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SOLAR ELECTRIC POWERED REVERSE OSMOSIS WATER DESALINATION SYSTEM FOR THE RURAL VILLAGE AL MALEH: DESIGN AND SIMULATION

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Desalination of brackish water by using reverse osmosis (RO) system powered by solar PV has been till now not tried and examined in Palestine. This paper proposes the rural village Al Maleh for erection and testing of the first PV-powered RO system. Al Maleh is highly qualified for testing of such systems since it has a lot of mineral hot water springs of a salinity of about 3400 ppm. Based on the climate conditions in Al Maleh the paper presents the design of the PV-powered RO water desalination system. The obtained design results can be used for an economic feasibility study of this technology [Mahmoud, M. Techno-economic feasibility of PV-powered water desalination in Palestine. Special Case: Al Maleh Village (under preparation for publish).]. The performance of the designed system is investigated by software simulation. The obtained results show that a daily production of 1 m^3 from the brackish water in Al Maleh would require about 820 peak watt of PV generator.

Keywords: Solar powered water desalination; Photvoltaic power systems; RO-brackish water desalination

1 INTRODUCTION

Water and energy are the major factors necessary for development and prosperity of social and economic sectors in rural areas. Palestine has a large number of rural villages lacking for water and electricity networks as well as for internal asphalted roads and sewage systems.

Connecting these villages with electric grids of the nearest cities seems to be impossible, at least for the coming 10 years, due to their remoteness, thin population and low electric energy demands. On other hand, Palestine has one of the highest solar energy potential of all countries of the world. It enjoys over 2800 sunshine hours every year, with an annual average daily solar radiation intensity amounting to 5.4 kWh/m^2-day [1]. These figures are encouraging for utilization of solar energy for electricity generation and desalination of brackish water, especially in non-electrified rural villages. Brackish water is available in very large amounts in some areas of Palestine, particularly in Gaza Strip and in the Jordan Valley. Al Maleh Village, which is located directly on the main street connecting the town Toubas with the Jordan Valley, lacks for electricity and contains a lot of brackish water springs is a very qualified rural village for erection of a solar-powered water desalination pilot project.

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Implementation of such a project will demonstrate the provision of potable water through exploitation of the available brackish water and will have also the following results:

- Determination of the performance of reverse osmosis (RO) water desalination systems powered by solar electric energy under Palestinian weather and environmental conditions;
- Determination of techno-economic feasibility of using solar electric systems [photovoltaics (PV)] for desalination of brackish water;
- Identification the effects of desalination of brackish water on the environment, health and social conditions, in rural areas;
- And building up of local capabilities and expertise in the field of water desalination by solar electric systems.

A proposal on this pilot project will be submitted to international agencies for financing, where it will be the first solar electric powered demonstration RO-desalination project in Palestine. The implementation can be conducted and supervised by the Renewable Energy Research Centre of An Najah National University.

This paper illustrates the design and sizing of the proposed solar-electric powered RO desalination system, as well as the simulation results of the system.

2 THE PROJECT SITE – AL MALEH

The old Arabic traditional name of this village is Hammam Al Maleh which means Bath of Al Maleh. It is elevated at 12 m below sea level in the northern part of the Jordan Valley. It has about 70 inhabitants working mainly in cattle breeding.

Since the village contains hot mineral springs, it is usually visited in winter by many people for natural therapy. The village is known with hot summer months, where the monthly average of maximum temperature for the six months: April–September amount to 41 °C while the annual-daily average is 22.4 °C [1]. The village lacks for all services such as electricity, water networks and telephone.

The presence of mineral hot springs, its mild warm climate in winter and its rural location in a pasture land, make it a promising potential site, that its infra structure can be properly developed by solar energy systems. The village is qualified especially for ecotourism projects based on exploiting the mineral springs for natural therapy. For all these reasons we propose it for erection of the first demonstration project in Palestine using PV for water desalination.

