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Design, Sizing & Simulation of Solar Powered Desalination Unit for Brackish Water in Jordan

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ABSTRACT

In the framework of a regional scientific cooperation project between USA, Israel, Jordan, and the Palestinian Authority, Jordan (represented by the National Energy Research Center – NERC) has received two desalination units. The first unit is a US-military RO-desalination unit (ROWPU), producing 16 gpm of fresh water and operated with diesel generator. The second unit designed for brackish water also produces 16 gpm fresh water, and is accompanied by a complete sixteen KWp - PV system. This paper describes the water situation in Jordan, the potential of solar radiation in the area, site selection criteria, and the designing, sizing and simulation of a photovoltaic power supply system for the second RO-desalination unit. Also the paper contains measurement and evaluation data concerning the water quality, energy consumption and efficiency of the (ROWPU), which has been installed and operated by NERC in the village of Qatar in Jordan.

INTRODUCTION

World wide populations suffer from water scarcity in many arid and desert-like areas. The only source of water available is salty water with conductivity of 1500-5000 μS/cm. A part from salinity, other important contaminants like, for instance, Pathogenic microorganisms, can further affect water quality. In the case of the Middle East and Northern Africa (MENA) basin, there are problems of fresh water supply of either a quantitative nature or a qualitative nature and the availability of water for drinking and agricultural purposes is vital for further economic, social and political development. Fresh water in Jordan is scary. The fast population growth and the rising water consumption aggravate this situation per capita. Desalination of brackish water can contribute towards the alleviation of the water scarcity problem, as the resources of brackish water in Jordan are large.

Reverse osmosis (RO) powered by photovoltaic (PV) is a promising solution for small-scale desalination units. Mohsen and Al-Jayyousi investigated the feasibility of different desalination technologies to cover the increasing water demand in Jordan. They carried out a multi-criteria analysis considering economic, technical and environmental criteria and compared the five most important desalination technologies Multi-effict desalination (MED), Reverse osmosis (RO), Vapor compression (VC), Electro dialyses (ED), Multi-stage flash (MSF) for the production of drinking water from brackish and sea water. They pointed out that the RO-technology with it's advantages of the suitability for both sea and brackish water and its low power requirements. RO is ranked first of the five desalination technologies. Furthermore, RO is very flexible in water quantity and quality, site location and start-up and shut-shown.

In countries without fossil fuel resources and in remote areas like Jordan, solar energy supplies can be economical in many cases for Stand-alone applications compared with fossil-driven small-scale desalination units, which are relatively expensive to operate in remote areas.

In the framework of a regional cooperation between USA, Israel, Jordan and the Palestinian Authority, Jordan has received two desalination units. The first unit is a US-military RO-desalination water purification unit (ROWPU)- installed and operated in the remote village of Qatar in the southern part of Jordan- produced 16 gallon per minute (gpm) of fresh water from brackish water (5000 ppm) and powered by diesel generator. The second RO unit- type dalta-15 manufactured by Environmental Crane, USA- is designed for desalination of brackish water (up to 5000 ppm) and to produced 16 gpm fresh water, and is a companied by a complete 16.8 kWp PV-system.

This paper describes the water situation in Jordan, the potential of solar radiation, site selection criteria, and the designing, sizing and simulation of a 16.8 kWp PV power supply system to power the second unit. Also, the paper contains the results of the evaluation data measurements concerning the water quality, energy consumption and efficiency of the first unit (ROWPU).

SECURING FUTURE WATER SUPPLY IN JORDAN

The agricultural sector is the main consumer of water in Jordan using 746 Million cubic meters (Mm^3) of the year 2000, mainly for irrigation purposes. Agriculture thus accounts for 61.6% of the national water demand. On the other hand the industrial water demand in year 2000 was only 78 Mm^3. It is, however, expected that the industrial water demand will be tripled by 2015. Domestic water consumption per capita is considerably lower than in other countries of the region. It is about 85 L/capita/ day. However the domestic water demand will increase rapidly in the future due to population growth rate and an increase of per capita water consumption by urbanizing the population. The water supply grid covers 97% of the population and water losses 97% of the population and water losses are estimated to be more than 30%.

