Optimum Design Of Photovoltaic Powered Sea Water Desalination System

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Abstract: Due to the increasing demand of potable water in many locations around the world, the sea water desalination is now one of the main sources of supplying potable water. The main problem facing water desalination is the energy consumption needed by water desalination process. The depletion of the fossil fuel and its continuous increasing cost accompanied with the increasing demand of potable water, make the problem of supplying potable water more sophisticated. With the continuous decrease of the prices of the PV modules, it is becoming more attractive economically to design a Reverse Osmosis (RO) water desalination system using Photovoltaic (PV) system and it's friendly to environment if compared to fossil fuel impact. Using RO water desalination technique for desalinate sea water with high salinity (up to 45,000 ppm) into potable water. Instead of depending on conventional fossil fuel, the proposed system depends on solar energy in supplying energy, specifically photovoltaic (PV) systems. In this work a system design and cost analysis for RO Water desalination system powered by PV system without, with storage batteries and hybrid system using diesel fuel are presented. Regarding to low efficiency and lifetime of batteries which that should be replace every four years and it's expensive prices, the main concept is using water desalination system working during days time with a large array size without batteries storage or diesel fuel in order to reduce total system cost . Optimality criterion is the cost per M^3 of desalinated water.

Index Terms : Simulate Reverse osmosis (RO) plant powered by PV systems, Photovoltaic (PV) System, Reverse osmosis (RO) System-Desalination, Economical analysis , PV Models, Fresh water, Salinity

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1 INTRODUCTION

Red Sea water desalination is considered since it is one of the most salient areas in the world. Salinity is the total amount of dissolved material in grams in one kilogram of sea water. Principal desalination membrane techniques:

1.1 Reverse Osmosis (SWRO)

Reverse osmosis (RO) is a membrane separation process that recovers water from a saline solution pressurized to a point greater than the osmotic pressure of the solution (Figure 1). The United States ranks second worldwide in desalination capacity, primarily relying on RO to treat brackish and surface water. In essence, the membrane filters out the salt ions from the pressurized solution, allowing only the water to pass. RO post treatment includes removing dissolved gasses (CO2), and stabilizing the pH via the addition of Ca or Na salts.

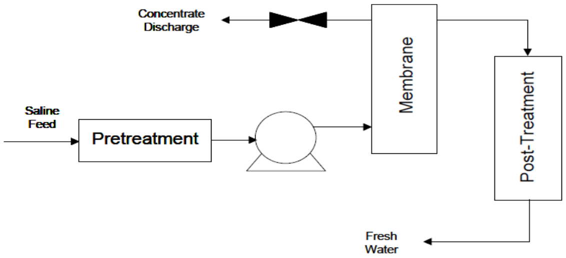

Fig 1.*Block diagram of reverse osmosis operations – optional pressure recovery devices not depicted.*

1.1.1 RO Modeling

Many mass transfer models have been suggested for RO membranes. A review of these models has been given by [7]. Among these are the solution diffusion model, the solution diffusion imperfection model, the finely porous model, the diffusion viscous flow model and the models based on irreversible thermodynamics. Some of these models have been used in the analysis of membrane modules of various configurations such as spiral wound and the hollow fiber membranes. The reverse osmosis process involves fluid flow across a semi-permeable membrane barrier as shown in Fig. 2. It is selective in the sense that the solvent passes through the membrane at a faster rate than the dissolved solids. The difference of this passage rates results in solvent solids separation. The solvent which is pure water in our case crosses the membrane with very low salt concentration. The concentrated water or brine is left behind.

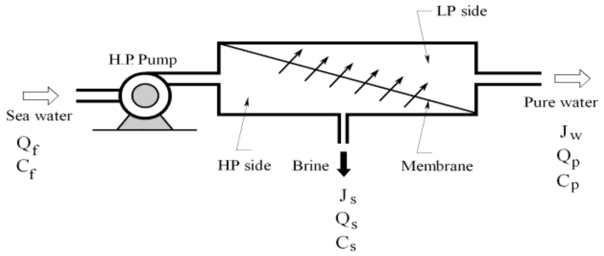

Fig2*.Reverse osmosis membrane module and nomenclature.*

In practice, a high-pressure pump driven by electric power or a diesel engine can produce the necessary high pressure. Any salt solution has a specific osmotic pressure individually depending mainly upon the solute concentration. For the seawater with a salt concentration of 35,000 ppm, the osmotic pressure is about 25 bars and the operating pressure applied on the seawater is usually larger than 55 bar. Reverse osmosis process can separate not only ions and low molecular weight substances in the feed water, but also most impure matters such as bacteria, virus and organic matters by the action of pressure difference across the membrane without any heat treatment and chemical addition.