A large number of brackish water springs in the village flow along a valley of about 1.5 km long to build a stream with a discharge specified here after [6]:

Month	*Litre/s*	*Month*	*Litre/s*
Jan	85	July	73
Feb	91	Aug	74
Mar	104	Sept	76
Apr	81	Oct	80
May	81	Nov	71
June	78	Dec	72
Total annual discharge: 2549×10^3 m^3/year = 291 m^3/hour			

The chemical analysis of the springs water are as follows [6]:

	mg/l		*mg/l*
TDS	3382.0	Cl	1763
Ca	350	SO_4	260
Mg	113.0	HCO_3	238
Na	725	NO_3	8
K	45.2		
Water temperature: 36 °C			
Conductivity: 6765 µs/cm			

The above mentioned data shows that the water is brackish and very appropriate for PV desalination. The product will be used as drink water by the villagers and the plant would demonstrate, for the first time in Palestine, the utilization of solar energy (PV) in water desalination.

3 WATER DESALINATION TECHNOLOGY

The desalination plants presently producing fresh water from saline water are operating mainly on the processes: multistage flash (MSF), vapor compression (VC), electro dialysis (ED) and reverse osmosis (RO). During the last decade, an increasing field of RO application for desalination of brackish water and sea water has been developed. The advantage of RO over the other processes is in the lower energy consumption. For example, while a MSF-plant requires approximately 3–5 kWh electrical energy plus about 60–80 kWh thermal energy per m^3 distillate, independent of the salt content of the raw water, the electrical energy requirements of RO-plants are about 5 kWh/m^3 of product for raw water with a salt content of 3500 ppm and increase to about 15 kWh/m^3 for sea water with salt content of 35,000 ppm [8–10]. Therefore, most renewable energy powered desalination plants are RO. Reverse Osmosis is a separation phenomenon, which separates fresh water from seawater or brackish water through semipermeable membranes. Admitting hydrostatic pressure of about 50 bar, which over compensates the osmotic pressure difference, desalinated water is separated from the concentrated phase through the membrane to the dilute phase. The obtained fresh water has a salinity in the range 300–500 ppm with a conductivity of about 450 µs/cm.

3.1 System Configuration

The construction of the proposed RO plant is illustrated in Figure 1 [11]. The brackish water is fed by the well pump into the raw water storage tank. Before entering the desalination system, the raw water passes a sand filter and a cartridge filter to remove excess turbidity or suspended solids, which may cause problems in pump operation and instrumentation, if they enter the RO system, may plug the flow passage or deposit on the membrane surfaces causing changes in product water and salinity. The two RO-modules are served by two high pressure piston pumps each of 1000 litre/h capacity at 55 bar. The feed water is distributed across the membranes by means of transverse stream filtration and by this a part of the water is desalinated as it permeates the membranes. The remaining brine is drained off. The pure water flows from the modules to a storage tank. The desalination plant is divided into two units so that in case of a break-down in one unit the remaining one is still operational. The operating pressure is adjusted by manually operated valves. The product water is stored in an intermediate tank.