Water supply has been covered by surface, ground and spring water. In addition, processed waste water has been used mainly for industrial purposes. It is also used for irrigation in many other countries.

The total water supply in Jordan was 915 Mm^3 in the year of 2000 and the consumption of all hole sectors was 1212 Mm^3 and the deficits was 297 Mm^3. These figures indicate the dramatic situation of Jordan's water supply.

Jordan which is extremely suffering from water shortage has huge brackish water resources distributed over different basin and many wells. Table (1) shows the brackish ground water resources.

Table 1. Brackish water resources in Jordan

Ground water-Basin	**Resources (MCM)**	**Potential Annual Extraction (MCM)**
Jordan Valley	2800	54
Dead Sea	3200	67
Wadi Araba	1000	8
Azraq	1680	29
Sirhan	50	5
Hammad	4000	13

POTENTIAL OF SOLAR ENERGY IN JORDAN

Solar irradiation in Jordan is relatively high. The yearly average horizontal radiation is a round 5.6 kWh/m^2/day. On a tilted surface, the mean values vary from (5.9 to 6.84) kWh/m^2/day. For the proposed site of the desalination system, Aqaba area, the annual average of solar radiation is 6, 16 kWh/m^2/day.

DESIGN AND SIZING OF THE PV-RO SYSTEM

Site selection criteria:

Site selection is based on the following criteria:
Availability of brackish water.
Potential of solar radiation.
None availability of electric grid and fresh water in the site
The social, economic and ecological situation of the beneficiaries.
Demand and quantity of fresh water.

PV-RO system (Fig. 1) is divided in two sub systems, the RO- unit and the PV- power system.

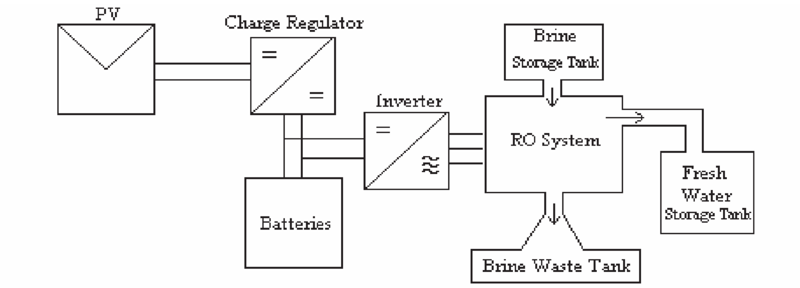

Figure 1. Block diagram of PV-RO System powered by PVs.

DESIGN OF THE RO-DESALINATION UNIT:

The capacity of the desalination unit and the daily seasonal operation are determined by the water demand. The desalination process is selected taking into account the capacity of the plant, the feed water quality and the product water requirements. The energy requirements of each desalination process are estimated on the basis of the unit capacity, the feed salinity as well as operating characteristics of the plant. Based on the above mentioned design criteria and site selection criteria, the RO-desalination unit type (Delta-15 CIP) is designed and manufactured by Crane Environmental Co., Chicago, USA with the following performance specifications:

Feed Water TDS (mg/L): 4000
Feed Water Temperature (^{0}C): 25
Production (gpm): 16
Permeate TDS (mg/L) : >100
Recovery (%): 60
Feed Water Max. Silt Density (SID): 5.0
Feed Water Max. Nephelometric Turbidity Unit (NTU): 1.0
Feed Water Chlorine Tolerance (mg/L): 0.1
Concentrated LSI: 1.5
Min. line pressure required: 20
3rd Year R.O Feed Pressure (psi): 230
3rd Year concentrated pressure (psi): 185
Power Input: 3X385 V 50 Hz 14A

Design of the PV-power system (PVPS):

The most challenging problem associated with the implementation of PVPS powered desalination unit, is the optimum matching of the intermitted PVPS power output with the steady energy demand for the desalination process. Power management and demand side management are the two options available to solve this problem. In the first case, an appropriately controlled hybrid power supply system that is able to provide a steady energy output is used and it is sized at the nominal power demand of the desalination process. In the second case, the desalination process operates only when the energy output of the PVPS is able to cover the energy demand.

The energy balance between energy production from PVPS and auxiliary energy sources (Storage battery bank, electric grid … etc) and the energy demand of desalination processes is used for determining the capacity of the energy system.

