

# Design of photovoltaic system powered a small-scale SWRO desalination plant

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**Abstract:** This paper illustrates a proposed design to the Center for Solar Energy Research and Studies (CSERS) - Tajura, for the erection and testing of a stand-alone photovoltaic (PV) system for the powering of a small scale seawater reverse-osmosis (SWRO) desalination plant. The plant promises to deliver up to 0.25 m<sup>3</sup>/hour of potable water from seawater with a salinity of about 38,000 ppm and the osmotic pressure of 26.4bar.

In the current paper, ROSA Software by Dow chemical company was used to establish suitable membrane unit at this capacity. A unit of 4 inch of SW30-4040, with a feed pressure of 48 bar, and a salt recovery (R) of 20% with total dissolved solids (TDS) of 190ppm was selected.

Also results showed that, the electrical consumption of the SWRO plant was 2500 W, and the specific energy consumption was 10 kWh/m<sup>3</sup>. The size of the selected stand-alone photovoltaic (PV) system to power a SWRO plant with a mean production capacity of 1.5m<sup>3</sup>/day (6 hours operating per day), is 48V nominal voltage, 72 PV modules (shell SQ85-P), and 16 batteries with the capacity of 383Amp-Hour each.

## تصميم منظومة تحويل فولتضوئي لتغذية محطة صغيرة لتحلية مياه البحر تعمل بتقنية التناضح العكسي البشير خليفة الفقيه

مركز بحوث ودراسات الطاقة الشمسية. طرابلس-ليبيا

**ملخص:** هذه الورقة توضح التصميم المقترح لمركز بحوث ودراسات الطاقة الشمسية - تاجورا، لتركيب واختبار منظومة تحويل فولتضوئي منفصلة عن الشبكة لتغذية محطة بمقياس صغير لتحلية مياه البحر تعمل بتقنية التناضح العكسي. هذه المحطة صممت لتحلية مياه البحر بملوحة تبلغ حوالي 38,000 جزء من المليون ويضغط أسموزي 26.4 بار، لإنتاج 0.25 متر مكعب في الساعة من الماء العذب.

في هذه الدراسة استخدم برنامج روزا الصادر عن شركة داوو للكيمائيات وذلك لاختيار وحدة الأغشية المناسبة عند هذه الإنتاجية. وكان الغشاء المناسب من نتيجة البرنامج هو الغشاء نوع SW30-4040 , 4 بوصة، ومن نتائج التصميم أن الضغط الداخلي بلغ 48 بار ونسبة الاستخلاص 20 % وكمية الأملاح الذائبة للماء المنتج هي 190 جزءا من المليون. وجد كذلك أن استهلاك المحطة للكهرباء كان 2500 وات، وبلغ استهلاك الطاقة النوعية 10 كيلووات. ساعة لكل متر مكعب.

وكذلك فلقد وجد من نتائج تحجيم منظومة التحويل الفولتضوئي عند 6 ساعات تشغيل في اليوم وبمتوسط إنتاج يبلغ 1.5 متر مكعب في اليوم، أن مقدار الجهد كان 48 فولت، وعدد الألواح المستخدمة من نوع SQ85-P هو 72 لوح، وبلغ عدد البطاريات المستخدمة 16 بطارية بسعة 383 أمبير.ساعة لكل منها.

**Keywords:** Desalination, SWRO, Photovoltaic, Tajura

## 1. INTRODUCTION

The desalination plants presently producing freshwater from saline water are operating mainly on the processes: multistage flash (MSF), Multi effect distillation (MED), vapor compression (VC), electro dialysis (ED) and reverse osmosis (RO). Desalination with renewable energy resources is an attractive choice in places where fresh water is scarce, and raw (brackish or sea) water and renewable resources are available. Electricity for membrane desalination and thermal heat for phase-change desalination are the common types of energy used that could be supplied by renewable energy systems.

