

Modeling and Optimization of Brackish Water Solar Desalination Plant Working on Reverse Osmosis Process

Asma Adda, Wahib Mohamed Naceur, Mohamed Abbas, Mohamed Tabet

Abstract : Nowadays, brackish and sea water desalination has become one of important fresh water sources in arid and semi-arid regions suffering from water scarcity. The reverse osmosis process which is one of desalination process requires large amount of electric energy, it's around 3.5–5.0 kWh/m³. Hence, solar energy-powered reverse osmosis systems are promising technologies for brackish and seawater desalination notably for small remote communities. These systems can be designed according to water demand and energy resource. This work aims to minimize the specific energy consumption (SEC) of a solar desalination plant working on reverse osmosis process to produce fresh water from brackish water (BWRO). Two scenarios are taken into account; (1) BWRO without recovery device, (2) BWRO with energy recovery device (turbine). A mathematical model and an algorithm in the MATLAB area have been developed and validated. The results show that the minimum value of specific energy consumption for the proposed plant is about 0.1269 kWh/m³ for 47% of water recovery.

Keywords: Reverse Osmosis process, renewable energy, specific energy consumption, modelisation, optimization

I. INTRODUCTION

Faced with growing water demands in the world and particularly in Algeria, producing fresh and drinking water of acceptable quality with minimal cost is the main objective of all researchers [1]. The use of membrane process desalination is increasingly important to solve the water supply problem for human consumption.

The energy requirements for seawater desalination using thermal-based technologies are on the order of 7-14 kWh/m³ when compared to 2-6 kWh/m³ for membrane based technologies [2,3]. The energy requirements are lower for RO, but energy consumption still remains the major operational cost component due to the high pressure pumps required to feed water to the RO process [4]. Renewable energy technologies are the best energy supply option for desalination systems, where energy supply from an electricity grid is not readily accessible.

Photovoltaic (PV) technology can be connected directly to RO desalination processes to supply the energy need of the pumps (water feed pump, cleaning, booster and high pressure pumps) as shown in figure 1.

It's important to note that energy consumption for RO desalination processes can be reduced by using energy recovery devices (ERD).

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In this context, we present, in this study, a mathematical model to optimize a BWRO plant coupled with a solar energy system (Photovoltaic system). The optimization of the BWRO/PV systems is done by using projected gradient Algorithm. The model aims mainly to calculate the optimal configuration of the system with minimum specific energy consumption after determining the optimal number PV panels and different operating parameters of desalination plant.

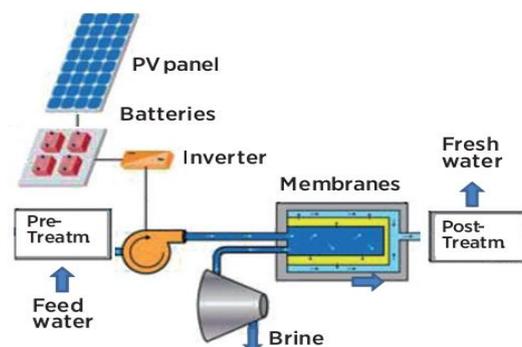


Figure. 1 Coupled PV and RO desalination plants [5]

II. MODELING -METHODOLOGY

The mathematical model developed in the present work consists of global model divided into two sub-models; one for photovoltaic generator and the second is dedicated for the reverse osmosis unit, where two cases are considered with and without recovery energy device

A. Modeling the PV modules

The main advantage of PV/RO systems is their ability to develop small size desalination plants. The electricity from PV systems can be used to drive high-pressure pumps in RO plants. The energy production unit consists of a number of photovoltaic modules, which convert solar radiation into direct electric current (DC) [6] Energy storage (batteries) is required for PV output power smoothing or for sustaining system operation when insufficient solar energy is available [7]. The model starts from a minimum number of PV modules which are able to provide the power supply for the RO unit A simplified simulation model is used to estimate the hourly output power of the PV generator; Photovoltaic power is given by [8]:

$$P_{PV} = S_{PV} G_i \times \eta_{pv}(T_{pv,i}) \quad (1)$$

The PV generator efficiency is expressed as:

$$\eta_{PV}(T_{a,i}) = \eta_{PV} \times [1 - \beta \times (T_{PV,i} - T)] \quad (2)$$

T_{PV} is calculated using the N_{occt} (Normal Operating Cell Temperature), it can be defined as follows :

$$T_{PV} = T_a + G_i \left(\frac{N_{occt} - 20}{800} \right) \quad (3)$$

The average number of the PV modules

$$N_{PV,m} = \frac{\bar{P}_{RO}}{\bar{P}_{PV}} \quad (4)$$

These different parameters are obtained from the PV module manufacturers.