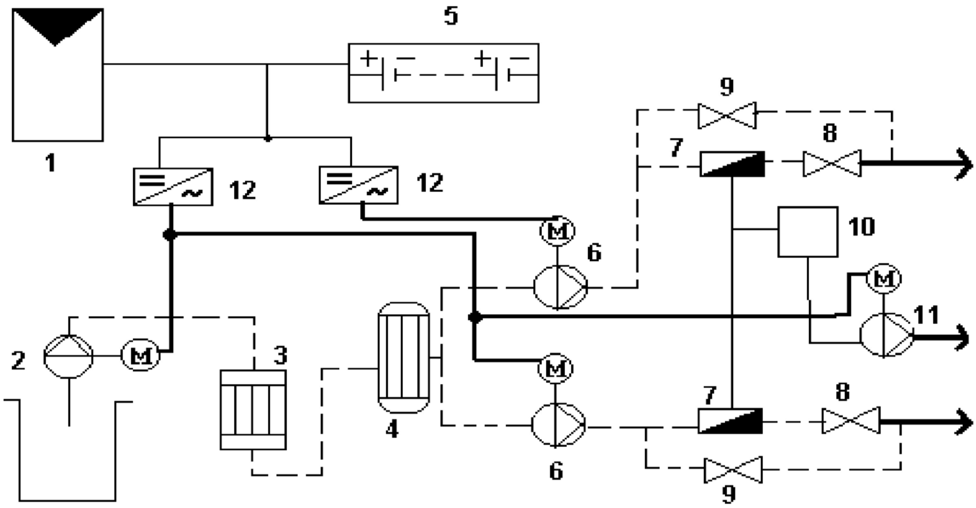

FIGURE 1 Block diagram of the proposed PV-powered RO desalination plant for brackish water in Al Maleh village. 1, Solar Generator; 2, Well Pump; 3, Sand Filter; 4, Cartridge Filter; 5, Battery Block; 6, High Pressure Pumps; 7, RO-Modules; 8, Regulating Valves; 9, Starting Valves; 10, Product Water Storage; 11, Product Water Pump; 12, DC/AC 3 Phase Inverter.

This potable water will be pumped to other storage tank where it can be chlorinated to prevent bacteria contamination.

3.2 System Design and Sizing

Design and sizing of the PV-powered RO desalination systems depend mainly on the daily fresh water requirement, salinity of brackish water and the climate parameters on the plant site [1–3] which are illustrated in Table I.

Salinity of brackish water	3382.06 mg/l (ppm)
Conductivity	6860 μs/cm
Temperature of brackish water	36 °C
Fresh water requirement (daily average)	10 m^3/day

The main goal of system sizing is to achieve the right balance between daily needs of electrical energy consumed by the loads and daily produced electrical energy by the PV generator. To achieve this we should start with the loads. The daily consumed electrical energy by the loads has to be identified at the beginning of system sizing, so as to calculate the daily needed PV electrical energy and the total peak power of the PV generator [4, 9].

3.2.1 Sizing the Brackish Water Pumping System

The RO-desalination plant should deliver 10 m^3/day. The efficiency of the RO unit that will be used is 50%, therefore, the daily amount of brackish water needed will be 20 m^3. The daily required hydraulic energy (E_h) is:

$$E_h = \rho g Q h,$$

TABLE I Design Parameters for the PV-Powered RO Desalination Plant

Month	*Solar radiation in Al Maleh (daily average) kWh/m^2-day*	*Temperature (°C) daily average*	*Relative humidity (%) daily average*	*Sunshine hours monthly totals (h) in Al Maleh*
Jan	3.01	13.5	69	182.3
Feb	3.38	14.9	65	177.5
Mar	5.05	17.5	59	241.1
Apr	6.7	21.5	50	29.1
May	7.05	25.7	44	275.2
Jun	8.34	28.5	44	355
Jul	7.69	29.9	45	344.6
Aug	7.29	29.8	48	356.5
Sep	5.92	28.5	51	305
Oct	4.65	25.1	55	267.4
Nov	3.28	19.7	62	191.7
Dec	2.65	14.6	71	189.8
Annual average	5.4	22.43	55.25	3177.1

where

ρ, standard water density $= 1000\,\text{kg/m}^3$,
G, gravity acceleration $= 9.81a\,\text{m/s}^2$,
h, total pumping head $= 8\,\text{m}$,
Q, daily needed brackish water $= 20\,\text{m}^3/\text{day}$.

The daily required energy from the PV generator (E_{PV}) is determined as [10]:

$$E_{\text{PV}} = \frac{E_{\text{h}}}{\zeta_{\text{inv}}}\zeta_{\text{mp}},$$

where

ζ_{inv}, efficiency of the DC/AC inverter $= 85\%$,
ζ_{mp}, efficiency of the motor-pump unit $= 50\%$.

