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Design and Implementation of Water Desalination System (RO) Using Renewable Energy Source

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Abstract

The shortage of sufficient available fresh water resources in Jordan to meet water needs forces the nation to look for new water supply sources also to meet the increasing demand for fresh water. In this manuscript, a case study for designing, optimizing and implementing an off-grid water desalination system using photovoltaic (PV) power generation system is introduced. The system is installed on a farm in Southern Ghore of Jordan valley where the access to the grid is not reliable enough to guarantee the desalination of the amount of water for the farm's irrigation needs. The study offers a framework to aid in designing similar pilot plants where the classic power generation prediction is greatly affected by the environmental conditions.

An off-grid PV system with a total nominal power of 10.4 kWp was designed, procured and installed in the southern part of Jordan Valley near Karma town. The system operates the pumping system as well as the reverse osmosis based desalination unit. A measurement system has been collection relevant data like temperature, radiation, voltage, current, water quality, pressure, etc. continuously for the last 4 years.

In this paper we will present the sizing procedure used, the system design and evaluate the design using the collected data of the run-time of 4 years. Data about the water quality and amount of desalinated water will equally be used to evaluate the system. The paper will end with recommendations to adapt the system design in deferent part of the Middle East and North Africa (MENA) region.

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Keywords

Photovoltaic system; system design; system sizing.

1. Introduction

Water is a scarce resource in the Hashemite Kingdom of Jordan [0]. The population increase following the crisis in the neighboring countries increases Jordan's water scarcity and quickly outdates any projections of the water situation. One available water source consists of brackish water in the Southern Ghore valley with a yield of about 60 Mm³/yr (Hadadin et al. 2010), (Mohsen et al. 1999). The energy demand for pumping systems and the water desalination itself is an important factor in using this water source. Jordan is poor in fossil energy

resources wherefore renewable energy is of increasing importance in Jordan. Over the years, many systems have been developed that use renewable energy for water desalination (Charcosset et al. 2009).

According to the national water strategy priority is given to the further development of land and water resources in the Jordan Rift Valley, which is the food basket of the country” (UNICEF, 2012) In Jordan brackish water is in important water resource .In 2010, 80 million m³ of fresh water have been retrieved from brackish water using desalination in 21 stations over Jordan. (Jordan Valley Authority, 2010) Equally in the Jordan valley, brackish water is an important fresh water resource.

Desalination has become a major water resource in many areas of the Middle East. This process powered by conventional energy (Fuel, oil,...etc.) is widely used to desalinate both seawater and brackish water. Desalination of brackish water using RO-desalination process powered by photovoltaic power system technology is still at the beginning and not widely used. Jordan has a high potential of brackish water and it is recommended that “desalination of brackish groundwater by the private sector shall be promoted” (The Hashemite Kingdom of Jordan, Ministry of Agriculture, and National Center for Aagriculture research and technology transfer (NCART), 2004)[6]. But in some locations that are sufficiently rich in brackish ground water, electricity networks are not or only partially available. The option using diesel generators did not provide a practical solution.

With an average of 5.6 kW/m² per day solar irradiation in Jordan is very high. Even in winter (December and January) average values of 4.2 kW/m² per day are measured (PVGIS, 2017). Therefore, solar energy as reliable energy source can be used to power decentralized desalination plants.

Based on the objectives of the project, several possible sites in the Jordan valley were evaluated. The Jordan valley is an import region for agriculture in Jordan and possesses substantial groundwater resources of brackish water with salinity of 2000 to 4000 ppm. In addition, many locations are not connected to the electricity grid or the electricity grid is not stable resulting in long power outages. In order to desalinate water for irrigation purposes, farmers in these regions depend on an alternative energy source for their desalination systems. The site of the project has been chosen at a private farm in Jordan Valley north to the Dead Sea. The farm is located at the geographic coordinates: 31°54'40" North, 35°34'49" East with an elevation of 315 m below the sea level as shown on the Jordan map.

An off-grid PV system with a total nominal power of 10.4 kWp was designed, procured and installed in the southern part of Jordan Valley near Karma town. The system operates the pumping system as well as the reverse osmosis based desalination unit. A measurement system has been collecting relevant data like temperature, radiation, voltage, current, water quality, pressure, etc. continuously for the last 4 years.

The system must allow for pumping and desalination water to supply 18 to 20 m³ / day of fresh water during a daily operation time from 9:30 am to 3:00 pm, i.e. for 5.5 hours.