Solution-Diffusion Model

Lonsdale et al. (1965) developed the solution-diffusion model assuming that the solute and the solvent dissolve in the homogeneous non porous surface layer of the membrane and then are transported by a diffusion mechanism under the chemical potential gradient in an uncoupled manner. The solvent or water flux Jw is defined as the volume of water passing through a unit area of the membrane. The water flux, Jw (= Qw/A), and the solute flux, Js according to solute diffusion transport mechanism are given by [1]:

$$J w = a (\Delta P - \Delta\pi) \qquad (1.1)$$

$$J s = b (C wall - C p) \qquad (1.2)$$

Where P (= Pb − Pp) is the applied pressure difference across the membrane, Pb the pressure in the bulk solution at the high pressure side, and Pp is the pressure in the permeate. π is the osmotic pressure difference of solute across the membrane. The subscript b indicates the bulk solution on the high pressure side, subscript p refers to the permeate and subscript wall refers to the membrane surface (on the high pressure side). Cwall is the solute (wall) (membrane surface) concentration at the membrane surface, Cp is the permeate side solute concentration and a, b are the solvent (membrane) and the solute (salt) permeability coefficients. The solute concentration at the membrane is usually greater than in the bulk solution due to polarization effects. In real membranes with imperfections and micro porous structures, the solution-diffusion mechanism might not be valid. Equations (1.1) and (1.2) show that for a given membrane:

- **a)** The rate of water flow through a membrane is proportional to net driving pressure difference across the membrane.
- **b)** The rate of salt flow through a membrane is proportional to the concentration differential across the membrane and is independent of applied pressure.

1.1.2 Salt Rejection

The solute (salt) rejection, SR, is defined as [3]:

$$SR = 1 - \frac{C_p}{C_b} \qquad (1.3)$$

the value of SR is a measure of the salt flow rate with the brine.

1.1.3 Osmotic Pressure and Osmotic Coefficient

The osmosis pressure, (in bars) of a solution can be determined experimentally by measuring the concentration of dissolved salts in a solution. The osmotic pressure, π, is obtained from the data given by [5] for the NaCl– H2O system at 25°C (concentration range: 0 - 49.95 kg/m3) and is correlated as:

$$\pi=0.7949C-0.0021C^2 + 7.0 \times 10^{-5}\ C^3 - 6.0 \times 10^{-7}\ C^4 \qquad (1.4)$$

Another equation is suggested by [6], (in Pa), which is given as: $\pi = (0.6955 + 0.0025\,T) \times 10^8\ \frac{C}{\rho}$ (1.5)

Where:
T is the temperature, °C
ρ is the solution density, kg/m3.C is the concentration of all constituents in the solution, kg/m3.There is not much difference between the results of the analysis, when using each data source consistently. Therefore, the osmotic coefficient, bπ, can be obtained as

$$b_\pi = \frac{\pi}{C} \qquad (1.6)$$

1.1.4 Characteristics of the Spiral Wound

The hydrodynamics in a spiral wound element are to a minor extent dependent on the overall geometry of the channel, but are critically influenced by the presence of the spacer material. The characteristics of the spacer-leafs are hence important. The hydraulic diameter d_h is given by [4]:

$$d_h = \frac{4\,\varepsilon}{\frac{2}{d}+(1-\varepsilon)a_{SP}} \qquad (1.7)$$

Where the void fraction (bulk porosity or void age), d is the channel height and a_{SP} is the specific surface area of the spacer, i.e. the ratio of its surface area to its volume. It is given by: a SP= 8 / d SP, where d SP is the spacer thickness. For a flow Q through the spacer filled channel, the velocity is hence defined as:

$$V = \frac{Q}{B\,d\,\varepsilon} \qquad (1.8)$$

Whereas d is approximated by the spacer thickness dSP, the width B should b taken as total width of the membrane leaves in their unwound state. The permeate spacer has normally a significantly lower porosity than the concentrate spacer. For the common concentrate spacers, the filament is approximately 0.3 - 0.4 mm thick. The void age approximates 0.9.