The Peak Sun Hours (PSH) is calculated as:

$$\text{PSH} = \frac{E_{\text{sd}}}{G_{\text{o}}},$$

where

E_{sd}, the daily average of solar radiation intensity in Al Maleh $= 5.4\,\text{kWh/m}^2$-day,
G_{o}, the peak solar radiation intensity $= 1000\,\text{W/m}^2$.

Considering a safety factor of 1.25 the peak power of the PV generator (P_{PV}) is calculated as:

$$P_{\text{PV}} = \frac{(1.25 \times E_{\text{PV}})}{\text{PSH}}.$$

A small single phase surface motor pump (rated at 220 V, 50 Hz) [10] would be appropriate for this subsystem.

3.2.2 Sizing the RO System

The RO system consists of 2 units where each one will have the following specifications:

- Each unit will operate without interruption for 5 hours per day and will deliver 1 m^3 of fresh water per hour.
- Every 1 m^3 of processed fresh water needs about 2 kWh of electrical energy.
- The unit operates electrically at an input of $\sim 3 \times 380$ V and 50 Hz.

Therefore, the needed electrical energy by each RO-unit and the electrical rated power of the RO-unit are computable as E_{RO} and P_{RO} respectively. The required electrical energy from the PV generator for one RO-unit (E_{PVR}) is computed as:

$$E_{PVR} = \frac{E_{RO}}{\zeta_{inv} \times \zeta_{B} \times \zeta_{R}},$$

where

ζ_{inv}, efficiency of the DC/AC inverter = 85%,
ζ_{B}, efficiency of the storage batteries = 80%,
ζ_{R}, efficiency of the batteries charge regulator = 85%.

Considering a safety factor of 1.25, the actual PV peak power P_{PVR} for the two RO-units is computed as:

$$P_{PVR} = 2.5 \times \frac{E_{PVR}}{\text{PSH}}.$$

Adding to this power the PV peak power obtained for the pumping system, we obtain the total peak power of the PV generator for the RO-desalination system (P_{PVT}).

Substituting the climate and design parameters in the illustrated equations, we obtain the results shown in Table II

To satisfy the design requirements, the PV generator will consist of efficient PV-modules manufactured by Siemens – Germany (Type: SM55), which has the following characteristics:

Module area $A = 0.425\,m^2$
Short circuit current $I_{sc} = 3.45$ A
Open circuit voltage $V_{oc} = 21.7$ V
Maximum power point current I_{mp} @ STC = 3.15 A
aximum power point voltage V_{mp} @ STC = 17.3 V
Temperature coefficient of I_{sc}, $\mu I_{sc} = 0.0012$ A/K°
Temperature coefficient of V_{oc}, $\mu V_{oc} = 0.077$ V/K°
Cell temperature at NOCT = 45 °C

Note: STC: standard test conditions (Global irradiance = 1000 W/m^2, cell temperature = 25 °C, air mass = 1.5); NOCT: nominal operating cell temperature.

TABLE II Results of PV–RO System Design.

E_h (kWh/day)	0.436	P_{RO}	2
E_{PV} (kWh/day)	1.026	E_{PVR} (kWh/day)	17.3
PSH (hour/day)	5.4	P_{PVR} (kW_P)	8.009
$P_{PV}(W_P)$	237.5	P_{PVT} (kW_p)	8.28
E_{RO} (kWh/day)	10		

The IV–Curve of the PV-Module SM55 is shown in Figure 2

The interconnection of the PV-Modules (series/parallel) should be configured so that the output voltage of the PV generator will fit with the nominal voltage of the battery block and the input of the inverter. Figure 3 shows the interconnection of the PV generator.

With this circuit the PV generator will have the following electrical characteristics:

Open circuit voltage V_{oc}@STC = 390.6 VDC (=18 × 21.7 V)
Short circuit current I_{sc}@STC = 28.35 ADC (=9 × 3.15 A)
Total peak power, 8910 WP

It is clear from Figure 3 that we were obliged to raise the number of the necessary PV-modules from 150 to 162 to have an integer number of the parallel PV strings. Thereby, the PV peak power was enlarged by 660 Wp which cause the Safety Factor to increase from 1.25 to 1.35.