In this paper we will present the sizing procedure used, the system design and evaluate the design using the collected data of the run-time of 4 years. Data about the water quality and amount of desalinated water will equally be used to evaluate the system.

2. System Design and Sizing

The design and selection of the desalination technologies depend on the raw water quality and quantity to be desalinated. The water source at the project site is underground brackish water and it is not useful for human purposes and irrigation for some vegetables and fruit plants. Several samples of this water were collected and analyzed as shown in Table 1.

Table 1. Average brackish water analysis in the selected project site

Parameter	Unit	Value
pH		7.35
EC	μS/cm	3750

Continued on next page

Table 1 continued

Turbidity	NTU	1.1
Mg ⁺⁺	mg/L	40.8
Ca ⁺⁺	mg/L	69
Total Hardness	mg/L as CaCO ₃	336
K ⁺	mg/L	47.5
Na ⁺	mg/L	267.1
TDS	mg/L	2590
TSS	mg/L	1068
TS	mg/L	3124
SO ₄ ⁻	mg/L	249.4
PO ₄ ⁻⁻⁻	mg/L	0
Cl ⁻	mg/L	92.5
NO ₃ ⁻	mg/L	60
COD	mg/L	40.4

In order to design the system, relevant parameters must be specified. These are related to the main components of the system: the pumping system for the brackish ground water as well as the desalination unit. Based on these system parameters, the PV system will be designed.

Based on the required amount of desalinated water and the measured water quality (see Table 1) the desalination unit was specified by the following parameters:

Table 2. Parameters of the desalination unit

Parameter	Value
Quantity of potable desalinated water	3 m ³ /h
Quantity of raw brackish water feed	5 m ³ /h to 6 m ³ /h
Raw water temperature	25 to 28°C
Recovery factor	60 – 70 %
High pressure pump	8 – 12 bar Motor: 3 phase 3 to 4 kW
Membrane process	One stage content with 3 elements connected in series
Type of membrane	Spiral wound, composite polyamide, permeate flow > 34 m ³ /d, salt rejection minimum 99 %, active area 400 ft ² (= 37.1 m ²)
Pre filtration	Yes
Energy consumption	< 2 kWh/m ³

The brackish water is underground water (well) that is pumped from the underground. The pump equally has to be powered using solar energy.

In order to determine the required energy to operate the pump we need to determine the hydraulic energy that is required to pump the required amount of underground water to the desalination unit. The pumping head for the described system is in 40 m depth. The amount of water to be pumped daily is around 30m³/d (3m³/h multiplied by 6 operation hours per day (estimated) and then divided by the RO recovery ratio 60%). So, it is needed to extract from the well a water volume of 30m³/d at a pumping head of 40 meters during the daytime, especially in peak sun hours (around 5 to 6 hours per day). The hydraulic energy needed to pump water per day is (1000 kg/m³ × 9.81 m/s² × 30 m³/day × 40 m = 11772000 Joules/day = 3.27 kWh/day). Dividing the hydraulic energy by the motor and pump efficiencies (0.8 × 0.6 = 0.48), gives the electrical energy needed which equals 6.8 kWh/day. Assuming that the water volume will be extracted during 4 hours in the daytime, the electrical power of the pump will equal

around 1.7 kW. Multiply this figure by 1.2 to compensate for mechanical (piping) and electrical (wiring) losses, the electrical power of the pump will be around 2 kW (2 horsepower). Accordingly, the total daily electrical energy consumption is 10 kWh ($2 \text{ kW} \times 5 \text{ h}$).

2.1. PV System Design

The block diagram illustrated in Figure 1 shows the design of the PV system adopted. . The PV array is divided into different sub-arrays. Each PV sub-array has multiple PV modules which are electrically connected in series and paralleled together using a combiner box equipped with a main DC circuit breaker. The battery bank has multiple battery units to meet the voltage and current requirements of the system. DC/AC inverters are used to convert DC power into AC power form to meet the load requirements. The AC power is distributed to the loads represented by the well's submersible pump and the RO unit. According to the system size depending on the loads needs, the nominal DC bus voltage is 48V and the nominal AC voltage is 400V, 50Hz (same as the RO unit need).