2. DESIGN PROCEDURES

A tourist village needed to supply 1000 m3 water per day, where that the capacity of RO plant is 40 m3 per hour (960 m^3/day) and load power is 150 KW.

2.1 There Are Three Different Types Of Water Desalination System:

2.1.1 Standard PV powered water desalination system with storage batteries.

The standard system's block diagram of standard PV powered Reverse Osmosis (RO) water desalination system with storage batteries is indicated in Fig. 4.

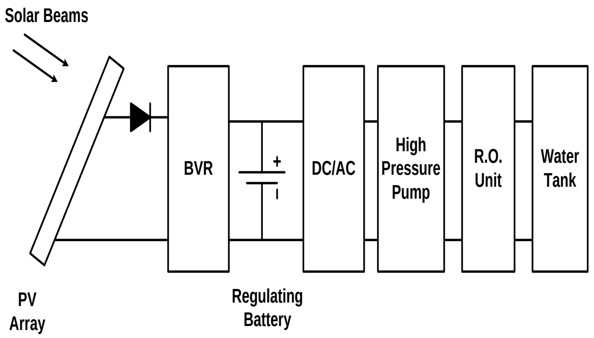

Fig4.*Block diagram of Standard PV powered water desalination system with storage batteries.*

The standard system is designed to be operated 24 hours per day.Fig.5 since stored solar energy is available only during sunshine hours (approximately 8 hours per day from t_1 to t_2); one has to store energy from day to night. Thus a storage battery is needed.

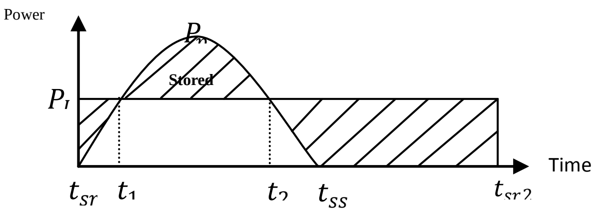

Fig5. *Principles of operation of 24 hours system*

Where that: P_L is the load power, t_{sr} is sunrise time and t_{sr} is sunset time. The standard system operation is simply as follows:

1. The solar power is converted into electric power that charges the storage battery through a Battery Voltage Regulator (BVR) that prevents the overcharging and deep discharging of the battery.
2. The battery feeds an inverter to convert the DC power of the battery into AC power.
3. The AC output power of the inverter is used to operate high pressure pump that drives the RO unit.
4. The output of the RO unit is potable water.
5. The potable water is stored into tank.

2.1.2 Standard PV Powered water desalination system without storage batteries.

The standard system's block diagram of standard PV powered Reverse Osmosis (RO) water desalination system without storage batteries is indicated in Fig. 6.

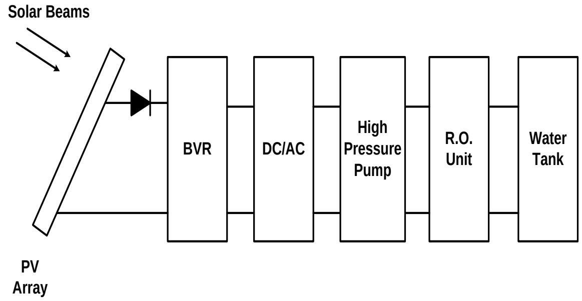

Fig6. *Block diagram of Standard PV Powered water desalination system without storage batteries.*

The standard system is designed to be operated 8 hours only per day.Fig.7 since the solar energy supply the system during sunshine hours from t_1 to t_2,

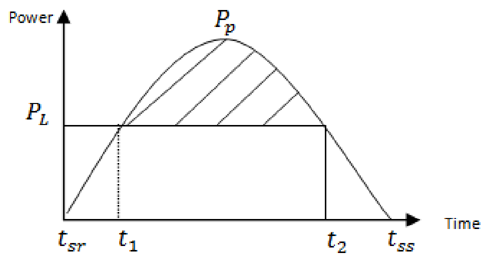

Fig7. *Principles of operation of 8 hours system*

Where that: P_L is the load power, t_{sr} is sunrise time and t_{sr} is sunset time. The standard system operation is simply as follows: The solar power is converted into electric power that supplies DC /AC inverter. The inverter converts the DC power of the PV array into AC power. The AC output power of the inverter is used to operate high pressure pump that drives the RO unit. The output of the RO unit is potable water. The potable water is stored into tank.