We combined equation 2 and 3 in 1:

$$P_{pv} = S_{PV} \times G_i \times \eta_{PV} \times [1 - \beta \times (T_a + G_i \left(\frac{N_{occt} - 20}{800} \right) - T)]$$

B. Modeling of RO unit

The reverse osmosis model is performed for different configurations of the reverse osmosis process from 1 to n stage, and also for process without energy recovery and process with energy recovery system

C. Process without recovery energy

Generally in this state, the high pressure pump acts as an energy recovery device it must ensure a water flow rate at a given pressure, while absorbing the minimum energy

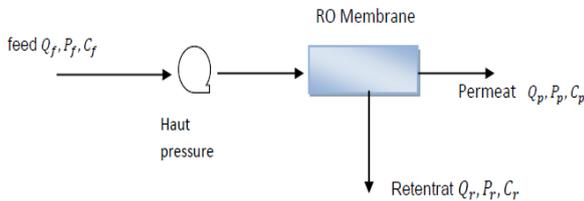


Figure 2. Reverse osmosis process without energy recovery

We define the specific energy consumption by the energy required for producing one cubic meter of permeate with a salinity desirable [9]. In a reverse osmosis process without installation of recovery energy device, the selection of the high pressure pump is very important [10,11].

The specific energy consumption is defined as follows:

$$SEC = \frac{w_{pump}^0}{36.6 \eta_p Q_p} \quad (6)$$

The work of the high-pressure pump w_{pump}^0 is given by the following relationship:

$$w_{pump}^0 = p_f Q_f \quad (7)$$

The recovery ratio of the membrane is given as the following formula:

$$y = \frac{Q_p}{Q_f} \quad (8)$$

According to the relations 1, 2 and 3 the specific energy consumption is calculated as following:

$$SEC = \frac{P_f}{36.6 \eta_{pump} y} \quad (9)$$

D. Process with recovery energy device

The turbine the classical device used in the small plant to reduce the consumption energy of the process of desalination worldwide [12].

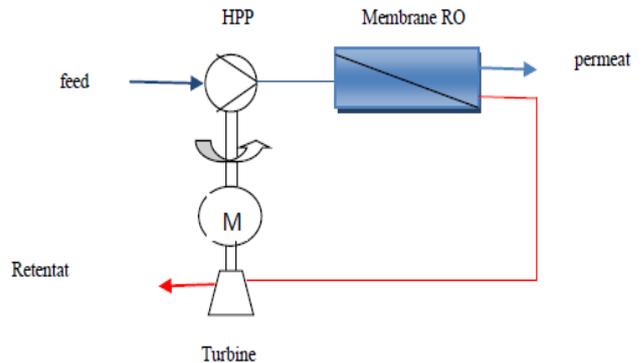


Fig 3. reverse osmosis process with turbine

The specific energy consumption of the turbine is expressed as follows:

$$SEC_{turb} = \frac{1}{36.6} (P_f - \Delta P) \times \eta_{turb} \left(\frac{1}{y} - 1 \right) \quad (10)$$

Therefore the specific energy consumption of the process is equal to the difference between the pump power and the energy recovered by the turbine [16]:

$$SEC_{turb} = \frac{P_f}{36.6 \eta_p y} - \frac{1}{36.6} (P_f - \Delta P) \times \eta_{turb} \left(\frac{1}{y} - 1 \right) \quad (11)$$

The RO unit power is expressed as:

$$P_{RO} = SEC_{RO} \times Q_p$$

E. Mathematical solution method

One ways to solve a problem of constrained optimization is to fit a projection gradient algorithm so as to comply, at each iteration and constraints [13]. The principle of the method is based on the gradient calculation of the objective function based on various parameters and recalculates, under constraints in order to assess the specific energy consumption