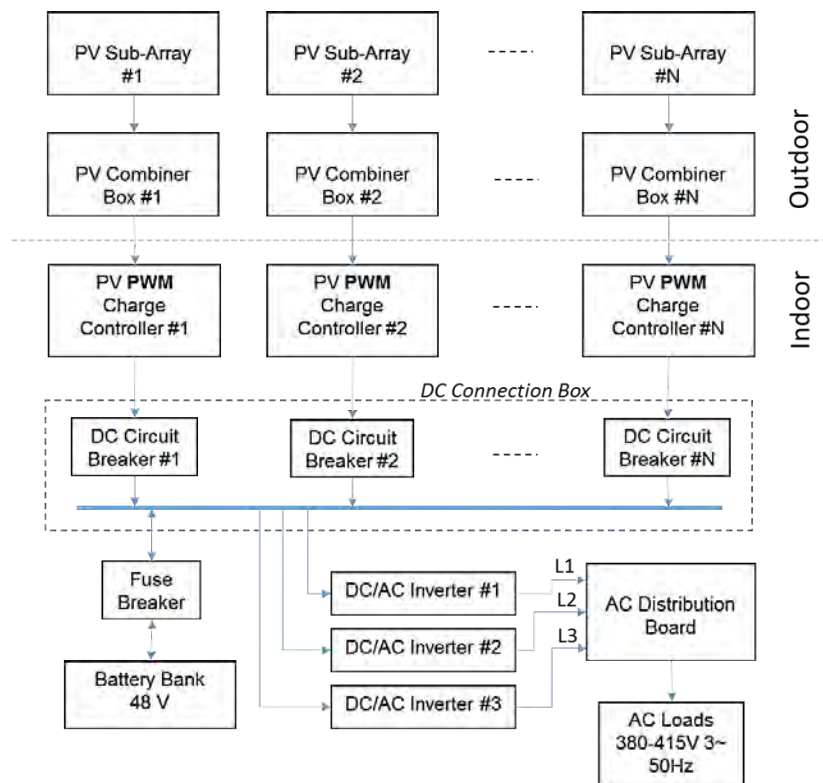


Figure 1. Design Block Diagram of the PV System

2.2. Sizing of Photovoltaic and Storage System

The PV system of the RO unit was sized according to the sizing procedure as follows:

- Calculate the Daily Peak Sun Hours (PSH)
- Calculate the daily electrical energy to be consumed by the desalination system
- Calculate the daily electrical energy to be produced by PV array
- Calculate the peak power of the PV array
- Calculate the battery bank capacity

The photovoltaic (PV) and the storage systems have been designed specifically for the given energy requirements and project site. The PV sizing results for the RO unit are summarized in Table 3.

Table 3. Sizing Result for the RO unit

PV Array	7.6 kWp
Battery Capacity	33.3kWh
Maximum PV Charging Current	158.33 A
Maximum Rated AC Power Output	6.3 kVA

The PV system required for the water pumping system was sized according to the sizing procedure as follows::

- Brackish water well Characteristics
- Calculation the daily hydraulic energy consumption (DHE) to pump the daily quantity ($Q=30\text{m}^3/\text{day}$) of brackish water from the well
- Calculation of the required output daily energy from the PV-generator (EPVout)
- Calculation of the required input daily energy of the PV-generator (Epin)
- Calculation the area of the PV- generator APV
- Calculation of the Peak power of the PV-generator PVWP

The PV-generator sizing results for the PV- water pumping system can be summarized in Table 4.

Table 4. PV Sizing Results for the WaterPumping System

PV Array	2.513 kWp
Battery Capacity	10.2kWh
Maximum PV Charging Current	50.3 A
Maximum Rated AC Power Output	4.1 kVA

2.3. System Parameters

The designed system consists of the following elements:

- Solar photovoltaic power system (SPVPS) with a 10.4kWp (16m² per array) solar photovoltaic array subdivided into 5 sub arrays, to convert the solar radiation into electricity,
- 5 charge controllers to control the process of charging and discharging the storage batteries and to regulate the output voltage of the solar array to give a fixed DC-Voltage for the storage batteries and the inverters,
- 3 inverters to converts the produced direct current (DC) to alternate current (AC),
- Stand-by storage batteries with a capacity of 50 kWh/day,
- A submersible motor-pump system, which pumps 35 m³ of brackish water from the well with a depth of water dynamic level (40 m),
- A brackish water reverse osmosis desalination system (BWRODS) to desalinate the pumped brackish water and to produce and supply 18 to 20 m³ /day of fresh water during an daily operation time (5.5h) from 9:30 am to 3:00 pm
- Measuring and monitoring systems to measure the input and output parameters of the systems mentioned above and the climatic data at the project site

In order to validate and analyze the project a sophisticated measurement system has been installed.