2.1.3 Hybrid water desalination system.

The standard system is designed to be operated 24 hours per day.Fig.9 since the solar energy supply the system during sunshine hours from t_1 to t_2, otherwise the system supply from the diesel generator. The standard system's block diagram of hybrid Reverse Osmosis (RO) water desalination system is indicated in Fig. 8.

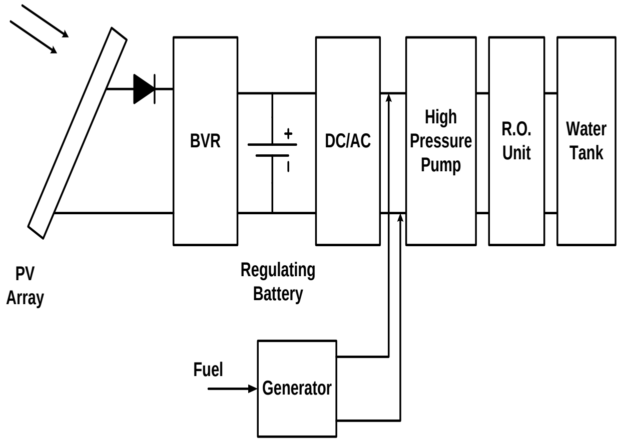

Fig8. *Block diagram of Hybrid RO water desalination system.*

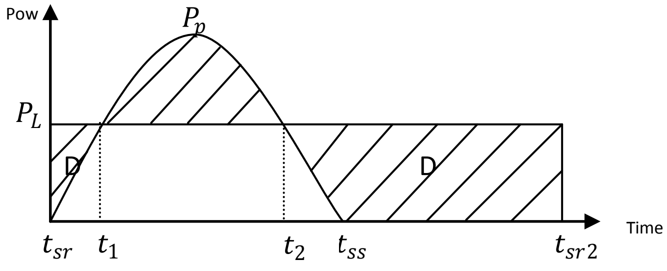

Fig9. *Principles of operation of 24 hours system*

Where that: P_L is the load power, t_{sr} is sunrise time, t_{sr} is sunset time, D is diesel generator .The standard system operation is simply as follows;

1. The solar power is converted into electric power that supplies DC /AC inverter.
2. The inverter converts the DC power of the PV array into AC power.
3. The power generator converts diesel fuels into AC electric power that supplies high pressure pump.
4. AC output power of the inverter, generator are used to operate high pressure pump that drives the RO unit.
5. The output of the RO unit is potable water.
6. The potable water is stored into tank.

2.2 PV Standard Modules

Our design is based on 200 W, 24 V PV modules.
Design Considerations: Water production =1000 M^3/ day
Battery Storage Characteristics
Depth of discharge (DOD) =0.7, Charge efficiency=0.8, Discharge efficiency=0.9, Battery Voltage (V_B) = 25.
Diesel Generator Characteristics
Maximum Output = 175,000 watts, Continuous Output =173,500 watts, Maximum Load = 456 Amps, Continuous Load = 452 Amps, Fuel is No. 2 Diesel, Fuel consumption at full load = 10.5 gallons/hour
Inverter Characteristics
DC Input: Input rated voltage (VDC) = 360V, Input rated current (A), Input DC voltage range (VDC) = 200~600V.
AC Output: Rated AC output power = 150KW, Phases = 3 phase, 4 wire, Output rated current (A) = 362A, Output voltage (V) = 415AC±5%, Output frequency accuracy (Hz) = 50Hz ± 0.05%.

2.3 Simulation Program

MATLAB Simulation software is used to simulate the dynamic behavior of a system that is represented by a mathematical model. While the model is being simulated, the state of each part of the system is calculated at each step of the simulation using either time-based. A detailed simulation program is developed considering climatic conditions of Egypt.