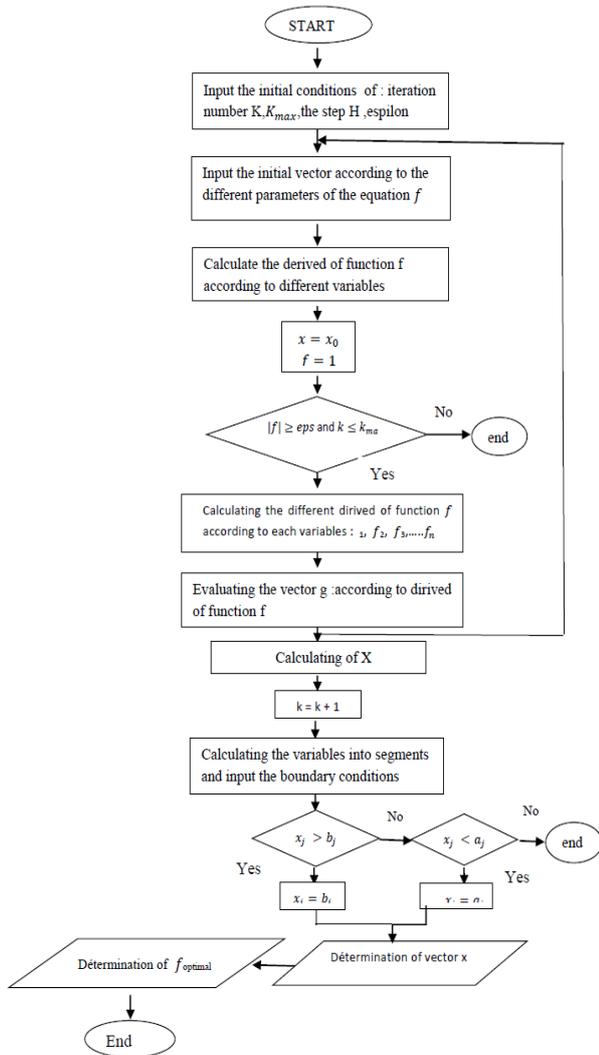


Fig 4. Flowchart of projection gradient method

F. The case study

To validate the proposed optimization methodology on real site, a model from reference [14] has been selected. The characteristics of the PV/RO desalination brackish water unit are illustrated in table 1.

Table 1. Characteristics of the PV/RO unit in Kser Ghilene village [14]

Characteristics	Values
Working temperature C ⁰	35
Feed water concentration (TDS) ppm	3500
feed water flow rate (m ³ /h)	2.25
Recovery ratio (%)	32.23
feed Pressure (bar)	6
product flow water (m ³ /h)	0.625
power (kw)	2.06
specific energy consumption (kwh/m ³)	0.98

Table 2. Characteristics of haut pressure pompe

Characteristics	Values
Model HYDRA_cell	
Efficiency %	72.25
Flux max (m ³ /d)	20

Table 3. Characteristic of the PV module

Characteristics	Values
Model PW 6-230	
Efficiency %	10
Nominal Power	230
Surface (m ²)	1.84

Table 4. Characteristics of the PV/RO plant obtained from the model

Characteristics	Values
Feed Pressure (bar)	5.8522
RO Efficiency %	47
HPP efficiency	85
Turbine efficiency	90
Specific energy consumption (kwh/m ³)	0.1269

G. PV array sizing

The voltage of the PV array is 96 A, two inverters, one for RO plant and the other for the auxiliary loads (feed water pump, for example). Taking into account number of hours of the plant function (6 hours per day), the daily total energy required is 27 kWh. The total PV power is 5.4 kW. We should also take into account the array thermal losses. For this, an increase of 25% in the array size is considered, so the PV field must produce 6.75 kW to satisfy the PV/RO plant needs. Among the PV modules available in Algerian market, we choose polycrystalline silicon with 140 W typical peak power rate (V_n = 18 V, I_n = 7.78 A, I_{sc} = 7.5 A, V_{co} = 22.3V). The number of modules required is 49 for without batteries option and 58 modules with storage, such as indicated on figure 5