3.2.3 Sizing the Storage Battery Block

To facilitate a constant flow of fresh water output of the RO unit, a storage battery block specified as follows will be necessary.

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$$C_B = [(E_{PV} + E_{RO})/\text{DOD} \times \zeta_B)] \times N_a$$

where

C_B = storage capacity of the battery block in kWh
E_{PV} = energy required for pumping of brackish water.
E_{RO} = energy consumed by the RO-system.
N_a = days of autonomy.
DOD = depth ofdischarge = 75% which is the maximum allowable discharge percentage of battery block full charge.

N_a = 1.5 days, which means that the battery block will satisfy the loads without being charged for 1.5 days without sun. Therefore, the battery block capacity will amount to 27.565 kWh

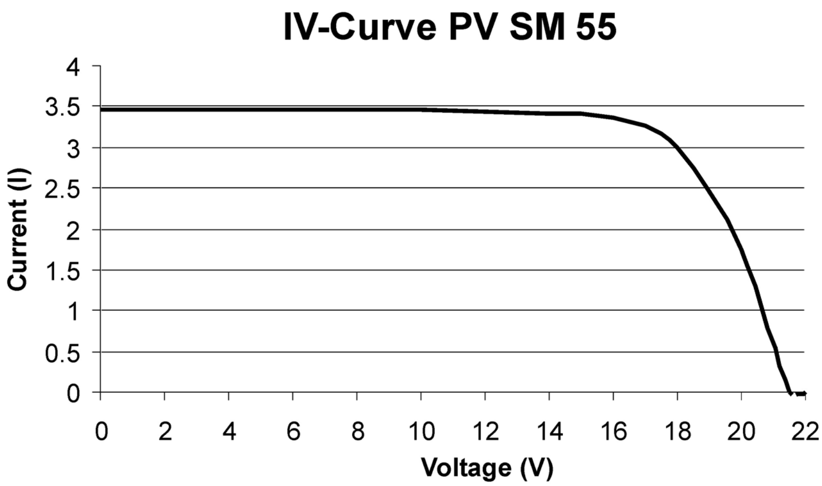

FIGURE 2 IV-curve for PV-module (Type SM55).

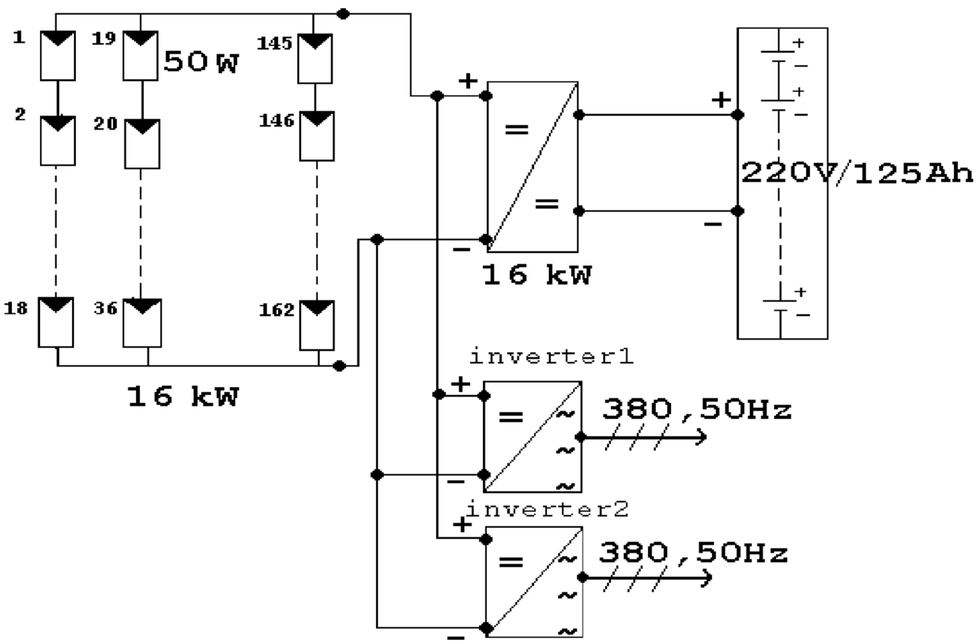

FIGURE 3 The interconnection of the PV generator (Slope 32°, Azimuth = 0°).