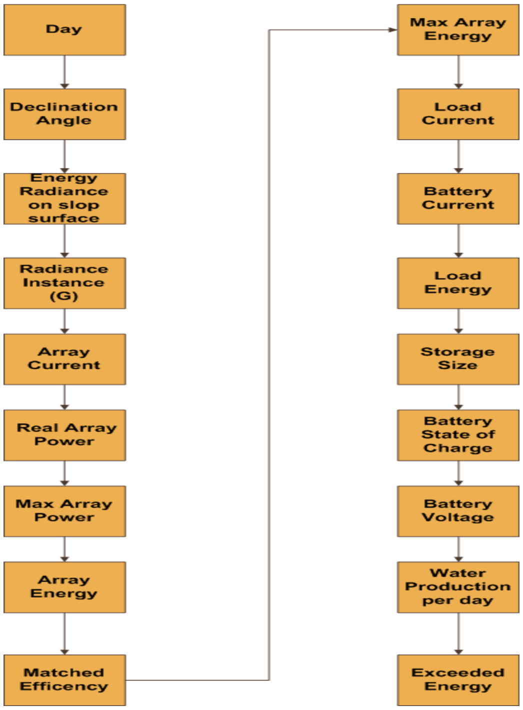

Fig10. *Simulation program flow chart for the system design*

3. DESIGN

1. Design without Tracking
2. Obtain the array size for each solution at fixed Tilt angle β=30.
3. Calculate water production per array size using Matlab simulation program.
4. Compare water production cost from each solution Design with Manual Tracking
5. Obtain the size for each solution at Tilt angle changing every day.
6. Calculate water production per array size using Matlab simulation program.
7. Compare water production cost from each solution.
8. Results

3.1 Designs without Tracking

To determine the array size required to generate RO water plant energy, Array size = $\frac{E}{\frac{kwh}{day}*ή}$ (1.9) .Let ή is the total efficiency which includes the (mismatching, the inverter and the battery efficiency) ή = 0.8 Monthly average .water production for arrays sizes [804K, 1002K, 1251K, 1500K, 1752K, and 2001K] is shown below:

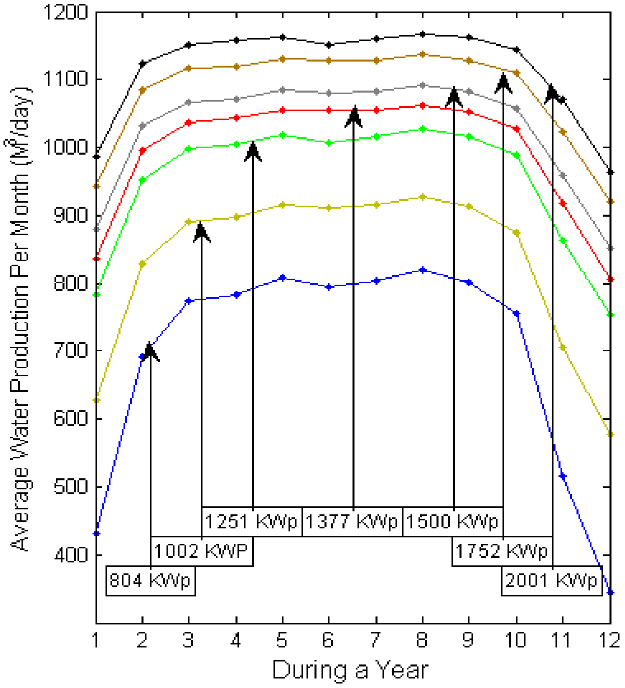

Fig11. *Monthly average water per array size (KWp) at β=30*

Total Water Production per year for arrays sizes [804K, 1002K, 1251K, 1500K, 1752K, and 2001K] is shown below:

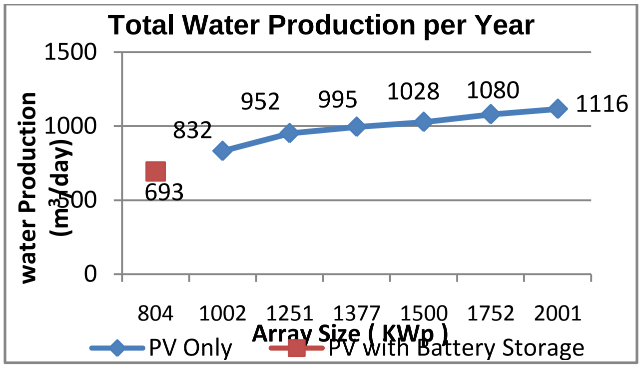

Fig12.*Total cost (EGP) per m3 for each system at β=30*

Compare water production cost for every solution

Table 1.1 Total cost (EGP) per m3 for each solution at β=30

Array Size (KWp)	**PV**	**RO (Unit)**	**Battery Storage**	**Tank (m^3)**	**Cost (EGP)**
804	Small	One	Large	1000	9.14
1002	Small	Three	NO	1000	6.45
1250	Large	Three	NO	1000	5.78
1250	Large	One	Generator	1000	7.54
1377	Large	Three	NO	1000	5.76
1500	Large	Three	NO	1000	5.59
1752	Large	Three	NO	1000	5.63
2001	Large	Three	NO	1000	5.66