Based on the above mentioned criteria, the PVPS is designed as a hybrid system (Fig. 2), which includes three power sources: Photovoltaic power system (PVPS), Storage Battery Bank and Utility grid. The PVPS operates normally as a stand-alone power system, independent of the utility grid. It is able to charge the storage battery bank and to power the AC-load of the desalination unit for 6 hours during a sunny day. When the system is no longer able to keep up with AC-power of the desalination unit, before the storage battery bank become deeply-discharged, it change over directly to the utility grid to operate the desalination unit and recharge the battery bank. When the batteries become well-charged, the system disconnects from the utility grid and once again operates the desalination unit from the batteries.

In order to design any hybrid power system, a special control and relaying circuitry is required. In this system, inverters play the leading role during the operation, as they connect between system's DC & AC buses. They include, internally, the required circuitry to obtain the hybrid characteristics. The PV-generator of the system will charge the storage battery bank using PV charge controllers (PVCC) and feeds the AC load of the desalination unit via the inverters. PVPS is basically composed of the following components (Fig. 2):

PV-generator: It converts directly sunlight into DC-power. It consists of PV-modules mounted on racks and connected electrically in series & parallel groups.

Battery bank: It stores DC-electric energy in order to cover the shortage of load power during cloudy weather conditions and dark time.

PVCC: It regulates the battery state of charge and protects the batteries against both over-charging and deep-discharging states.

Three-phase inverter: It converts DC-power into 3-phase AC-power in order to operate the AC-load of the RO unit. On the other hand, the utility grid-connected power supply operates the AC load directly from the grid and charges the batteries via a 3-phase rectifier inside the inverter. The inverter operates as an inverter and as a rectifier (Fig. 2)

Sizing of the PVPS-System:

The system is designed according to the rated power requirements of the desalination unit and its daily operation time (O_t) for 6h/day, taking into consideration that the load is normally operated by the PV array generator and/or storage battery bank independent of the utility grid, which is used only as a backup power source. Therefore, the hybrid system sizing procedure is based mainly on the PV-stand –alone sizing procedure. The following steps describe the system components sizing procedure:

a. AC Load Sizing.

The electrical load of the RO-unit (RO_{el}) is rated at 3-phase, 380 V_{AC} and 14A (max.) and designed to operate 6h/day. Therefore, the daily energy consumption of the unit (RO_{de}) is calculated according to the following equation:

$$\begin{aligned} RO_{de} &= RO_{el} \text{ X } O_t \\ &= \sqrt{3}X380VX14AX6h/day \\ &= 55221.6 \text{ Wh/day} \end{aligned}$$

b. Storage Battery Bank Sizing

In order to determine the required battery capacity, the following parameters are considered:

- Battery system voltage (B_{SV}): 48 V
- Days of Autonomy (D_A): 1 day
- Batteries depth of discharge (D_{OD}): 80%

Accordingly, the daily consumed DC load ampere-hours (D_{Ah}) is calculated as follows:

$$D_{Ah} = RO_{de} / B_{SV} = 1151.8 \text{ Ah}$$

Therefore, battery capacity (B_C) is calculated as $B_C = (D_{Ah}/ D_{OD}) \text{ X } D_A = 1439.8$ Ah.

Finally, 24 sealed lead. Acid batteries (type Concorde PVX-2580L, each rated at 12V, 255 Ah) are selected to build the battery bank. The battery bank is configured of 6 parallel strings with 4 series batteries in each string.

c. PV Array Sizing

The following parameters affect the PV-array sizing procedure:

D_{Ah}, Average Peak Sun Hours (PSH), which is 5.85h, over –design safety factor (S_f=1.25), where S_f is considered due to the system components losses. Accordingly, the PV array peak current (PV_{Pc}) is calculated as:

$$PV_{Pc} = D_{Ah} / PSH = 197.91 \text{ A}$$

A PV module type Kyocera KC-120-1 was selected (to build the PV-array generator) with the following specifications:

P_{max} = 120 Wp, V_{pm}= 16.9 V, I_{pm}= 7.10 A, V_{oc} = 21.5 V, I_{sc} = 7.45 A,
where V_{pm} and I_{pm} are the voltage and current at max. operation point.