and will consist of 110 Lead-Acid battery cells of high cycling stability (>1000) connected in series each rated at 2 V/125 Ah.

3.2.4 Sizing the Inverters and the Charge Regulator

As shown in Figure 1, two identical inverters will be necessary. To satisfy the illustrated design, each inverter should have the following specifications: Nominal power: 5 kVA; Nominal maximum input voltage 400 VDC; Nominal output voltage 380 V, 3∼50 Hz; Output characteristic: constant voltage and frequency.

One charge regulator will be necessary to protect the battery block against deep discharge and overcharge. The specifications of this regulator are Nominal power as follows 10 kW; Nominal maximum input voltage – 380 VDC; Nominal output voltage – 220 VDC.

4 SIMULATION OF THE SYSTEM

The main purpose of simulation is to achieve preliminary conclusions about the system prior to its installation. In general, there are several primary points that are very important in any PV-simulation:

- The PV-module characteristics: these would be taken from manufacturer's data sheets of the selected PV-module illustrated in Figure 2.
- Daily load profiles: every load in the system has its own wattage and operation intervals during the day, these have to be recognized.

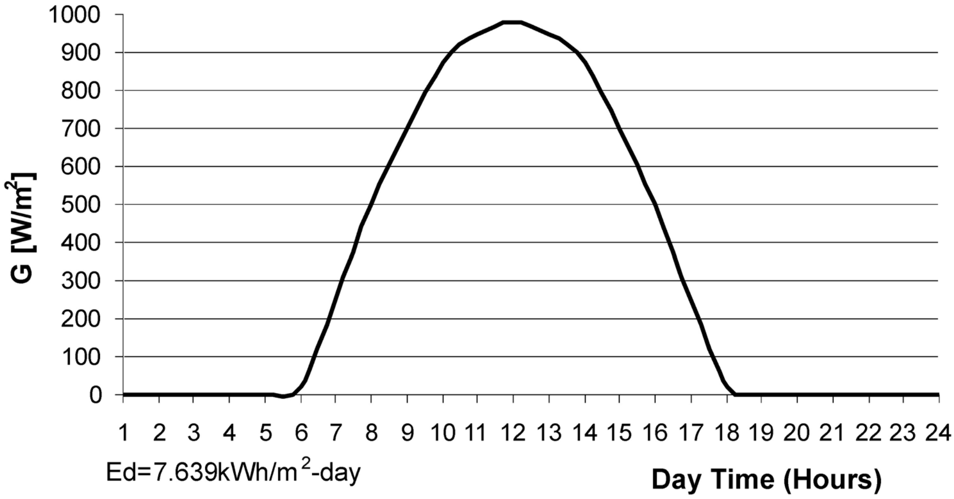

FIGURE 4 Solar radiation intensity according to SSD-model.

- Climatic data: climatic features of the selected site fluctuates dramatically from the annual average. Climatic parameters such as monthly averages of solar radiation sunshine duration, ambient temperature, mean wind speed, etc. affect the simulation process.
- The mathematical models used in the simulation: they are simplifications of what happens in nature and had been discussed in Section 3.