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 its lower energy consumption. For example, while a MSF-plant requires approximately 3–5kWh electrical energy plus about 60–80kWh thermal energy per m<sup>3</sup> distillate, independent of the salt content of the raw water, the electrical energy requirements of RO-plants are about 2-5 kWh/m<sup>3</sup> of product for raw water with a salt content of 3500 ppm and increase to about 15kWh/m<sup>3</sup> for sea water with salt content of 35,000 ppm [1]. For all the above reasons, reverse osmosis is becoming the technology of choice with

continued advances being made to reduce the total energy consumption and lower the cost of water produced.

The benefits of implementing renewable energy technologies with desalination systems are well known as illustrated in Figure 1 [2]. Solar photovoltaic PV-RO systems are considered one of the most promising options especially for small systems used in remote areas, where the electricity grid is very far from the plant and expensive to extend. Diesel generators could be used in these areas and constitute a lower capital cost; but fuel, transportation, and generator maintenance costs make their operations costly compared to renewable energy systems[3]. Stand-alone systems rely on PV power only, and they can comprise only PV modules and a load or can include batteries for energy storage.

The PV-RO technology has been implemented for the desalination of both brackish water (BW) and seawater (SW), yet only in small and medium systems (less than 75 m<sup>3</sup>). It is interesting to note that until 2010, no PV-RO experimental study has been done on a larger scale. Most systems have been developed in different parts of the world with intense fresh water scarcity but in the same time with abundant solar energy potential (e.g Mediterranean region, Australia, North Africa and Middle East).

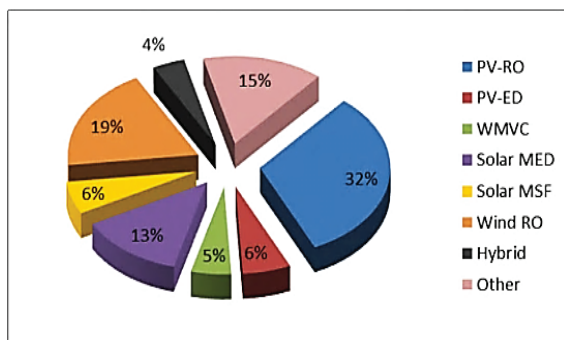


Figure (1). Distribution of renewable energy powered desalination technologies [2].

This paper illustrates the design and sizing of the proposed photovoltaic system powered SWRO desalination plant.

## 2. THE PROJECT SITE - TAJURA

Libya as many other countries in the arid region is dependent on groundwater resources, which are in short supply. However, it has an infinite water resource available in the coastal towns and cities being located on the Mediterranean Sea with 1950 km coast, albeit of a highly saline nature in the range between 35000 ppm to 38000 ppm [4]. Therefore, seawater desalination is vital for the present and future water demand in Libya and must be considered for application in remote areas characterized by high solar insolation and where the electricity grid is very expensive to extend.

The Center for Solar Energy Research and Studies (CSERS) located in Tajura-Tripoli, needs currently small scale Photovoltaic powered seawater desalination system for research and development activities. The Center has a site for this project on Tajura coast beside the seawater desalination plant

(SWRO) by capacity 10,000 m<sup>3</sup>/day for Nuclear Research Center (NRC), and Tajura raw seawater analysis shown in Table 1. This location is at Latitude: 38.52°N, Longitude: 121.50°W, as shown in Figure 2.

## 3. PV-RO SYSTEM

Sunlight can be converted to electricity by using solar cells which can be connected together to form Photovoltaic module (PV). PV is used to provide electric power for many applications, among them, small scale seawater reverse osmosis (SWRO) desalination system.

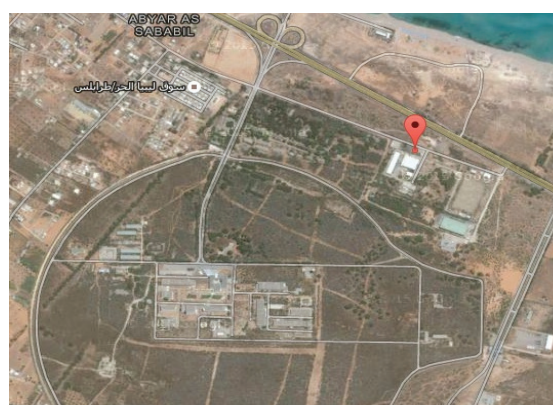


Figure (2). The project site - Tajura

Table (1). Tajura raw seawater analysis [4]