It has to be noted that these specifications are under test standard conditions STC (1000 W/m^2, 1, 5 AM, 25^{0}C).
Regarding the electrical connections between the PV modules within the PV-array, every 4 modules are connected in series to obtain the nominal system voltage 48 V_{DC}.The peak current (I_{pm}), which will flow in every string (4 series-connected modules) is 7.1 A. The needed number of strings (Ns) is calculated according to the following equation:

$N_S = PV_{PC} / I_{pm} X S_f = 34.843 \sim 35$,
where S_f is a safety factor (1.25).

The total number of the PV modules N_{PV} is:

$N_{PV} = N_s X S_{PV} = 140$,
where S_{PV} is the number of PV-modules in the string.

The 140 PV-modules are connected as 35 parallel strings; each string contains 4 PV-modules connected in series.

d. PV Charge Controller (PVCC) Sizing

The key in PVCC sizing is to determine the max. current which will flow from PV array (PV_{mc}) through PVCC, which is calculated according to the following equation:

$PV_{mc} = I_{sc} X N_s X S_f = 325.9$ A,
where I_{sc} is the short circuit current.
The current (325.9A) is too high to be accommodated by single PVCC, therefore, 6 PVCC's rated each at 60 A are selected, resulting in dividing the PV array into 6 sub-arrays and configured as: 5 sub-arrays with 6X4 modules per sub-array, and 1 sub-arrays with 5X4 modules.

e. Three Phase Inverter Sizing

The inverters play the leading role during system operation. In this hybrid system three single-phase hybrid inverters (type Xantrix SW 3048E), in additional to a 3-phase software are used to provide the required 3-phase AC power supply. They are connected, as shown in (Fig.2), with a special three phase interface cable (stacking cable), which carries a clocking signal to provide the phasing information from the master inverter to the other two slave inverter. Also, these inverters are used to work in the reverse directions as battery charges. Each of these inverters is rated at: 48 V_{DC}, 50A_{DC}, 230V_{AC}, 14A_{AC}, 3300VA, 50 Hz, sin wave.

Fig.2 illustrates the final details of system components, in additional to three by pass switches, which are used to operate the load directly from the utility grid, in case of system failure.

SYSTEM SIMULATION

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

- The PV-panel characteristics
- Daily load profiles
- Climatic data: Climatic features of the selected site fluctuate dramatically from an annual average. Climatic parameters such as monthly averages of solar radiation, sunshine duration, ambient temperature, main wind speed, affect the simulation process.
- The mathematical models used in the simulation are:
    a. Solar radiation G(t) as a function of time (t), the most sophisticated approach is the standard solar day (SSD) model as shown in Fig.3.

$G(t) = G_{max}\ \sin(\pi t/T)$, where T is the length of SSD or sunshine period, also
$G_{max} = \pi\, G/2\, T$

where is the monthly average daily of G(t).

For the above calculation, G and T must be knows for each day to be simulated. For the site of the system, G and T data were obtained are shown in Fig. 4