4.1 Simulation of Solar Radiation as a Function of Time

Solar radiation intensity (W/m^2), hourly and monthly-daily averages, through which the annual daily average of solar radiation (E_{sd}) is computable beside other climate parameters, are available. According to actual measurements (see Tab. I) in Al Maleh area $E_{sd} = 5.4\,kWh/m^2$-day. Selecting the model of 'Standard Solar Day' (SSD) for simulation is the most sophisticated

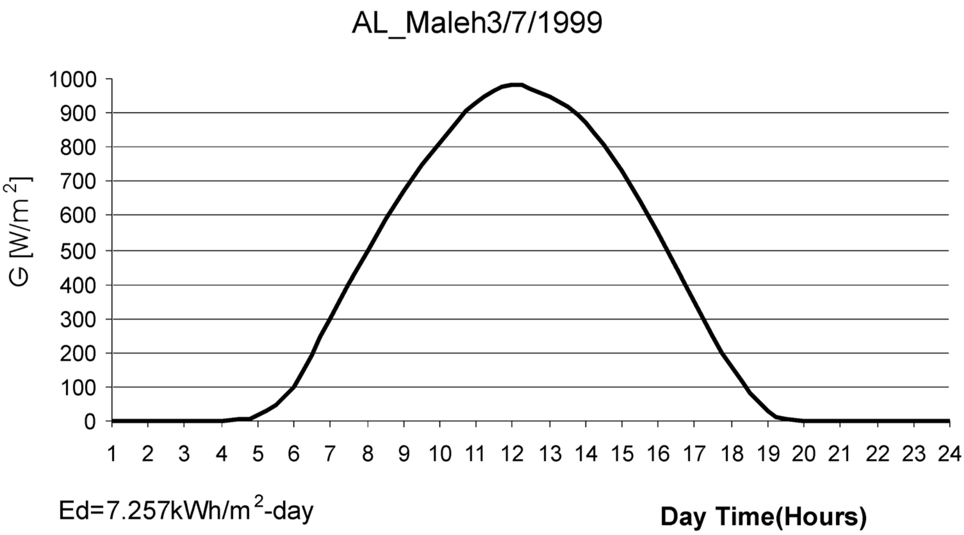

FIGURE 5 The solar radiation measurement in Al Maleh village area.

approach to predict the hourly out put of a PV system. Using the SSD-model, the solar radiation intensity would follow a sinusoidal pattern as shown in Figure 4.

$$G(t) = G_{\max} \sin\left(\frac{\pi t}{T}\right)$$

where $G(t)$ is instantaneous value of solar radiation intensity ($\mathrm{W/m^2}$); $G_{\max}$ is peak value of daily solar radiation intensity ($\mathrm{W/m^2}$); T is sunshine duration (length of SSD) (h).

The total daily solar energy on a surface E_{d} is the integral of $G(t)$:

$$E_{\mathrm{d}} = \int_0^T G(t)\,\mathrm{d}t = \int_0^T G_{\max} \sin\left(\frac{\pi t}{T}\right)\mathrm{d}t = \frac{2G_{\max}}{\pi}$$

$$G_{\max} = \frac{\pi E_{\mathrm{d}}}{2T}.$$

Hence, E_{d} and T must be known to simulate the solar radiation variation in function of time.

Figure 5 illustrates one day measurement in Al Maleh area where the variation of $G(t)$ coincides very well with the SSD-model illustrated in Figure 4.