The measuring system as in Figure 2 is designed to measure, analyze and evaluate the input-and output data of the systems (Solar photovoltaic power system, raw water pumping system, RO-desalination system and climate data).

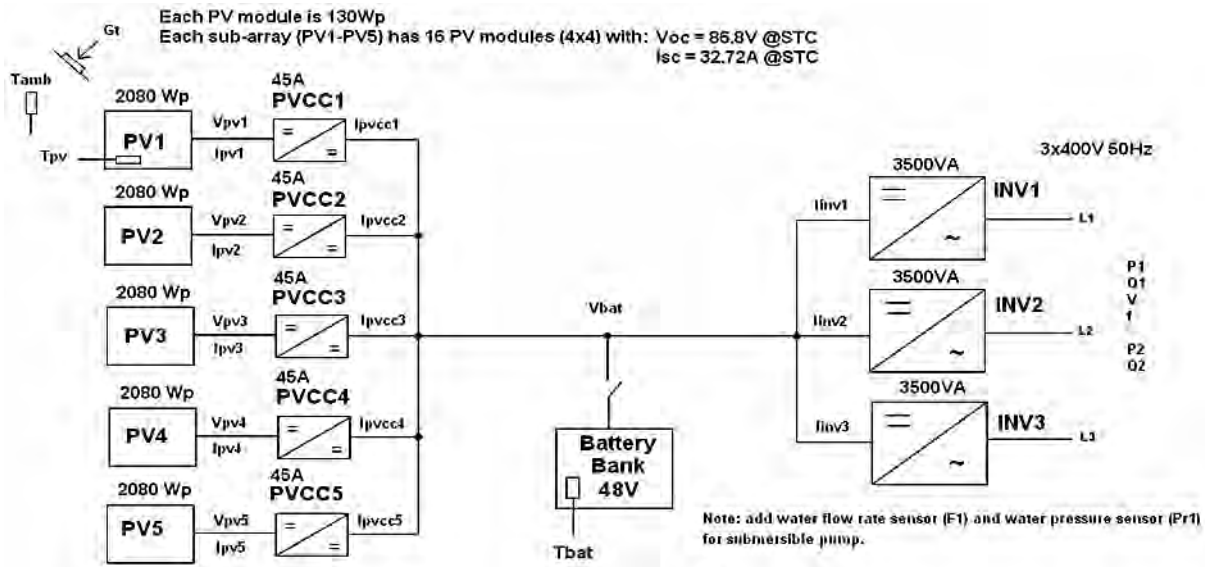


Figure 2. Block Diagram of the Measuring System

3. Results and Analysis

For the energy analysis, the tilted solar radiation sum received over the course of the said recording period was calculated by integrating solar irradiance values over time. Every one meter square of surface area has received around 1203 kWh (in the year 2015) of solar energy during the above mentioned recording period. The maximum 10-minute average solar irradiance reading was recorded in 19/06/2015 at 12:30pm which was 1202 W/m². The daily average of solar radiation sums was 5.8 kWh/m². Solar radiation and temperature data are depicted in Figure 3.

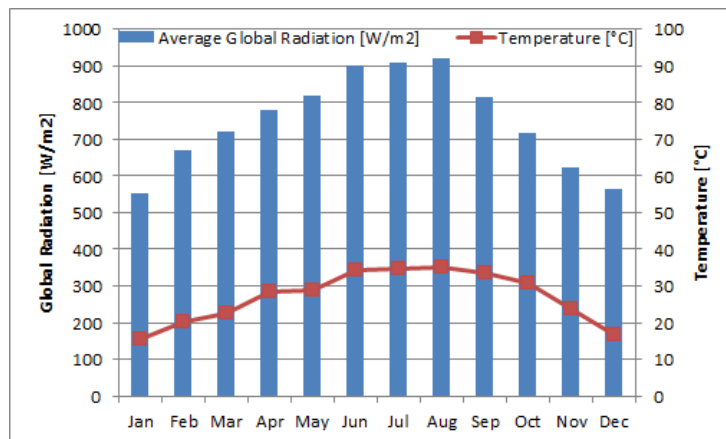


Figure 3. Average Global Radiation and Temperature in year 2015

The solar energy which was received by the surface of the PV array and each PV sub-array (5 sub-arrays) was calculated by multiplying the incident solar radiation (kWh/m²) by the surface area of the PV array and each sub-array. It was found 34279 kWh for each sub-array. The output energy of each PV sub-array was calculated in order to estimate the PV energy conversion efficiency that, equally the input and output energy values for each PV