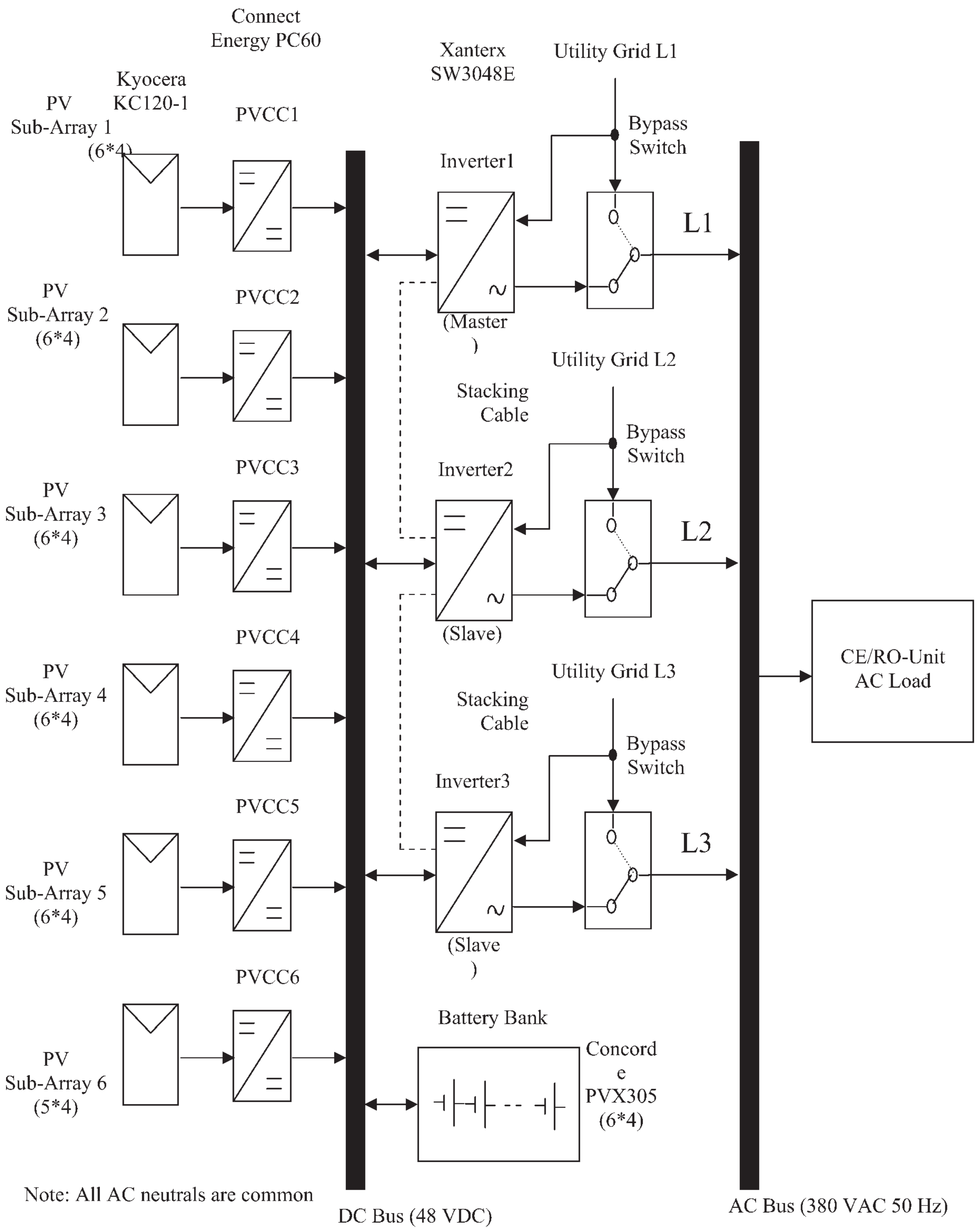

Figure 2. Design and sizing block diagram of PVPS.

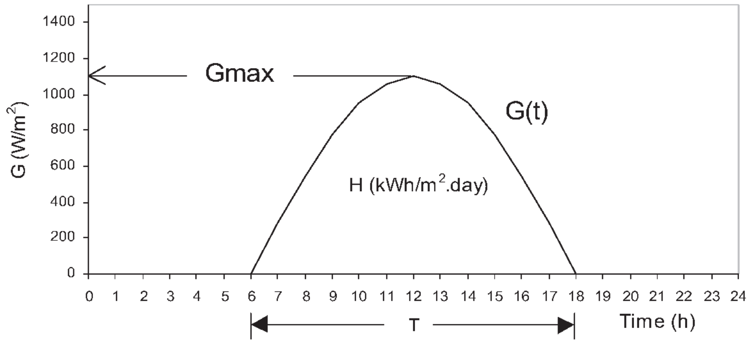

Figure 3. Standard solar day model.

b. PV array output power as a function of instantaneous solar radiation.
c. Input-output characteristics of the auxiliary system, such as DC/DC converters, DC/AC inverters, storage batteries and loads.

The system components are modeled as the following:
PV array: we will assume that the relationship between output DC power and global solar irradiance is linear, also, the cell temperature is constant @ NOCT, about 10% loss in output DC power), where NOCT is the normal operating cell - temperature.

where P_{peak} is the peak power of the PV-array @ STC.

