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Modeling of Reverse Osmosis Water Desalination Powered by Photovoltaic Solar Energy

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Abstract

Sea water contains 35 g/L of salt, while the maximum concentration for water intended for human consumption is 400 mg/L (fresh water). Freshwater is an essential component in our daily life; but its availability is on the decline due to population growth and climate change. To meet the demand for fresh water in regions where reserves are insufficient, several countries have adopted seawater desalination. Several physical methods allow the production of fresh water from seawater, one of them being distillation and reverse osmosis, and there is great potential to use renewable energy sources such as solar photovoltaics.
In order to model the phenomenon of reverse osmosis solar-based desalination, the author presents generalities of deslination technologies in the first part of this paper. The second part is devoted to the presentation of different water desalination systems combined to renewable energy, and their benefits and drawbacks from different perspectives. In the third part, the author describes the model of a PV water desalination system using Matlab Simulink software. Based on the simulation results, the author concludes this paper with the prospects of the presented work.

Keywords: reverse-osmosis, desalination, modeling, irradiation, Matlab

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1. Introduction

Drinking water is a necessity for survival, but its availability is not assured everywhere, and the situation is getting worse as the population increases amid pollution and global warming.

An estimated 71% of our planet is covered by water, but more than 97% of this volume is salty or brackish. Of the remaining 3% fresh water, 2.1% is frozen in glaciers or around the poles, reservoirs that are very difficult to use. This leaves only 0.9% of the water reserve to cover human needs (consumption, agriculture, etc). This water in rivers or groundwater is not equally distributed around the globe. The problem of water scarcity has been on the rise in recent years. This situation has been more pronounced in some developing countries with freshwater bodies, where the high population growth creates additional pressure on the limited water resources.

To date, there are many seawater desalination systems, majority of which have reached an industrial stage.

Today, more than 15,000 desalination units in 120 countries (USA, Australia, Spain, Qatar, Saudi Arabia, Algeria, ...) produce about 40 million m^3 of water per day, three quarters of which comes from seawater and a quarter from brackish water. Of this 40 million m^3, 75% is for human consumption, and 25% for industrial or agricultural use [1, 2].

In Morocco, water resources are limited and largely already mobilized through existing storage and transfer facilities. The superficial flows are weak, and some floods are often brief and intense, also precipitation experiences a large regional disparity. Of the total available water resources from effective rain, only 16 billion m^3 can be mobilized under acceptable technical and economic conditions. In total, Morocco has a natural potential for water resources, estimated in the average year at nearly 20.7 billion m^3, an average per capita endowment of nearly 691 m^3/year [1].

To overcome these problems of water scarcity, and to improve the quality and quantity of drinking water, desalination of seawater and brackish water is an option to supplement the demand in management actions.

For years, water desalination has represented an effective yet energy-consuming method to tackle the issue of water shortage [3]. Therefore, taking into account the current energy world market and increasing fossil fuel prices, renewable energy powered desalination is emerging as a viable solution.

In this work, the author will specify the actors of desalination and the impacts of this practice on the environment. We present the different desalination techniques used today. We then focus on desalination using renewable energy. Finally, a study of a photovoltaic solar desalination system used to produce 1 L of fresh water and its simulation results using Matlab™ is presented.

2. *Desalination technologies*

2.1. Thermal desalination technologies

Historically, Gulf countries have been the first to use desalination and are currently the largest desalinated water producers in the world. Some countries like Qatar rely on this method for 95% of the water needs. In Europe, Spain is by far the leading country producing desalinated water. In 1850, the first studies on osmosis were performed. In 1960, the rise of the Persian Gulf countries with huge energy resources but relatively little drinking water led to 90% of installation of

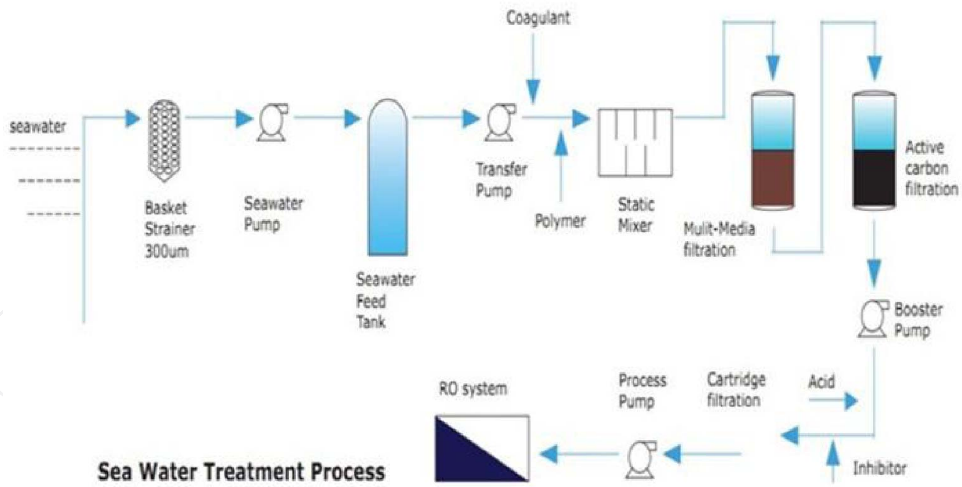

Figure 1. Desalination seawater process.

desalination plants. Later, in the 80s, more efficient polyamide membranes were born. About 20% of installations in Riyadh station–Saudi Arabia which was the first installation of reverse osmosis for brackish water. Today, reverse osmosis represents 50% of installations.