charge controller (5 ones) were estimated to find the energy efficiency of each charge controller.). The maximum Efficiency of PV array in March is 11% and the minimum is 6.5% in December. The Efficiency of PV array and Solar radiation data are depicted in Figure 4.

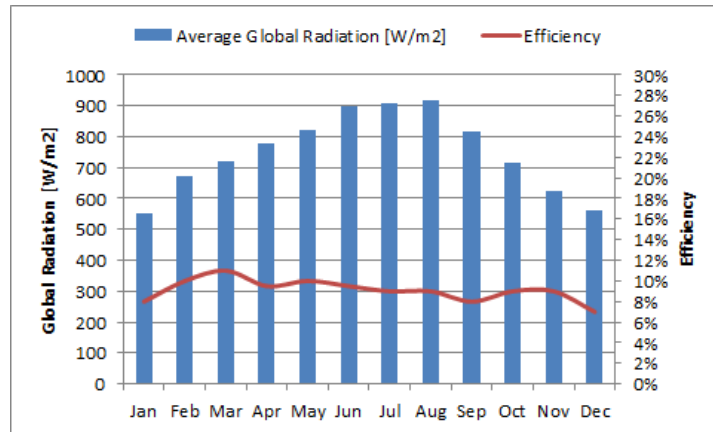


Figure 4. Average Global Radiation and Efficiency in year 2015

The total PV energy produced by the PV array during one year is 11504 (Figure 5). The total annual energy consumption by loads is 6215 kWh (Figure 6). The maximum energy production was in August is 1589 kWh and the minimum is 410 kWh in February.

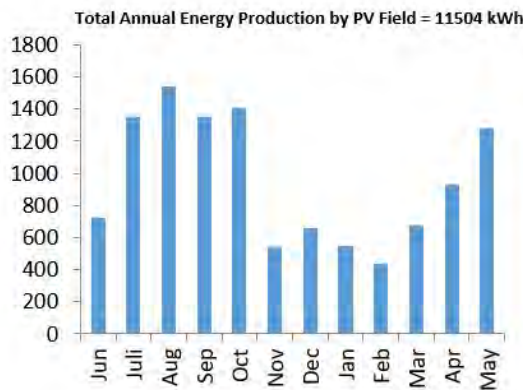


Figure 5. Monthly PV Energy production in kWh

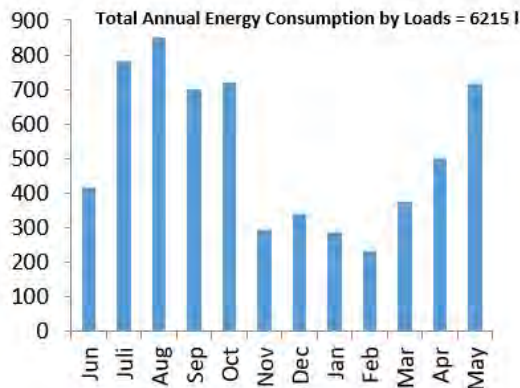


Figure 6. MonthlyLoads Energy Consumptions in kWh

4. Conclusion

In this paper we have described the use of a photovoltaic system to power water pumps and a reverse osmosis desalination unit in Jordan Valley. The system is a standalone system providing a local farm with fresh water needed for irrigation and household use. The farm has no stable connection to the local electricity grid. Quantity and quality for the agricultural production has significantly increased.

We have presented the system sizing and design and discussed some measurement results related to PV energy and Efficiency which produced by the PV array during one year.

A photovoltaic system has been designed and implemented in Jordan valley for desalination purpose. The daily average of solar radiation sums was 5.8 kWh/m². The total PV energy produced by the PV array during one year is 11504 .The total annual energy consumption by loads is 6215 kWh.

The authors recommend fostering the use of photovoltaic system in standalone desalination plants for agricultural use in the Jordan valley.

5. Acknowledgments

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