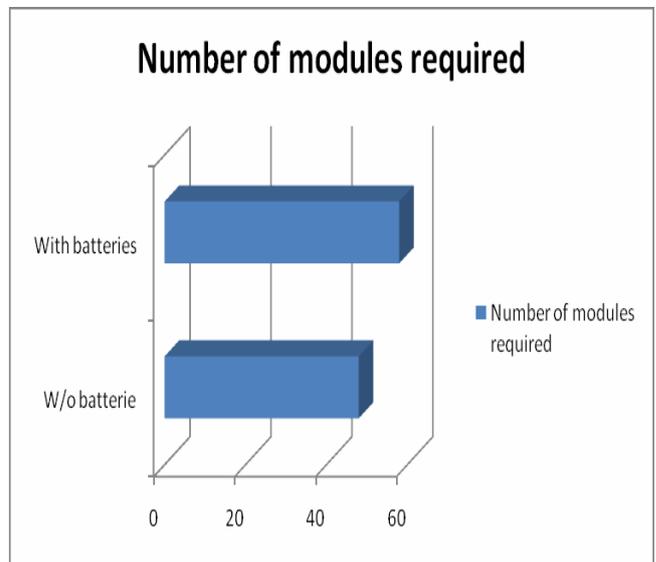


Fig. 5, PV modules required

Concerning the specific energy consumption and in order to optimize it using a turbine as energy recovery (figure 6) device for the same PV/RO plant, the mathematical model developed can reduce the energy to up 87% and the optimal recovery of the unit go to 47%, as mentioned on figure 7.

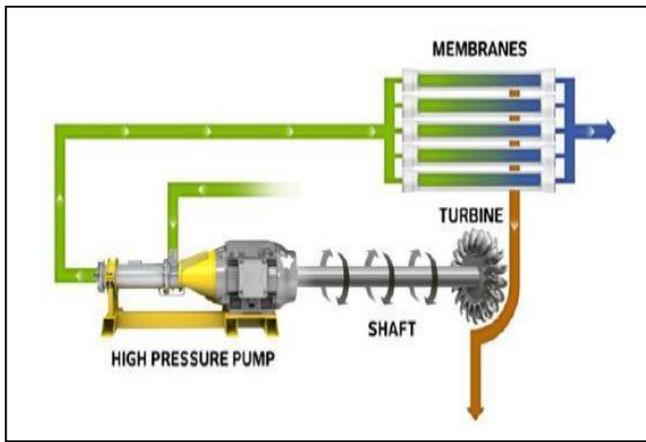


fig.6, Pelton turbine schematic

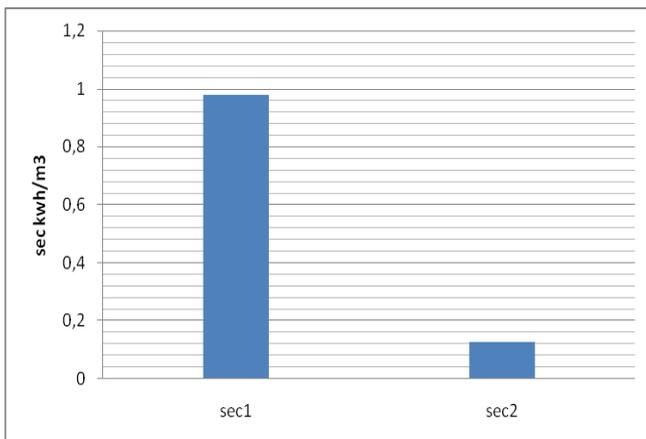


Fig 8.evaluate of specific energy consumption of the plant Sec1 :actually energy of unit ,sec2 :energy obtained from the model

in order to optimize the specific energy consumption of the plant, the model reduce the energy to up 87%and the optimal recovery of the unit go to 47%.

III. CONCLUSIONS

Desalination energy consumption is critical problem from worldwide, small scale PV/RO desalination units represent possible alternative for potable water supply for such areas. In this paper, we presented, in the first step we modeled the RO system, the photovoltaic. In the next step, we chose Kser Ghilene Village to validate the program of the projection gradient method writing in MATLAB software .The program reduces the specific energy of the plant to 87% with a recovery 47%.

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