Currently, most plants are organized according to the following (figure 1) [4].

There are different techniques to desalt water; some are more adapted to a given environment than others. Presently, five techniques are used in two families: distillation processes and membrane processes (figure 2).

(1) *Multi-Stage Flash (MSF)*

This technology first appeared in 1960 to cope with scaling problems experienced by multi-effect distillation processes. Successive expansion distillation consists of placing a vacuum chamber (figure 3), isolated and containing only seawater. It is kept in equilibrium with its vapor at a temperature t and pressure p.

When hot water is introduced into the chamber, and p is less than the saturation pressure, there is an instantaneous vaporization by relaxation. The heat of the steam is transferred to the cold water circulating in the condenser tubes. It is then condensed on a tubular bundle located in the upper part of the enclosure. Pure distilled water can then be recovered. Saturation vapor pressure is the pressure at which the gaseous phase of a substance is in equilibrium with its liquid or solid phase at a given temperature in a closed system [5].

(2) *Multi-Effect Distillation (MED)*

The MED evaporator consists of several consecutive single cells (figure 4), in which the pressure and the temperature of the first (hot) to the last (cold) are

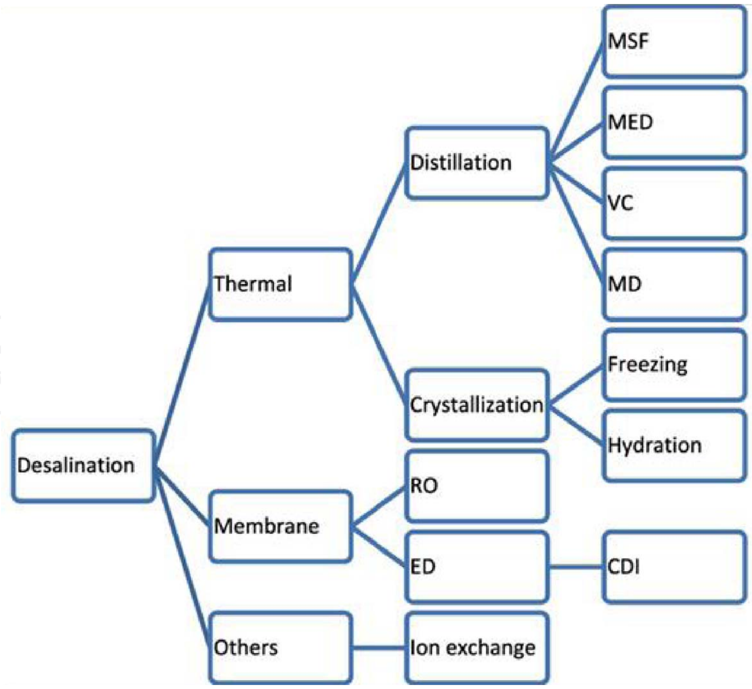

Figure 2. Different distillation technologies.

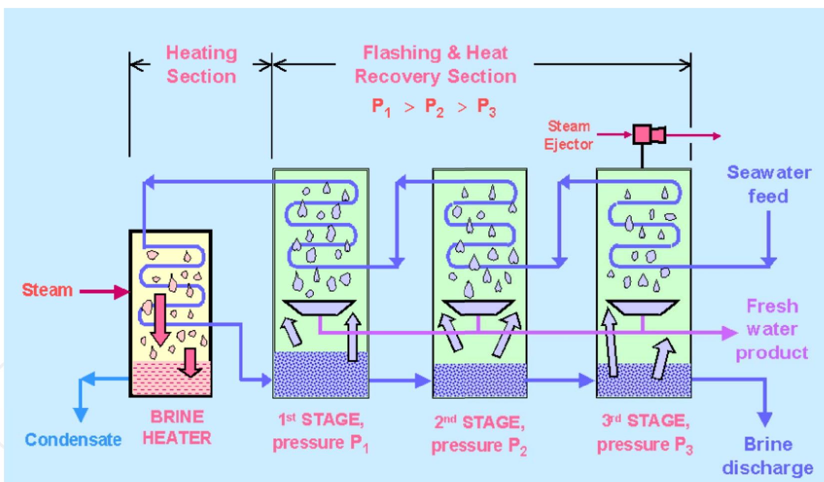

Figure 3. Multi-stage Flash distillation (MSF) [6].

decreased. Each cell (also called effect) contains a bundle of tubes. The top of the beam is sprayed with the seawater flowing around the tubes by gravity. The resulting vapor of the first effect condenses at the second effect and the latent heat (latent heat = heat caused by the passage of one substance from one physical state to another). Then the third effect acts as a capacitor for the vapors from the second effect, and so on ...

