum amount of fresh water by running the plant during peak sun hours. Results show that feed groundwater of salinity 10,930 μs/cm desalinated to be 53.7 μs/cm permeate water with SEC 1.7 kwh/m^3.

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