DC/DC converter: the efficiency (η_{con}) was assumed to be equal to 90%.
$P_{con,dc} = P_{PV,dc} X\ \eta_{com}$

DC/AC inverter: the efficiency (η_{inv}) will be assumed equal to 90%.
$P_{inv,ac} = P_{con,dc} * \eta_{inv}$

Batteries: the efficiency of the batteries (η_b) was assumed constant (80%). The battery state-of-charge (SOC) expresses the residual capacity of the battery as a (%) of the rated battery capacity.

Load (RO-unit): It was mentioned in the system sizing procedure that the unit must operate 6 hours/day. For simulation purposes the unit will be operated at 8:00 am and powered off at 14:00 pm working with a rated power of 9.22 kW. We select this period because the solar irradiance during this period is valuable. Simulation was performed for a typical day in each month of the year. Detailed simulation results are shown in Figs. 4, 5 & 6 for the period 1995-1998 applied in the simulation process

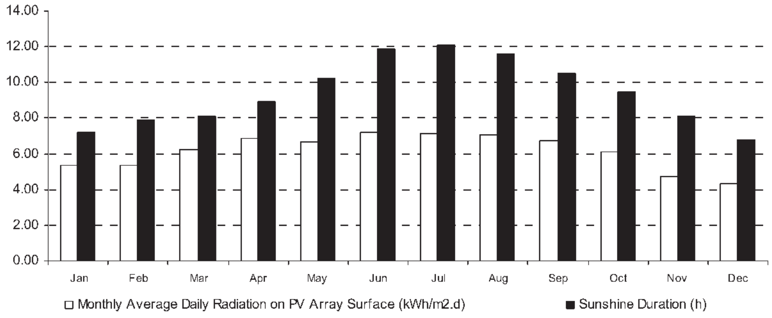

Figure 4. Solar data of Aqaba area.

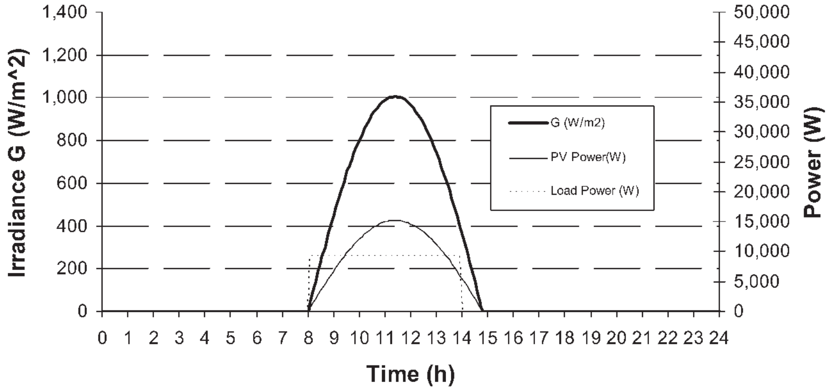

Figure 5.Typical solar day, PV power & load power diagram for a typical day on December.

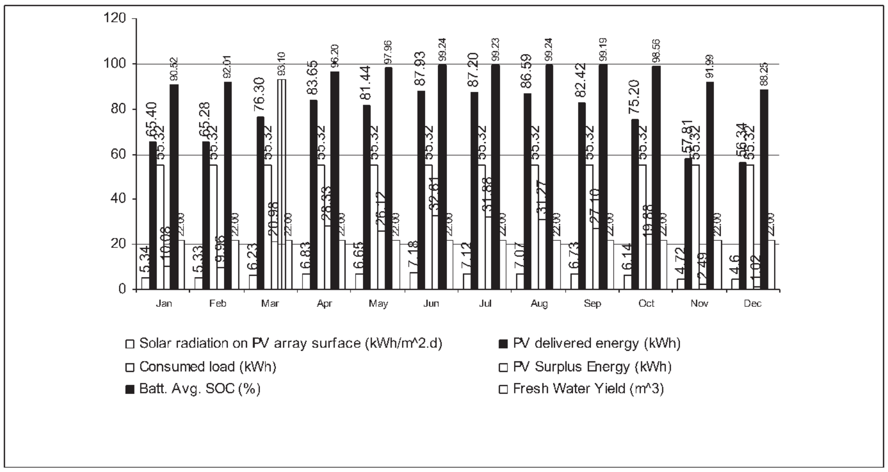

Figure 6. Typical Yearly Simulation Results of RO-Desalination System.