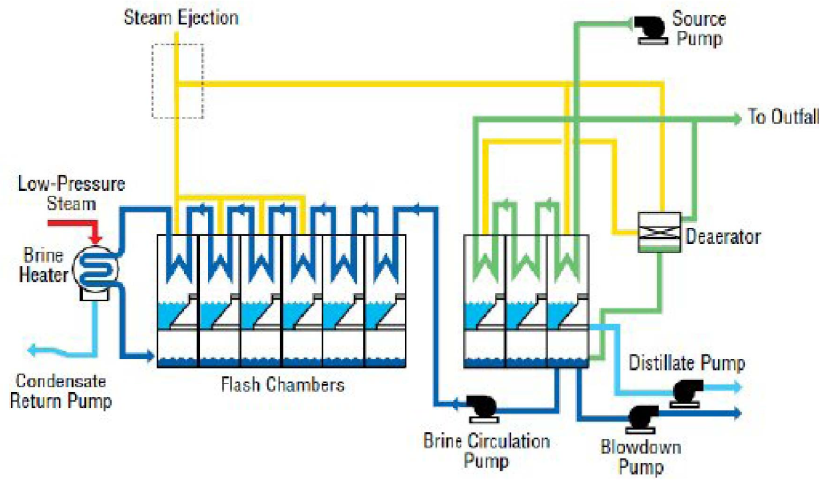

Figure 4. Multi-Effect Distillation (MED) [6].

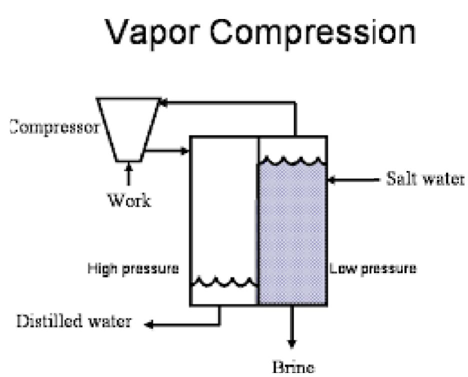

Figure 5. Vapor compression cycle [6].

The brine and the distillate are collected [7] in each cell from which they are extracted by centrifugal pumps. The operating principle of the MED method is illustrated in figure 4.

For industrial use of MED, it is sufficient to multiply the effects. This highly efficient process produces almost pure water from seawater.

Multi-effect distillation plants are now constructed with vertical long tube bundles or horizontal thin film tubes.

The costs of this process today vary between 900$ and 2,000 $ per m^3.

(3) *Vapor compression (VC)*

The vapor compression distillation process is shown in figure 5. When the steam is compressed, its temperature and pressure increase while its volume decreases.

In this process, the water to be desalinated is boiled in a thermally insulated enclosure. The steam produced is sucked by a compressor that raises its saturation

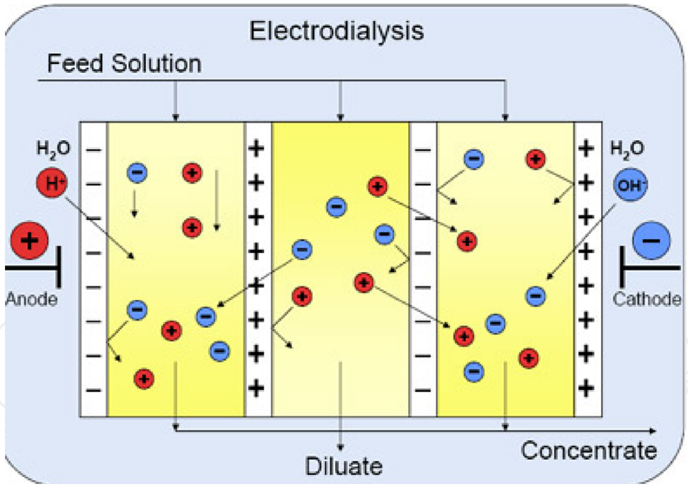

Figure 6. Electrodialysis process [6].

temperature. This vapor then passes through a tubular bundle and condenses, causing boiling of the salt water.

One of the advantages of the VC process is its low energy consumption and its simplicity of operation [8].

2.2. Distillation technologies

(4) *Electrodialysis: ED*

Electrodialysis uses the ionic state of salts dissolved in water: most salts in solution in seawater are positively charged ions (cations) or negatively charged ions (anions). We can illustrate the operation of electrodialysis by the following scheme (figure 6).

When an electrical voltage is exerted, the ions move towards electrodes of opposite charges. Between these electrodes, anion exchange membranes (only permeable to negative ions) and cation exchange membranes (only permeable to positive ions) are alternately placed. The electrical voltage causes a migration of ions present in the water that will concentrate in one compartment (concentrate) while the other compartment is depleted in salt.

This technique reduces the concentration of salts in certain compartments and increases it in other compartments.

In the electrodialysis process, electricity consumption is proportional to the salinity of the water. This explains why this process is generally used for the desalination of brackish water (having salinity lower than that of marine water).

The electrodialysis has an efficiency of about 45% per pass, so it takes several passes for satisfactory desalination.

(5) *Reverse Osmosis (RO)*

Osmosis is a natural phenomenon. If we consider two solutions of different saline concentrations separated by a membrane, the water migrates spontaneously from the diluted solution to the more concentrated solution. If a higher pressure is applied to the osmotic pressure (equilibrium pressure), the solvent will migrate from the concentrated solution to the diluted solution, reverse osmosis occurs [7, 9].