Components	Seawater composition (mg/l)
Calcium Ca <sup>++</sup>	455
Magnesium Mg <sup>++</sup>	1427
Sodium Na <sup>+</sup>	11600
Potassium K <sup>+</sup>	419
Silica Si <sup>+</sup>	2
Sulphate SO <sub>4</sub>	2915
Chloride Cl <sup>-</sup>	20987
Bicarbonates HCO <sub>3</sub>	133
Nitrate NO <sub>3</sub>	0
TDS	37938
PH	8 (without unit)

The construction of the proposed PV-SWRO plant is illustrated in Figure 3, PV-

SWRO plant design of single stage system with capacity of 6 m<sup>3</sup>/day, consists of the following components: 1- Feed water unit, 2 - Pretreatment system, 3- High pressure pump, 4- Membrane element unit, 5- Permeate treatment and storage unit, 6- PV panels, 7- Inverter, 8- Batteries.

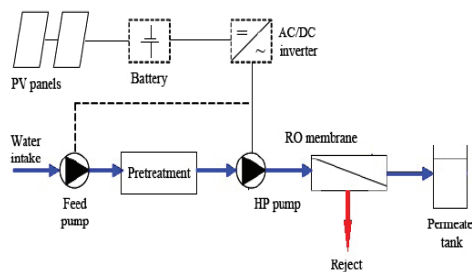


Figure (3). Schematic diagram of SWRO desalination plant with capacity of 6 m<sup>3</sup>/day

#### 4. RESULTS OF DESIGN AND SIZING

Design and sizing of the PV-powered RO desalination systems depend mainly on the daily fresh water requirement, salinity of seawater and the climate parameters on the plant site.

##### A. Design of SWRO plant

The daily production of desalinated water (Permeate)  $M_d$  is 6 m<sup>3</sup>/day, so the hourly production rate of desalinated water ( $M_h$ ) is 0.25 m<sup>3</sup>/hr.

The open intake (SDI < 5) system of Tajura desalination plant consists of raw seawater feed pipes and raw seawater basin. Seawater from Mediterranean Sea is fed by gravity through submersed two pipelines 1300 m, 60 cm Length and Diameter pipe

respectively, and the seawater basin capacity of 2880 m<sup>3</sup>.

Design of seawater Reverse Osmosis plant spiral wound membrane by the Dow chemical Company for Filmtec elements 4» were selected in the design, and used ((FilmTec ROSA Software, Version 7.2)) to select membrane elements unit [5][6].

FILMTEC SW30-4040 as shown in Table 2, defined as membrane element have the highest flow rates available to meet the water demands of both sea-based and land-based desalinates, may also be operated at lower pressure to reduce pump size, cost and operating expenses. Membrane type from Polyamide thin-film composite.

The number of elements needed (NE):

$$(NE) = \frac{\text{The total membrane area } (A_m)}{\text{Active area of element } (A_E)} \quad (1)$$

The total membrane area:

$$A_m = \frac{1000 \times M_h}{\phi} \quad (2)$$

Where:  $\phi$  = The average fluxes of 4 inch element seawater desalination =17 L/(hr .m<sup>2</sup>) [6].

Table (2). Specifications of 4 inch SW30-4040 membrane for seawater

Active area $A_E$ (m <sup>2</sup> )	Permeate flow rate( m <sup>3</sup> /day)	Applied Pressure (bar)	Salt Rejection (%)
7.4	7.4	55	99.4

- 1000 convert from m<sup>3</sup> to liter.
- $M_h$  = is the hourly production rate of desalinated water 0.25 m<sup>3</sup>/ hr.

So the number of total elements (NE) 1.98 (from the above Equations) = 2 elements

of SW30-4040 membrane in one pressure vessel.

All this data given to ROSA Software for Dow Membranes Company as shown in Figure 4, to calculate feed pressure, TDS for product water, and required power energy for membranes unit. All the results for membrane unit from ROSA software are shown in Table 3, and Table 4.