FIRST DESALINATION UNIT (ROWPU)

The National Energy Research Center (NERC) has carried out detailed tests and analysis in order to study the performance characteristics of RO technology. Field tests have been carried at different operational settings. Data are collected, evaluated and analyzed. Three interested figures are concluded: Fig. 7 shows the power consumption of the system at different values of working pressure. Fig. 8 shows the effect of pressure on permeate output and Fig. 9 outlines the variation of the recovery ratio with pressure. From these figures it can be seen clearly that power consumption, permeate flow rate and recovery ratio are increasing with pressure increase.

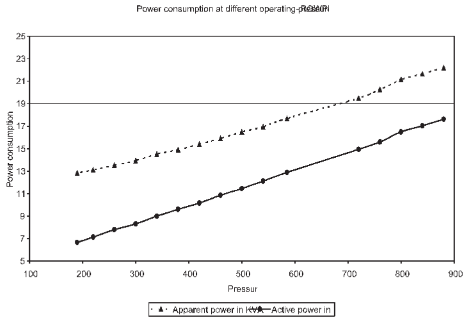

Figure 7. Power consumption at different operating pressure rate.

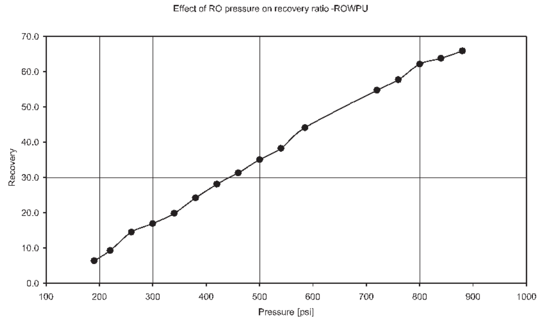

Figure 8. Flow rate values at different operating pressure.

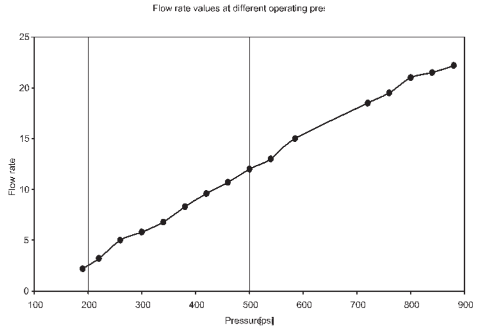

Figure 9. Effect of RO pressure on recovery ratio.

Table2 shows that economic evaluation results of desalinated water costs ($/m³) using different supply energy systems.

Table 2. Economic evaluation results

Energy Supply System	**Desalinated Water Costs ($/m³)**
Solar Energy	2.79
Diesel Generator	3.87
National Electric Grid	3.17

CONCLUSION

A photovoltaic power system was designed, sized and simulated to power a RO desalination unit (type RO-Delta 15) for 6h/day and to produce a 16 gpm of fresh water from brackish water with salinity of 5000 ppm the results of the designing and sizing of the system components where:

- Photovoltaic generator consists of 140 modules with a total peak power of 16.8 kWp.
- 6 charge controllers each related with 60A.
- 3 inverters single phase, each rated with 48 VDC/230 VAC, 3300 VA.
- 24 storage batteries with a total capacity of 73, 44 kWh.
- The electrical load of the RO-unit is 9.22 kW.

The simulation results of the system where:

- Average daily PV produced electrical energy: 95.46 kWh/day
- Average daily load consumed electrical energy: 55.32 kWh/day
- Average daily surplus electrical energy: 20.23 kWh/day
- Average daily batteries SOC: 95.18%
- Min. Batteries SOC: 90.35 %
- Max. Batteries SOC: 100%
- Average daily produced fresh water: 22 m^3/day
- Average daily feed brackish water: 36.66 m^3/day
- Average daily solar radiation: 6.14 kWh/m^2.day
- daily operation period: 8:00 am – 14:00 pm
- Average daily sun shine period: 9.4 h

Finally, the results of evaluation measurement data of the first RO-unit (ROWPU) shows the power consumption, permeate flow rate and recovery ratio are increasing linearity with increasing of the pressure.

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