The osmotic pressure π is given by:

$$\pi = C.R.T \tag{1}$$

C: the concentration of the solution. R: the constant of the perfect gases, T: the temperature in K of the solution.

Osmotic pressure is defined as the minimum pressure that must be exerted to prevent the passage of a solvent from a less concentrated solution to a more concentrated solution through a semi-permeable membrane.

For proper operation, a commercial reverse osmosis desalination plant must contain the following components:

- A pretreatment system: it is essential in this process because the membranes must remain clean.
- High pressure pumps: they provide the necessary pressure to pass salt water through the membrane.
- A module accompanying the membrane: it is essential to allow the membrane to withstand pressures above 25 bar (osmotic pressure of seawater in the presence of fresh water).
- A post-treatment system: it stabilizes the quality of produced water and prepares it for distribution.

The orifices of the semi permeable membranes are in the range of 0.1 to 20 nanometers. The membranes are therefore particularly sensitive to chemical scaling and clogging by suspended solids and certain natural organic materials. Therefore, chemical and clarification pretreatments must be of high quality and maintained permanently.

Membranes are most often made of cellulose acetate or synthetic polymers (polyamides, poly sulfones). They can be flat or tubular or hollow fibers obtained by spinning polymers.

The membranes are characterized by their qualities of chemical stability (pH, oxidant ...), thermal stability, microbiological stability (bacterial degradation for

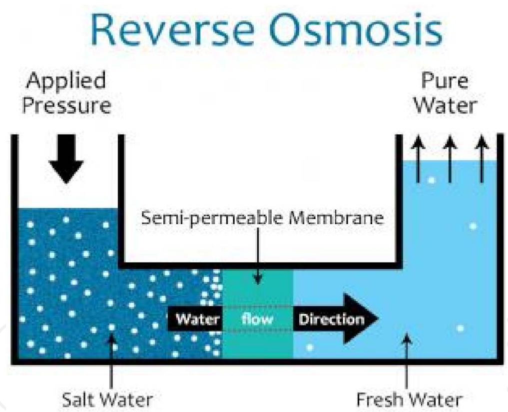

Figure 7. Reverse osmosis process [6].

cellulose acetate membranes) and thermal resistance. Their cost ranges from 40–50% of the investment of a unit of reverse osmosis.

To be implemented, the membranes must be mounted in supports called modules. A pressure-resistant enclosure is always needed. There are three types:

- Spiral module: a flat membrane is wrapped around a hollow tube that collects the permeate.
- Tubular module: a tubular membrane is fixed on a porous support.
- Hollow fiber module: the liquid to be treated circulates perpendicular to the axis of the fibers and the permeate flows inside the fibers and then in a collector.

The operation of reverse osmosis is illustrated in figure 7.

2.3. Reverse osmosis

R.O benefits and drawbacks are summarized in Table 1:

Table 1. R.O benefits and drawbacks.

Benefits	Drawbacks
Energy efficient	Slow process 15 gal/day
Good for health	High cost
No impact on the environment	Water losses

2.4. Electrodialysis

Table 2 shows the benefits and disadvantages of electrodialysis.

Consumers of desalinated water are six times more at risk of heart problems, including that of dying of an attack, than those not consuming desalinated water.

Table 2. Benefits and disadvantages of electrodialysis.

Benefits	Disadvantages
	Consumes a lot of electricity and can desalinate brackish water such that the concentration of dissolved salts is generally between 1 and 10 g/l when it is on average 35 g/l for seawater
Economical material-supply while limiting the influential releases	45% pass yield so it takes several passes for satisfactory desalination
No loss of water: 90% of the water is recovered	

Figure 8. Effect of salt on agriculture.

The reason is that unlike groundwater, desalinated water is free of magnesium.

The seawater desalination produces 141.5 million m^3 brine per day. This brine, when discharged in excessive concentration in nearshore shallow or low currentology, can cause "dead zones" eradicating all traces of life, sometimes over large areas.

Re-mineralization processes are currently being added to overcome the magnesium and other mineral deficit due to reverse osmosis.

Figure 8 shows an example of the salt effect on agriculture.

To incorporate renewable energy in water desalination process, more specifically wind energy, which is nowadays considered a mature technology, there are two main factors that should be taken into consideration:

- Specific energy consumption (Table 3): the ability to produce as much water as possible from the available energy during any period [10].

Table 3. Specific energy per desalination technology [6].

Desalination technology	Specific energy (kWh/m^3)
Multi-stage Flash	6–9
Multiple Effect	10–14.5
Vapor Compression	7–15
Electrodialysis	0.7–2.2
Reverse Osmosis	3–13

- Operability under variable conditions: which actually keeps the thermal technologies away; they usually require a long start-up time and significant energy waste could result from frequent stops.

From Table 3, RO is the technology with the highest potential.

2.5. Renewable energy & RO

Reverse osmosis is now considered one of the successes of desalination techniques (with 60% of installed global capacity). In addition, it is the process that combines best with renewable energy [11–14], due to its:

- its low energy consumption,
- its simplicity of operation,
- its reduced maintenance,
- its quick start and partial ease of operation.