Osmotic pressure (bar)	26.4
Total membrane area (m <sup>2</sup> )	14.7
Pass Average Flux (lmh)	17.03
PH of Permeate	5.5

The feed flow rate of the membranes unit ( $M_f$ ):

$$\% R = \frac{M_h}{M_f} \times 100 \quad (3)$$

$$M_f = 1.25 \frac{m^3}{hr}$$

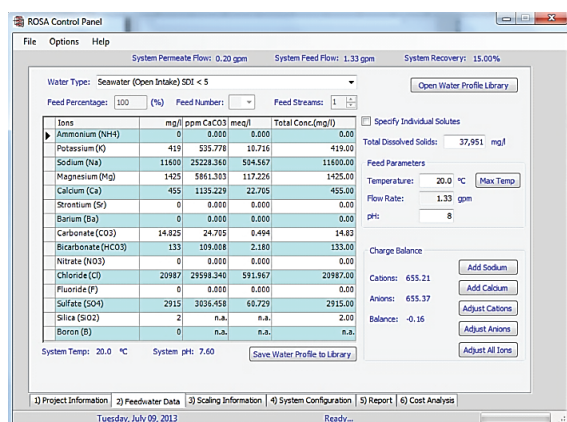


Table (4). The results for permeate and brain analysis

Name	Feed	Concentrate	distilled
K	419	522.92	3.25
Na	11599.9	14495.92	65.97
Mg	1426.9	1782.96	2.83
Ca	455	568.51	0.88
CO3	14.27	1.33	0
HCO3	127.9	155.79	2.24
Cl	20987	26204.9	111.89
SO4	2941.6	3705.78	1.93
SiO2	2	2.49	0.02
CO2	0.7	12.54	12.18
TDS	37973.9	47440.6	189.02
pH	8	6.83	5.5

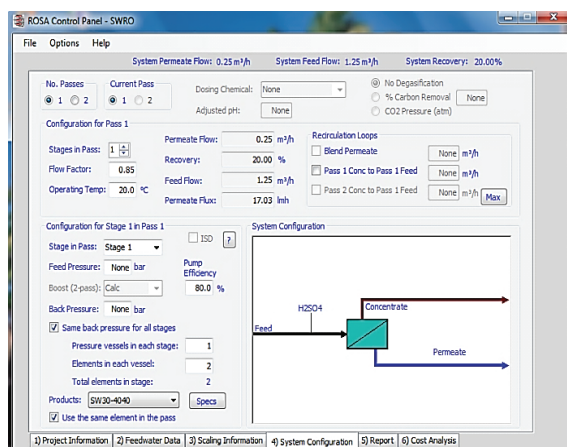


Figure (4). ROSA software of Dow Membranes Company

Table (3). Results for membrane unit from ROSA software

Power (KW)	2.07
Feed pressure (bar)	47.7
TDS Permeate (ppm)	189
Recovery (%)	20
Specific energy (KWh/m <sup>3</sup> )	8.3

The pretreatment system is the most important part of the plant. This system allows the membranes to perform according to the design .The pretreatment system is designed as follows:

1. Disc filters.
2. Chemical Dosing for Feed water.

$$M_{f,(intake)} = \frac{M_f}{R(1 - \beta)} \quad (4)$$

Disk filter is used for the micro filtration of solids, a very robust, mono block piece of machinery, with a minimum mesh of 20

microns and maximum 200 microns.

The seawater flow needed from the intake [7]:

Where:  $\beta$  is the fraction feed water lost at the pre-treatment plant (typically between 3% and 15%, depending on the process), in this process the water lost from pretreatment is almost 3 % at recovery (R) 98%.

$$M_{f(\text{intake})} = 1.35 \frac{\text{m}^3}{\text{hr}}$$

2 filters  $\frac{3}{4}$  inches disc filter size was selected at seawater flow 1.35 m<sup>3</sup>/hr, the disc material is from Polypropylene, filter body & cover from Reinforced polyamide, clamps from Stainless steel, and the filtration area was 0.016 m<sup>2</sup> for each one.