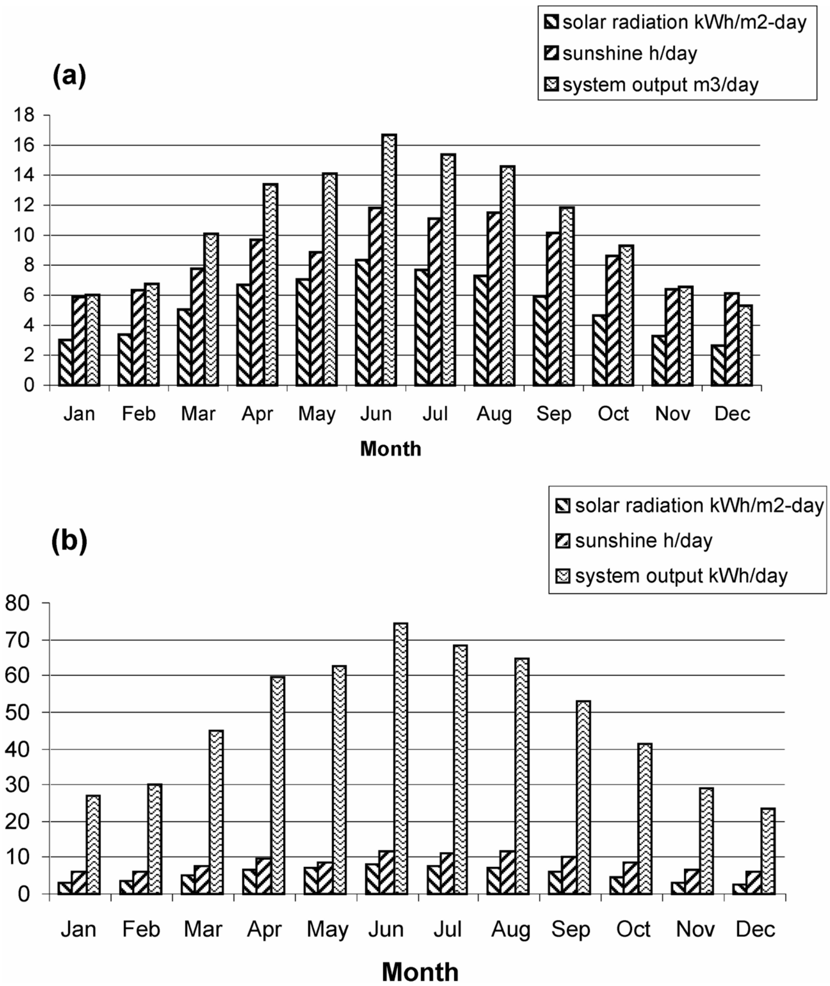

FIGURE 6 Simulation results of the PV-powered brackish water desalination system in Al Maleh village.

TABLE III Simulation Results of the PV-Powered Brackish Water Desalination System.

Month	E_{sd} *(kwh/m^2-day)*	E_{pvT} *(kWh/day)*	*M^3/day*
Jan	3.01	26.82	6.02
Feb	3.38	30.12	6.76
Mar	5.05	45	10.1
Apr	6.7	59.7	13.4
May	7.05	62.82	14.1
Jun	8.34	74.3	16.68
Jul	7.69	68.52	15.38
Aug	7.29	64.95	14.58
Sep	5.92	52.75	11.84
Oct	4.65	41.43	9.3
Nov	3.28	29.22	6.56
Dec	2.65	23.6	5.3

4.2 Simulation Results

Using the SSD-model, the mathematical models of the system components, considering NOCT for PV-modules and the measurement results of the climatic parameters illustrated in Table I, the simulation of the system using worksheet-based method (Software MS Excel) will deliver the results illustrated in Figure 6a and b and Table III.

4.3 Conclusions

The illustrated simulation results show that the desalination plant will produce 3962 m^3/year which corresponds to an average of 10.85 m^3/day. This means for Al Maleh a daily production of 1 m^3 fresh water would require 821.2 Watt PV-peak power.

As mentioned before the plant will operate for 5 h/day delivering $10.85/5 = 2.17$ m^3/h which is very close to the design criteria.

The simulation results show also that the water production varies linearly with the solar radiation intensity. It is obvious that this solar powered plant is matched with the seasonal daily consumption; it means that the system would produce about 3 times more fresh water in summer than in the cold winter months,where water consumption is less.

Moreover, a study of the author [11] had shown that the water cost of this plant would cost only about 0.7 of the water desalinated by utilizing conventional diesel generators. This result was obtained even the replacement of the storage batteries each 5 years had been considered.

The above mentioned results are encouraging to consider seriously the solar electric generators in stead of diesel generators, when planning to develop the infrastructure of non-electrified rural areas. However a prefeasibility study for each case should be carried out before making a final decision.

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