(a) Cases of small capacity units (0.5 to 200 m^3/day):

These small units operate with battery energy storage, resulting in high costs (limited life, energy losses …). Such units must take into account a difficult environment:

- climatic environment: high temperatures, humidity, wind, sand …
- human environment: low technological level, maintenance problems over time.

(b) Cases of large capacity units (>1000 m^3/day):

Battery energy storage is hardly feasible, so a connection to an electrical network is necessary to mitigate the hazards of renewable energy and ensure operation of the desalination unit 24 hours a day.

Two essential characteristics of renewable energy must be taken into account:

- Their high cost
- Their discontinuity: regular alternation day/night for the solar - more arbitrary climatic parameters (solar, wind) - where energy storage is a necessity.

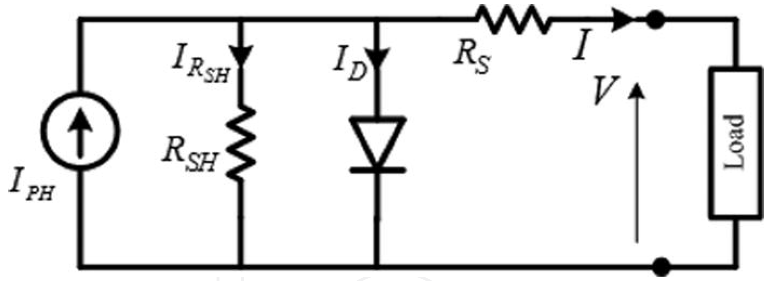

Figure 9. Equivalent circuit of photovoltaic cell.

3. PV desalination modeling

3.1. PV cell modeling

A basic modeling of a PV cell is shown in figure 9.

I_{PH} is an ideal current source. D is a diode denoting that the current flows in only one direction. R_{SH} is the shunt resistor that takes into account the inevitable current leaks that occur between the opposite positive and negative terminals of a photocell (micro short circuit in silicon in particular). R_S is the series resistance, which is due to the different electrical resistances that the current encounters on its path (intrinsic resistance of the layers, resistance of the contacts). Finally, the load is the impedance of the receiver which imposes the operating point on the photocell as a function of its current-voltage characteristic at the considered irradiation (in the case where the receiver is comparable to a resistor).

The operation equation of the solar cell is performed as follows:

$$I = I_{PH} - I_O\left(e^{\frac{V+IR_s}{v_t}}\right) - \frac{V + IR_s}{R_{SH}} \quad (2)$$

where v_t, the thermal voltage, is as follows

$$v_t = \frac{\eta kT}{q}$$

with $I_O = I_s$: the saturation current of the diode in ampere (A). I_{PH} =: the photovoltaic current.

q: Charge of the electron (1,6.10–19 C). k: Boltzmann constant (1,38 × 10–23 J/K).

n: Ideality factor (practically $1 \le n \le 5$). T: Temperature of the junction (in °K). $I_{PH} = I_{cc} \cdot (E_s/1000)$. E_s is the given irradiation.

Equation (1) is implemented in Matlab, and leads to the model of a PV cell shown in figure 10.

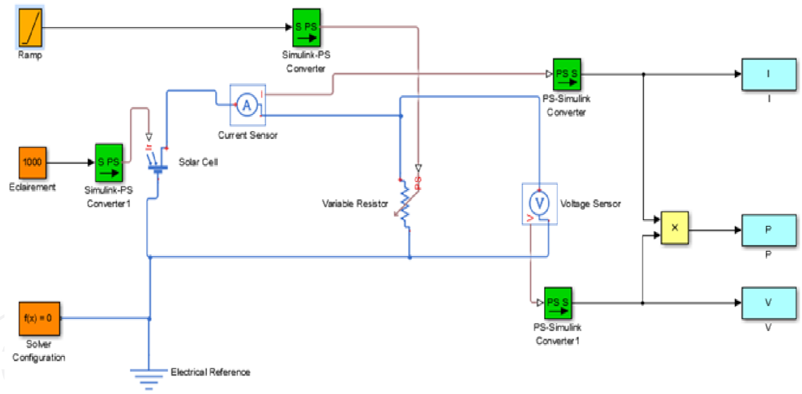

Figure 10. Model of a PV cell.

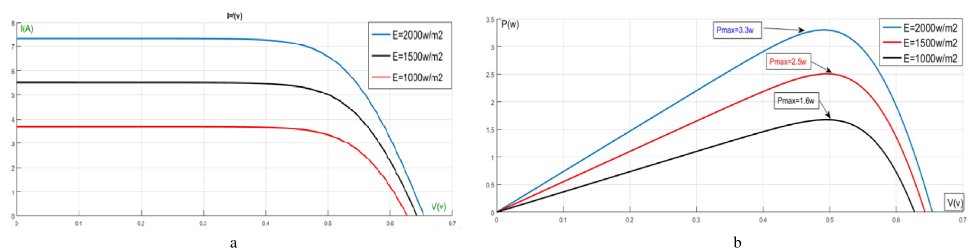

Figure 11. (a) Current versus the voltage of the PV cell under different irradiations. (b) Power versus the voltage of the PV cell under different irradiations.

Obtained results of the simulation of this PV cell under different irradiations are shown on figure 11, where figure 11(a) represents the current versus the voltage of the PV cell under different irradiations and figure 11(b) describes the evolution of the power versus the voltage of the PV cell.