Chemical dosing for feed water by acid addition (Sulfuric acid) as antiscalent processes.

Scaling of SWRO membranes may occur when sparingly soluble salts are concentrated within the element beyond their solubility limit. The tendency for CaCO<sub>3</sub> scaling has been traditionally predicted by the Langelier Saturation Index (LSI) method (Langelier, 1936) [6].

$$\text{LSI} = \text{pH (actual)} - \text{pH}_s \quad (5)$$

Where:  $\text{pH}_s$  = pH of solution if it were in equilibrium with CaCO<sub>3</sub>, i.e.:

$$\text{pH}_s = \text{p}_{\text{Ca}} + \text{p}_{\text{Alk}} + C_{(\text{T,TDS})} \quad (6)$$

Where:

$\text{p}_{\text{ca}}$  = log of Ca<sup>++</sup> concentration

$\text{p}_{\text{Alk}}$  = log of HCO<sub>3</sub> alkalinity

$C_{(\text{T,TDS})}$  = constant to include temperature

and TDS

At higher ionic strengths (seawater), the Stiff and Davis Index is a more accurate predictor of scaling tendency.

$$\text{SD} = \text{pH (actual)} - \text{pH}_{\text{SD}} \quad (7)$$

Where: SD = Stiff and Davis Index

$$\text{pH}_{\text{SD}} = \text{p}_{\text{Ca}} + \text{p}_{\text{Alk}} + K_{(\text{T,IS})} \quad (8)$$

Where: K=constant to include temperature and ionic strength.

To control calcium carbonate scaling by acid addition alone, the LSI or S&DSI in the concentrate stream must be negative. The scaling results for membrane unit from ROSA software are shown in Table 5.

Table (5). Scaling results (ROSA software)

	Raw Water	Adjusted Feed	Concentrate
pH	8	6.75	6.83
Langelier Saturation Index (LSI)	0.95	-0.31	-0.04
Stiff & Davis Stability Index (SD)	-0.04	-1.3	-1.11
Ionic Strength (Molal)	0.79	0.79	0.99
TDS (mg/l)	37973.97	37992.03	47440.6
HCO <sub>3</sub>	127.98	125.6	155.79
CO <sub>2</sub>	0.7	12.29	12.53
CO <sub>3</sub>	14.27	0.79	1.33
CaSO <sub>4</sub> (% Saturation)	22.26	22.43	29.3
SiO <sub>2</sub> (% Saturation)	1.59	1.69	2.12
Mg(OH) <sub>2</sub> (% Saturation)	0.49	0	0
Dosing rate of Sulfuric acid	23.97 mg/l		-

In SWRO desalination systems, electricity is a major consideration to sizing

$$\text{bhp} = \frac{(Q) \times (P)}{(36) \times (\zeta)} \quad (9)$$

the Photovoltaic. Power consumption by the system includes power for seawater

pumping (Booster pump), high-pressure pumping, and chemical treatment pumping. The power requirement of each pump is calculated using the equation:

Where Q rate of flow, p is pressure of the pump, and  $\zeta$  is efficiency of pump.

The Booster pump pumps the raw seawater from intake basin to the pretreatment stage with pressure 4 bar, 80% efficiency of the pump and power 0.2 kW. The high pressure pump pumps to membranes with pressure 48 bar, 80% efficiency of the pump and power 2.2 kW. And 0.1kW for the chemical treatment pumps (feed and Permeate water treatment).

The electrical consumption of SWRO plant was 2.5 kW. Specific energy consumption of SWRO plant was 9.6 kWh/m<sup>3</sup>.

Post treatment (Treatment of permeate) is a two stage treatment process of product water by adding the chemical materials, pH adjustment and the chlorination, as shown in Table 6.

**Table (6). Chemicals additions for permeate water treatment**

The Chemicals additions	Dosing rate (Kg chemical/Kg H <sub>2</sub> O)	Dosing rate (Kg chemical /hr)
Calcium Hydroxide (pH Adjustment)	1.4E-05	0.7
Sodium hypochlorite (Chlorination)	4E-06	0.2

### B. Sizing of stand-alone PV system:

Sizing of a stand-alone PV power system means determining how much energy is required to run the system and how many PV modules are needed to generate it. A PV system has to generate enough energy to

cover the energy consumption of the loads on RO plant.