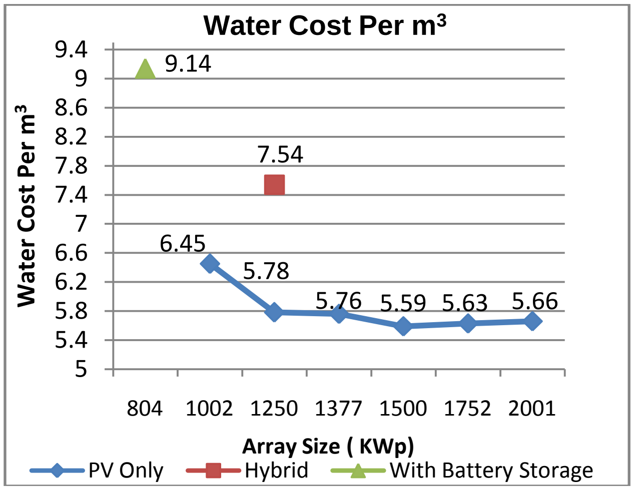

Fig 13: *Total cost (EGP) per m3 for each system at β=30*

3.2 Designs with Manual Tracking

To determine the array size required to generate RO water plant energy, Array size = $\frac{E}{\frac{kwh}{day}*ή}$ (1.10) Let ή is the total efficiency which includes the (mismatching, the inverter and the battery efficiency) ή = 0.8 .Monthly average water production for arrays sizes [804K, 1002K, 1251K, 1500K, 1752K, and 2001K] with change Tilt angle every day is shown below

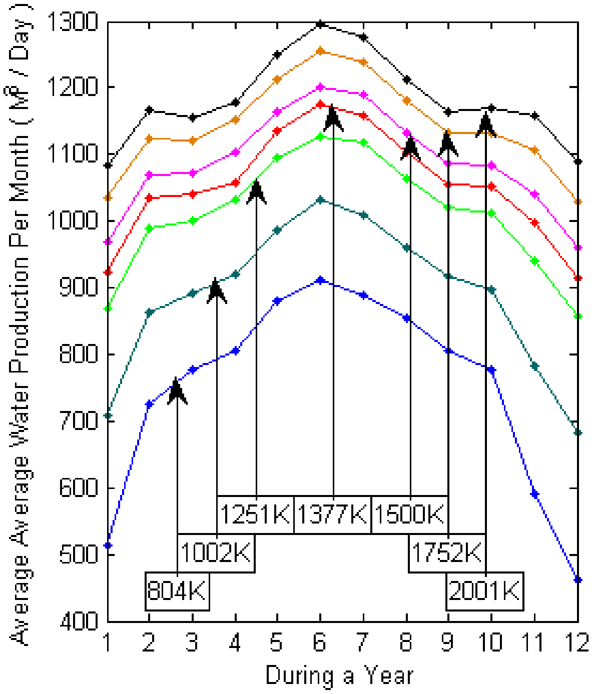

Fig14 *.Monthly average water per array size (KWp) with manual tracking*

Total Water Production per year for arrays sizes [804K, 1002K, 1251K, 1500K, 1752K, and 2001K] with change Tilt angle every day is shown below:

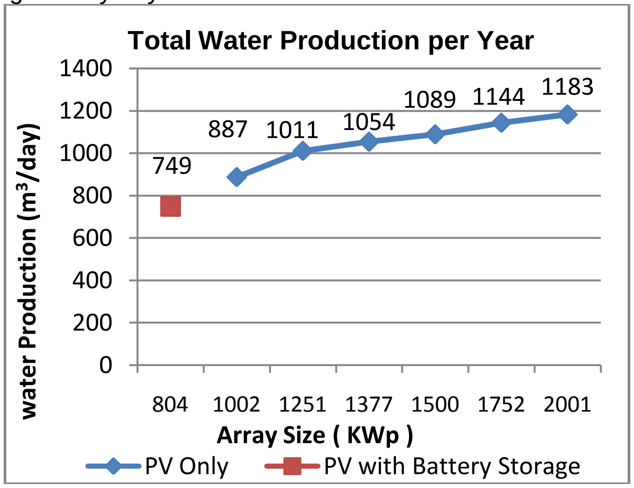

Fig15.*Total Water Production per year for arrays sizes*

Table 1.2 Total cost (EGP) per m3 for each solution with manual tracking

Array Size (KWp)	**PV**	**RO (Unit)**	**Battery Storage**	**Tank (m^3)**	**Cost (EGP)**
804	Small	One	Large	1000	9.14
1002	Small	Three	NO	1000	6.04
1250	Large	Three	NO	1000	5.45
1250	Large	One	Generator	1000	7.32
1377	Large	Three	NO	1000	5.43
1500	Large	Three	NO	1000	5.27

1752	Large	Three	NO	1000	5.32
2001	Large	Three	NO	1000	5.34

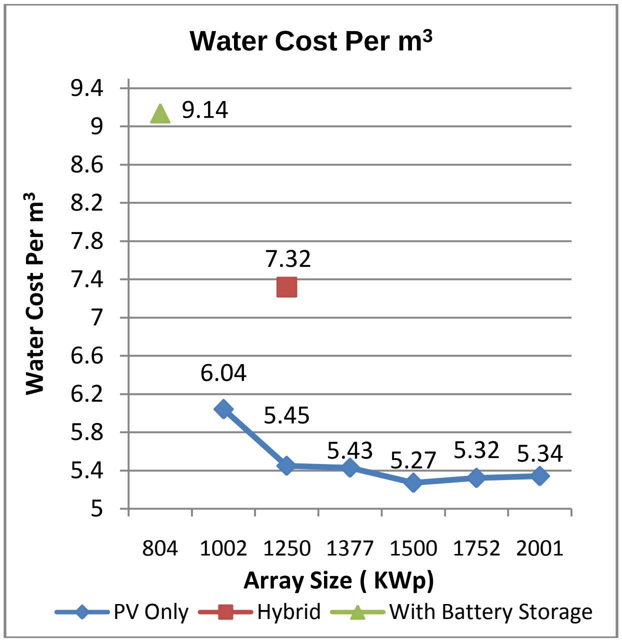

Fig 16: *Total cost (EGP) per m3 for each system with manual tracking*

3.3 If exceeded energy sold to Egyptian government where that 1KW sold to 1.02 EGP

Our system compared with governmental subsidized cost (6 EGP), Net Profit = Cost - governmental subsidized cost.

3.3.1 Exceed Energy without Manual Tracking

Table 1.3 Total cost (EGP) per M^3 for each solution at β=30

Array Size (KWp)	RO (Unit)	Battery Storage	Tank (M^3)	Cost (EGB)	Net Profit
804	One	Large	1000	6.61	-0.61
1002	Three	NO	1000	4.41	1.59
1251	Three	NO	1000	2.66	3.34
1251	One	NO	1000	2.10	3.90
1377	Three	Generator	1000	2.08	1.27
1500	Three	NO	1000	1.37	4.63
1752	Three	NO	1000	0.30	5.7
2001	Three	NO	1000	-0.1	6.1

