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 m³/hour of potable water from seawater with a salinity of about 38,000 ppm and the osmotic pressure of 26.4 bar.

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 190 ppm was selected.

Also results showed that, the electrical consumption of the SWRO plant was 2500 W, and the specific energy consumption was 10 kWh/m³. The size of the selected stand-alone photovoltaic (PV) system to power a SWRO plant with a mean production capacity of 1.5 m³/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.
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 m3 distillate, independent of the salt content of the raw water, the electrical energy requirements of RO-plants are about 2.5 kWh/m3 of product for raw water with a salt content of 3500 ppm and increase to about 15kWh/m3 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 m3). 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).

**Keywords:** Desalination, SWRO, Photovoltaic, Tajura
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 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 electric 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 m³/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.

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

| Components   | Sweater composition (mg/l) |
|--------------|----------------------------|
| Calcium Ca++ | 455                        |
| Magnesium Mg++ | 1427                   |
| Sodium Na+  | 11600                      |
| Potassium K+ | 419                        |
| Silica Si+   | 2                          |
| Sulphate SO4 | 2915                       |
| Chloride Cl- | 20987                      |
| Bicarbonates HCO3 | 133            |
| Nitrate NO3  | 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 m³/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 m³/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 m³/day, so the hourly production rate of desalinated water ($M_h$) is 0.25 m³/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 m³.

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):

$$NE = \frac{\text{The total membrane area} (A_{m})}{\text{Active area of element} (A_{e})}$$

(1)

The total membrane area:

$$A_{m} = \frac{1000 \times M_h}{\phi}$$

(2)

Where: $\phi$ = The average fluxes of 4 inch element seawater desalination =17 L/(hr .m²) [6].

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

| Active area $A_e$ (m²) | Permeate flow rate( m³/day) | Applied Pressure (bar) | Salt Rejection (%) |
|------------------------|-----------------------------|------------------------|-------------------|
| 7.4                    | 7.4                         | 55                     | 99.4              |

- 1000 convert from m³ to liter.
- $M_h$ = is the hourly production rate of desalinated water 0.25 m³/ 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.

![ROSA software of Dow Membranes Company](image)

**Figure (4).** ROSA software of Dow Membranes Company

| Power (KW) | 2.07 |
|-----------|------|
| Feed pressure (bar) | 47.7 |
| TDS Permeate (ppm) | 189 |
| Recovery (%) | 20 |
| Specific energy (KWh/m³) | 8.3 |

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

| Osmotic pressure (bar) | 26.4 |
|------------------------|------|
| Total membrane area (m²) | 14.7 |
| Pass Average Flux (lmh) | 17.03 |
| PH of Permeate | 5.5 |

The feed flow rate of the membranes unit (M₁):

\[
\% R = \frac{M_h}{M_f} \times 100
\]

\[
M_f = 1.25 \frac{m^2}{hr}
\]

**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 | 0.33        | 0        |
| HCO₃ | 127.9 | 155.79      | 1.93     |
| Cl   | 20987 | 26204.9     | 111.89   |
| SO₄  | 2941.6 | 3705.78     | 1.93     |
| SiO₂ | 0.7  | 12.54       | 12.18    |
| CO₂  | 0.7  | 12.54       | 12.18    |
| TDS  | 37973.9 | 47440.6     | 189.02   |
| pH   | 8    | 6.83        | 5.5      |

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.

\[
M_{f(\text{intake})} = \frac{M_f}{R(1 - \beta)}
\]

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]:

\[ M_{(\text{intake})} = 1.35 \text{ m}^3/\text{hr} \]

2 filters ¾ inches disc filter size was selected at seawater flow 1.35 m³/hr, the disc material is from Polypropylene, filter body & cover from Reinforced polyamide, clamps from Stainless steel, and the filtration area was 0.016 m² 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 CaCO₃ scaling has been traditionally predicted by the Langelier Saturation Index (LSI) method (Langelier, 1936) [6].

\[ \text{LSI} = \text{pH (actual)} - \text{pH}_{s} \]  

(5)

Where: \( \text{pH}_{s} \) = pH of solution if it were in equilibrium with CaCO₃, i.e.:

\[ \text{pH}_{s} = \text{p}_{\text{Ca}} + \text{p}_{\text{Alk}} + C_{(\text{T,TDS})} \]  

(6)

Where:

\( \text{p}_{\text{Ca}} = \log \text{of Ca}^{2+} \text{ concentration} \)
\( \text{p}_{\text{Alk}} = \log \text{of HCO}_3 \text{ alkalinity} \)
\( C_{(\text{T,TDS})} = \text{constant to include temperature and TDS} \)

\[ \text{SD} = \text{pH (actual)} - \text{pH}_{SD} \]  

(7)

Where: SD = Stiff and Davis Index

\[ \text{pH}_{SD} = \text{p}_{\text{Ca}} + \text{p}_{\text{Alk}} + K_{(\text{T,IS})} \]  

(8)

Where: \( K = \text{constant to include temperature and ionic strength.} \)

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

In SWRO desalination systems, electricity is a major consideration to sizing the Photovoltaic. Power consumption by the system includes power for seawater

\[ \text{bhp} = \frac{[Q_{\text{in}} \times P_j]}{(\text{36} \times T_j \times \zeta)} \]  

(9)
pumping (Booster pump), high-pressure pumping, and chemical treatment pumping. The power requirement of each pump is calculated using the equation:

\[ \text{Power} = \frac{\rho \cdot Q \cdot \zeta}{\eta} \]

Where \( Q \) rate of flow, \( \rho \) 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 0.1 kW 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/m³.

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 H₂O) | 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 Isc          | 5.45A                              |
| Open circuit voltage Voc           | 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:

\[
\text{Maximum DC power} = \frac{\text{Total energy demand}}{\text{Efficiency of an inverter}}
\]

\[
\text{Total amp - hour demand} = \frac{\text{Maximum DC power}}{\text{Nominal voltage}}
\]

a) Booster pump: 200W×6h = 1200Wh
b) High pressure pump: 2200W×6h = 13200Wh
c) Chemical treatment pumps: 100W×6h = 600Wh

Maximum AC power requirement: 200 + 2200 + 100 = 2500W
Total energy demand per day is 15,000Wh

Maximum DC power requirement: 15,000Wh / 0.9 = 16,667Wh
Total amp-hour demand per day: 16,667Wh / 48V = 347.23Ah.

2. *Determine total solar array current requirements:*

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

\[
\text{Total current generated} = \frac{\text{Total amp - hour demand}}{\text{The average peak sun hours} \times \text{Battery efficiency}}
\]

The required total current generated by the solar array is 347.23Ah / (0.8 ×5h) = 86.8A.

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 86.8A/4.95A = 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 48V/12V = 4 module. The total number of modules in the array is 18 × 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 347.23Ah × 7 days = 2430.6Ah. The minimal battery capacity for a safe operation is 2430.6Ah/0.8 = 3038.3Ah

Number of batteries in parallel is the minimal battery capacity by Amp-Hour capacity of selected battery: 3038.3Ah/383Ah = 8 batteries. Number of batteries in series is Nominal DC system voltage by selected battery voltage: 48 / 24 = 2 batteries. The total batteries: 8 × 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](image)

From the monthly data available, it has
been seen that the plant operates for an average of 8 hours per day (2.2 m³/day) in the summer, and 3.5 hours in the winter (0.86 m³/day), an annual average of production capacity is 1.5 m³/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 m³/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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