The energy yield of a PV system as illustrated in Table 7, depends on the type of PV modules, shell SQ85-P modules used in this project, specification of module shown in Table 8, and also depend on the meteorological conditions for solar radiation and ambient temperature in Tajura.

**Table (7). System specifications**

All loads AC	220 volts
Nominal DC system voltage	48 volts
Inverter efficiency	90 %
Battery Bus voltage	24 volts
Inverter ac voltage	220 volts
Inverter power output	3000 watt
Days of storage desired/required	7 days
The number of hours used per day	6 hours
Battery efficiency	80 %
The average peak sun shine hours in Tripoli	5 hours
PV module	SQ85-P
Capacity of selected battery	383 Amp-Hour
Selected battery voltage	12 volts

**Table (8). Specification of model shell SQ85-P**

Short circuit current I <sub>sc</sub>	5.45A
Open circuit voltage V <sub>oc</sub>	22.2V
Maximum system Open circuit voltage	600V
Rated power	85W
Rated circuit	4.95A
Rated voltage	17.2V

Estimate of the sizing of a PV array and batteries can be calculated using the following design rules [8]:

- Determine the total load current and operational time
- Determine total solar array current requirements
- Determine optimum module arrangement for solar array

- Determine battery size.

1. Determine the total load current and operational time:

Before starting determining the current requirements of loads of a PV system one has to decide the nominal operational voltage of the PV system. 24V nominal voltage. When knowing the voltage, the next step is to express the daily energy requirements of loads in terms of current and average operational time expressed in Ampere-hours [Ah].

In case of AC loads the energy use has to be expressed in the DC energy requirement since PV modules generate DC electricity. The DC equivalent of the energy use of an AC load is determined by dividing the AC load energy use by the efficiency of an inverter, which is typically 90%. By dividing the DC energy requirement by the nominal PV system voltage the Ah is determined.

The daily energy requirements of the pumps expressed in DC Ah are calculated as follows:

$$\text{Maximum DC power} = \frac{\text{Total energy demand}}{\text{efficiency of an inverter}} \quad (10)$$

$$\text{Total amp - hour demand} = \frac{\text{Maximum DC power}}{\text{nominal voltage}} \quad (11)$$

- a) Booster pump:  $200\text{W} \times 6\text{h} = 1200\text{Wh}$
- b) High pressure pump:  $2200\text{W} \times 6\text{h} = 13200\text{Wh}$
- c) Chemical treatment pumps:  $100\text{W} \times 6\text{h} = 600\text{Wh}$

Maximum AC power requirement:  $200 + 2200 + 100 = 2500\text{W}$

Total energy demand per day is 15,000Wh

Maximum DC power requirement:  
 $15,000\text{Wh} / 0.9 = 16,667\text{Wh}$

Total amp-hour demand per day:  
 $16,667\text{Wh} / 48\text{V} = 347.23\text{Ah}$ .

2. Determine total solar array current requirements:

The current that has to be generated by the solar array is determined by:

Total current generated:

$$= \frac{\text{Total amp - hour demand}}{\text{the average peak sun hours} \times \text{Battery efficiency}} \quad (12)$$

The required total current generated by the solar array is  $347.23\text{Ah} / (0.8 \times 5\text{h}) = 86.8\text{A}$ .

3. Determine optimum module arrangement for solar array:

Usually the PV module producers manufacture a whole series of modules that differ in the output power. The optimum arrangement of modules is the one that will provide the total solar array current (as determined in step 2) with the minimum number of modules. Modules can be connected in series or in parallel to form an array. When modules are connected in series, the nominal voltage of the PV system is increased, while the parallel connection of modules results in a higher current in the PV system.

The number of modules in parallel is calculated by dividing the total current required from the solar array (determined in step 2) by the current generated by module at peak power (rated current). The number of modules in series is determined by dividing the nominal PV system voltage



with the nominal module voltage. The total number of modules is the product of the number of modules required in parallel and the number required in series.