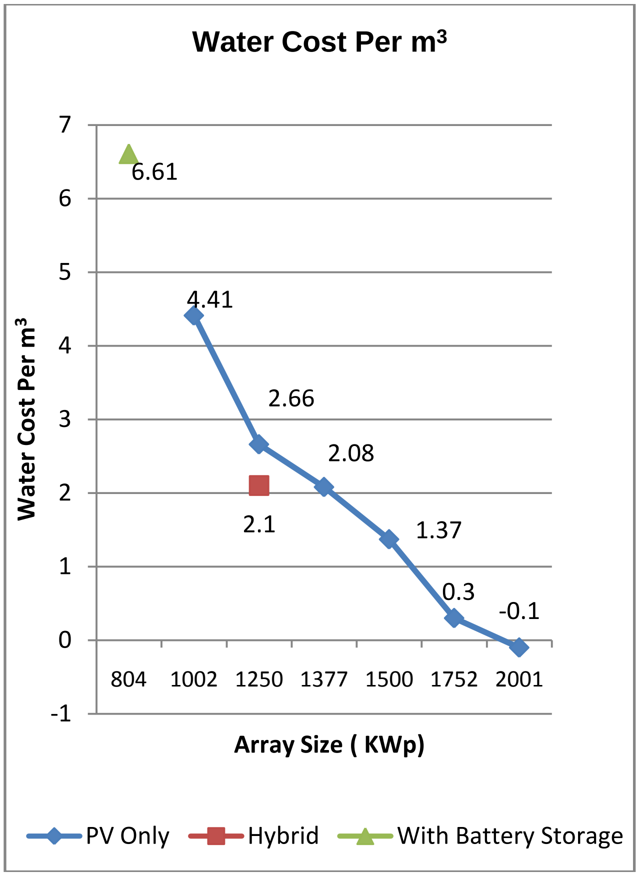

Fig 17: Total cost (EGP) per m3 for each system at β=30

3.3.2 Exceed Energy without Manual Tracking

Table 1.4 Total cost (EGP) per m3 for each solution with manual tracking

Array Size (KWp)	RO (Unit)	Battery Storage	Tank (M^3)	Cost (EGB)	Net Profit
804	One	Large	1000	6.35	-0.35
1002	Three	NO	1000	3.12	2.88
1251	Three	NO	1000	2.23	3.77
1251	One	Generator	1000	1.22	4.78
1377	Three	NO	1000	1.65	4.35
1500	Three	NO	1000	0.94	5.06
1752	Three	NO	1000	-0.2	6.02
2001	Three	NO	1000	-0.17	6.17

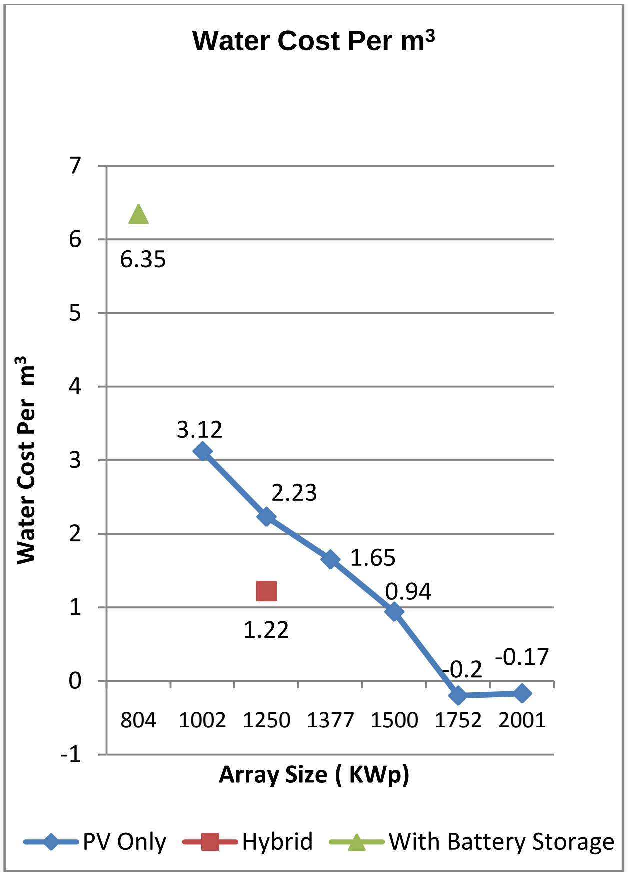

Fig 18: Total cost (EGP) per m3 for each system with manual tracking

4. CONCLUSION

This research showed that RO desalination system powered by PV array is a promising project since PV system cost is continuing reduction in cost. This research considered RO system producing 1000 m3 /day. It is shown that based on the cost of desalination m3. PV powered system is superior (less costly) on hybrid system using PV and diesel and it is superior on PV using storage. The analysis considered also manual tracking PV system and it is found superior on fixed PV. If exceeded energy is sold to Egyptian government (according to new laws approved by Egyptian government), the results shown that whenever array size increase the water cost decrease until reach to zero water cost, when array size is too large in case of 1751KWp, 2001KWp zero water cost and all water sold become profit only, with manual tracking the water cost decrease percentage approximately 6 %. Hybrid system water cost is lower than PV system only because the system uses only one RO unit and the output of exceeded energy is higher than PV system only. The highest water cost in case of PV system with battery storage (804 KWp) because batteries have to be replaced 5 times during PV array life time.

5. REFERENCES.

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