3.2. PV desalination model

Drinking water by desalination of seawater demands high energy. There have not been enough major research studies on reverse osmosis membranes operating under varying conditions. In this paper, a Matlab model is developed to study the effects of solar PV across the reverse osmosis system.

The high pressure pump acts as energy recovery; it must ensure a water flow rate at a given pressure, while absorbing minimal energy as shown in figure 12.

With:

$$Q_A = Q_P + Q_R \tag{3}$$

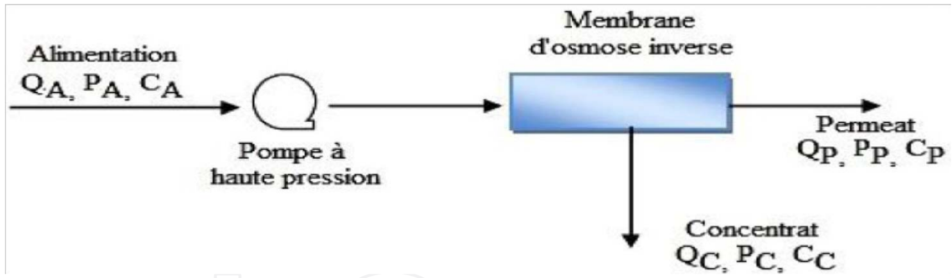

Figure 12. A method of reverse osmosis without energy recovery [15].

and

$$Q_R = Q_C \tag{4}$$

Q_A: The feed rate.

Q_P: The production throughput.

Q_R: The rate of rejection.

This model calculates based on the power from the photovoltaic generator and the feed rate.

To calculate the feed rate, we have used:

$$Q_A = P/(\rho^* H^* g) \tag{5}$$

with: P: Pump pressure (in Pa).

H: The head (given a value of 1 m).

g: Acceleration due to gravity (9.81 ms^{-2}).

ρ: The density of water.

The rejection flow is calculated as below [16]

$$Q_R = Q_A - (A^* S^* P_e/\rho) \tag{6}$$

with: Q_A: The feed rate.

A: The permeability of the membranes.

S: The membrane surface.

P_e: The effective pressure.

ρ: The density of water.

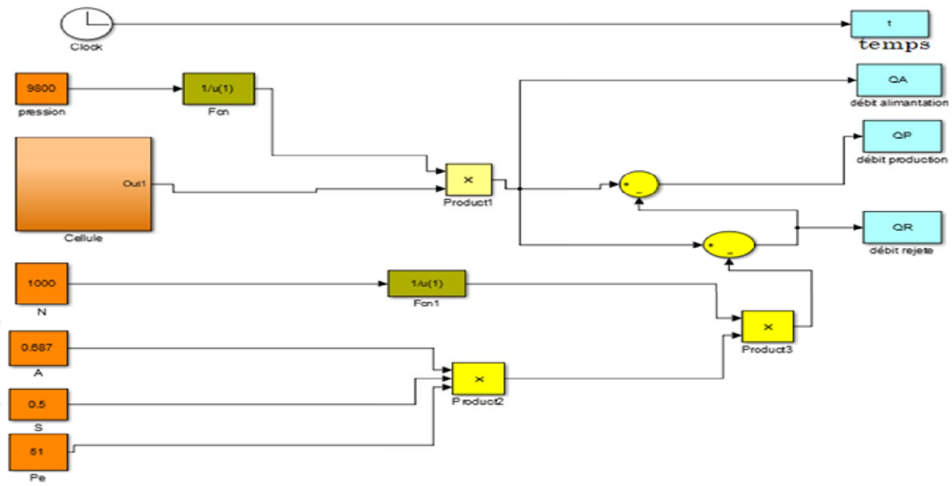

Figure 13. Matlab model of the PV desalination system.

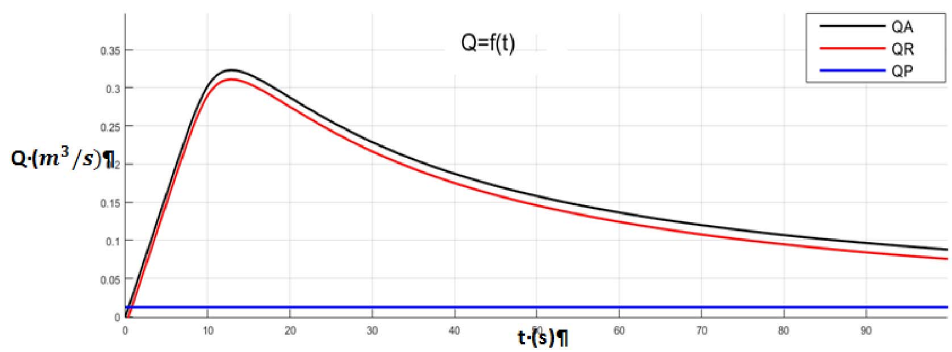

Figure 14. Temporal evolutions of the different flows.

From the equations (3), (4) and (5), the Matlab model of the PV desalination system is shown in figure 13.

Table 4 summarizes the values of the parameters above:

Table 4. The values of the used parameters.