PV-modules Shell (SQ85-P) are available at the center, and the specification of these modules is given in Table 8.

The required total current generated by the solar array is 86.8A. The rated current of a module is 4.95A. The number of modules in parallel is  $86.8\text{A}/4.95\text{A} = 18$  modules. The nominal voltage of the PV system is 48V and the nominal module voltage is 12V. The number of modules in series is  $48\text{V}/12\text{V} = 4$  module. The total number of modules in the array is  $18 \times 4 = 72$  modules.

#### 4. Determine battery size:

Batteries are a major component in the stand-alone PV systems. The batteries provide load operation at night or in combination with the PV modules during periods of limited sunlight. For a safe operation of the PV system one has to anticipate periods with cloudy weather and plan a reserve energy capacity stored in the batteries. This reserve capacity is referred to as PV system autonomy, which means a period of time that the system is not dependent on energy generated by PV modules, and is rated in days. The system autonomy depends on the type of loads.

The capacity [Ah] of the batteries is calculated by multiplying the daily total DC energy requirement of the PV system including loads and system losses (calculated in step 1 and expressed in Ah) by the number of days of recommended

reserve time. In order to prolong the life of the battery it is recommended to operate the battery using only 80% of its capacity. Therefore, the minimal capacity of the batteries is determined by dividing the required capacity by a factor of 0.8.

The total DC requirements of loads plus the system losses are 347.23Ah.. Battery capacity required by the system is  $347.23\text{Ah} \times 7\text{days} = 2430.6\text{Ah}$ . The minimal battery capacity for a safe operation is  $2430.6\text{Ah}/0.8=3038.3\text{Ah}$

Number of batteries in parallel is the minimal battery capacity by Amp-Hour capacity of selected battery:  $3038.3\text{Ah} / 383\text{Ah} = 8$  batteries. Number of batteries in series is Nominal DC system voltage by selected battery voltage:  $48 / 24 = 2$  batteries. The total batteries:  $8 \times 2 = 16$  batteries.

#### C. The system performance:

The following product water flow rate predictions as shown in Figure 5, are based on monthly average of solar radiation in Tajura, and these predictions are realizable [1].

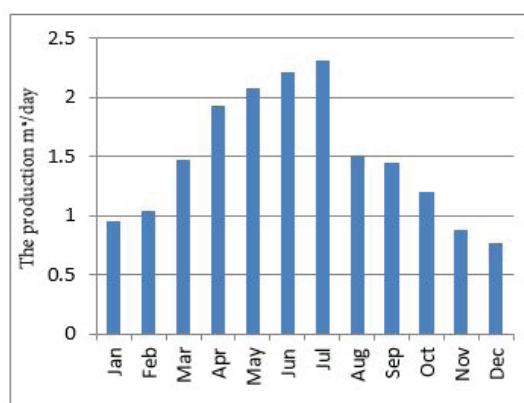


Figure (5). Product water flow, monthly average

From the monthly data available, it has

been seen that the plant operates for an average of 8 hours per day (2.2 m<sup>3</sup>/day) in the summer, and 3.5 hours in the winter (0.86 m<sup>3</sup>/day), an annual average of production capacity is 1.5 m<sup>3</sup>/day

## 5. CONCLUSION

This paper investigates a design system of small-scale stand-alone photovoltaic system incorporating seawater reverse osmosis (SWRO) plant, providing up to 0.25 m<sup>3</sup>/hour of potable water (operating at 48 bar), the plant will operate for 6 h/day. The implementation will be conducted and supervised by the Center for Solar Energy Research and Studies (CSERS). ROSA Software is a design program that predicts the performance of membranes in user specified systems, SW30-4040 element was selected in the software. PV-powered desalination units is coupled with a battery and an inverter.

From the monthly data available and product water flow rate predictions, we can see that the plant will operate for a maximum of 8 hours in the summer.

In general PV-SWRO technology is definitely less complex to operate and more environmentally friendly. Also ROSA Software is a powerful tool to membrane unit design.

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