Physical quantities	Numerical values
S (m^2)	1.6
P_e (bar)	46
ρ	1000
A (m/s/bar)	0016
P (pump osmosis)	3–13
P (pump pressure (Pa))	9800
g (ms^{-2})	9.81

Using these values, temporal variations of feed rates, production and rejection as a function of time are shown in figure 14.

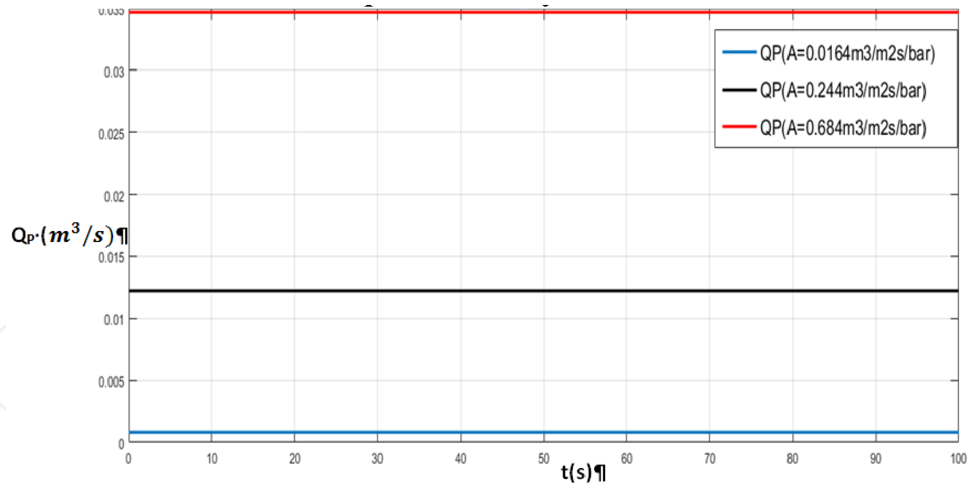

Figure 15. The effect of permeability on the production flow.

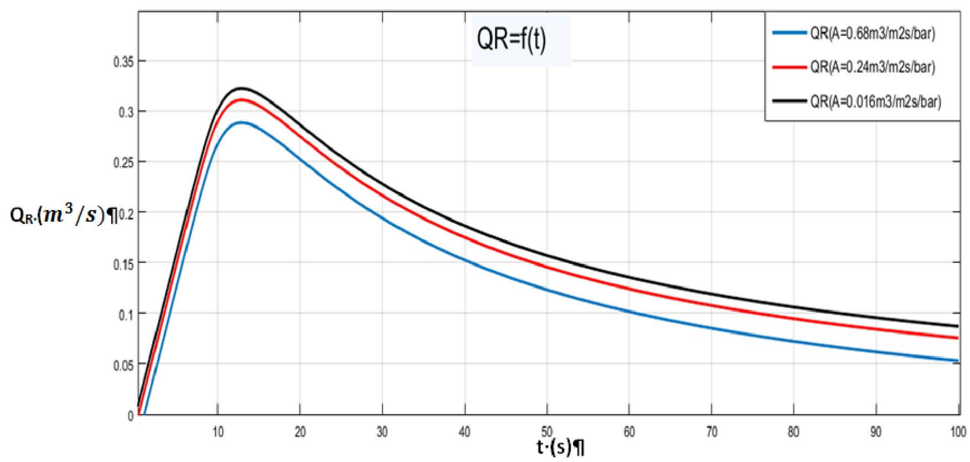

Figure 16. The effect of permeability on the rejection flow.

These simulations allow obtaining the temporal evolution of Q_P, Q_R for different permeability of membranes.

The minimum value of the permeability of a membrane is A = 0.016 m/s/bar. To highlight the effect of the permeability A on the production flow, we have chosen two values of A, greater than the minimum value.

Figure 15 shows the evolution of the production rate for different values of the permeability.

Figure 16 describes the effect of the permeability on the rejection flow.

From the simulation above, we observe that the increasing irradiation leads to a peak power up to the maximum value of 3, 3 W corresponding to an extreme

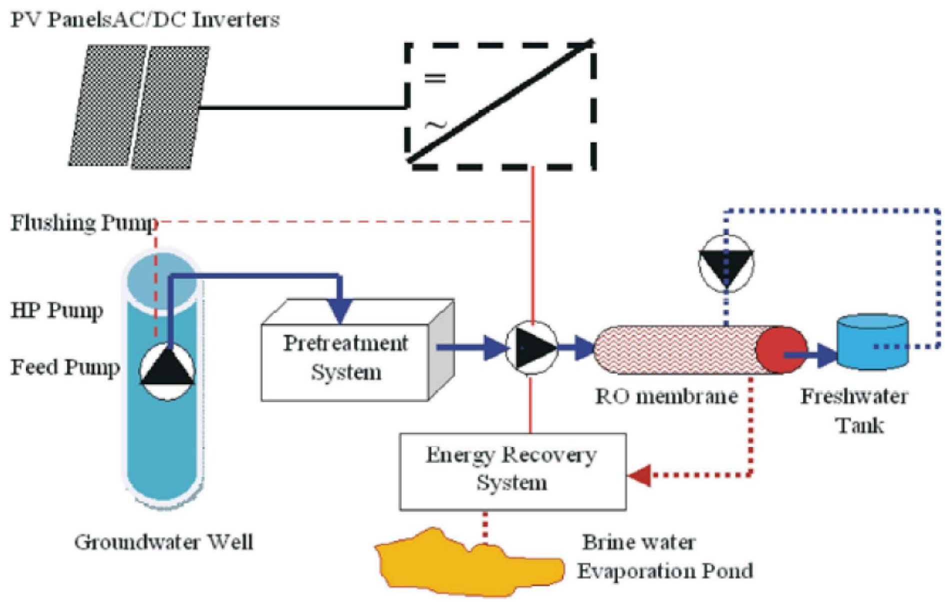

Figure 17. Solar powered RO desalination system for brackish/saline groundwater [17].

irradiation of 2 kW/m². Also, with an increase in the membrane permeability, we note a decrease in the amount of rejection flow, while the production rate increases.

4. PV desalination to produce 1 L of water

4.1. Data needed for the installation

From the beginning of the twentieth century, researchers have suggested separation of salt water through a membrane. Currently in Spain, 61% of new projects of sea water desalination use the reverse osmosis process. This technique provides an average of 1 L of fresh water from 2 L of seawater or brackish/saline groundwater.

Figure 17 shows an example of RO desalination plant with low energy PV.

Theoretically, production of 1 L of desalinated water in moderate isentropic conditions (constant temperature) requires an estimated energy of 0,536 Wh.

Under standard conditions, the maximum power for a PV cell (silicon) of 100 cm² is 1.25 W. Based on the data above, it is necessary to size the PV cell to produce 1 L of desalinated water. We can easily conclude that the size of the PV cell is D = 42.88 cm².

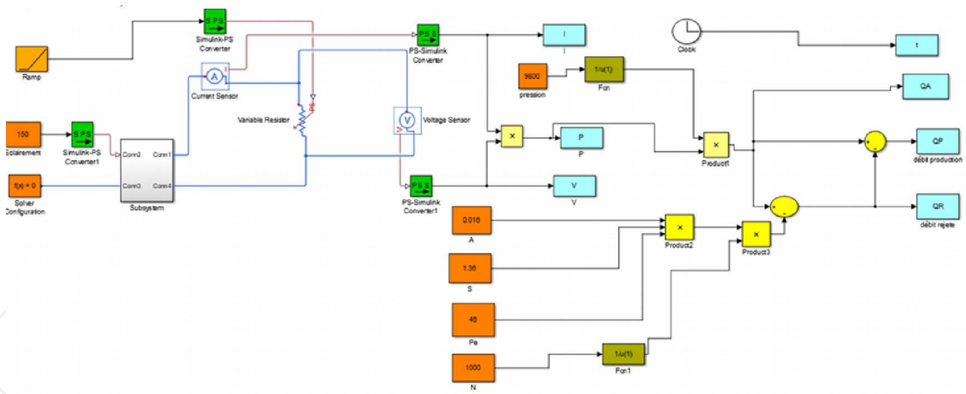

Figure 18. Matlab model of a PV panel and RO used for water desalination.

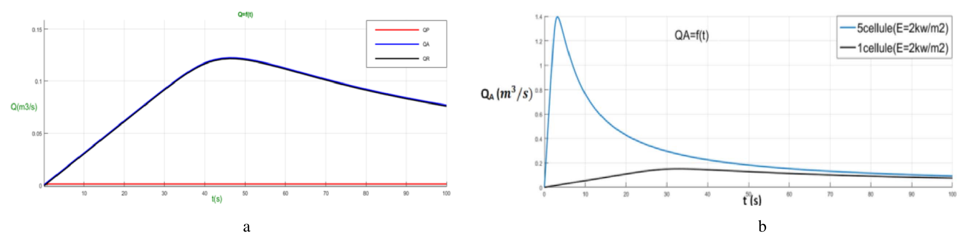

Figure 19. (a) The evolution of the production, supply and rejection flows. (b) The evolution of the supply flows for 1 cell and PV panel (5 cells in parallel).

4.2. Matlab modeling of PV panel to produce 1 L of desalinated water

Figure 18 shows the overall Matlab model of an RO desalination system, fed by a PV panel (5 PV cells in parallel), which is exposed to an irradiation of 1500 W/m².

The simulation results of the model above are shown in figure 19.

We can see that the production rate is 1 L/s.

Figure 19(b) shows that for an extreme irradiation of 2 kW/m², the supply flow increases when we move from one cell to a panel of 5 cells in parallel.

5. *Conclusion*

Desalination of seawater is one of the best solutions available today to reduce the problem of water scarcity which threatens most countries.

The most widely used process for desalination is reverse osmosis, which retains the salts and lets the water molecules through. This process requires energy to operate and can be obtained from a renewable energy source, which is photovoltaic solar energy in our model.

The novelty of the work presented in this paper, was to design a water desalination plant based on RO technology and PV energy in Matlab software. This station meets the need for water on earth and provides 1 L of desalinated water from 2 L of seawater or brackish/saline groundwater. The prospects of this work are to first extend the current study to an array of PV modules, to feed the desalination station, and then address the economic aspect of this installation, in order to perform a practical realization of this station prototype.

Conflict of interest

The author declares no conflict of interest.

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