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Optimum Design of a Photovoltaic Reverse-Osmosis System for Persian Gulf Water Solar Desalination

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Abstract: The present study describes the designing of an economically optimum PV-RO (photovoltaic reverse-osmosis) solar powered seawater desalinating unit which is capable for desalination of Persian Gulf water with the TDS of 40,000 ppm and produces potable water which complies with international standards. This unit has the capacity of producing 1424 m^3 of potable water per annum. In order to run continuously, desalinating units are equipped with lead-acid batteries, but these batteries are causing some problems and are costly. In this system, instead of storing electricity in batteries, potable water is stored in storage tanks to maintain constant flow rate of potable water. In this design, the number of photovoltaic cells to provide needed energy for the RO system is determined with the assumption that it should function with a minimum reception of solar energy. Economic assessment is also carried out to draw comparison between this system and conventional systems in terms of costs.

Key words: Photovoltaic, reverse-osmosis, seawater desalination, solar energy

INTRODUCTION

Water is becoming scarce as consumption increases due to population growth and rising standards of living. The average daily per person water consumption is in the order of 50 L in the developing countries and exceeds 500 L in certain western countries. These values represent the total average consumption for all activities without distinction while for the human nutritional purpose the daily requirement is only about 4 to 5 L per person for cooking and drinking. About 97.5% of the world's water resources are existed as salt water in the oceans and seas. A water-desalination unit is generally designed to reduce the number of dissolved particles to a maximum rate of 500 ppm. This process is highly energy intensive. At the present time a number of large desalination units are already in operation, most of these units are powered by fossil fuels (oil or gas) either directly for distillation processes or indirectly for processes using semi-permeable membranes (electro-dialysis or reverse osmosis). However, for a high capacity plant operating with a high plant factor -energy- related costs account for 40 to 50% of the total cost per cubic meter of fresh water (Rodriguez, 2002; Miranda and Infield, 2002; Davies, 2005). Most of the Middle Eastern countries can make investment in this industry due to their high oil revenues and access to inexpensive fossil fuels while other nations can't afford it.

Nowadays, total capacity of water desalinating units in worldwide is 38 million cubic meters per day which is increasing every year. This will lead to an increase in fossil fuel consumption and

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consequent pollution of environment. It is estimated that, in order to desalinate such amount of water, at least 8.5 EJ/Yr (equal to 2.36×10^{10}kWh year^{-1}) of energy is needed (Rodriguez, 2002).

Energy consumption as an important factor in every desalination units dictates the choice of the used desalination method and the final unit cost of desalted water. Many studies were made and proved that reverse osmosis consumes less energy than the other systems (Buros, 1981; Akili *et al*., 2008).

The cost of the consumed energy depends beside the performance of the plant on the quality of Energy (Darwish and Al-Najem, 1987; Asmerom *et al*., 2008) when compared to freezing or evaporation, reverse osmosis has the advantage that water can be separated from a solution at near theoretical minimum power requirements without the large energy investment which is required for a change of state (Riedinger and Hickman, 1982; Karagiannis and Soldatos, 2008). So, low energy consumption is a primary reason why reverse osmosis is rapidly becoming the sea water desalination process of choice. The seawater reverse osmosis process requires only 5 to 7 KW m^{-3} of energy to produce a cubic meter of potable water where it is about 1/2 the energy that is required by conventional distillation. The Principle set-up of a RO desalination plant is shown in Fig. 1.

If renewable forms of energy are used in such units, an important step towards reduction of pollutants would be taken and fossil fuel resources would be protected as well (Rodriguez, 2002; Miranda and Infield, 2002; Davies, 2005). Renewable energies are environment-friendly resources of energy which are recoverable from nature and are free from pollutants. Although water desalinating units using renewable forms of energy account for only 0.02% of total water desalination capacity in the world, they prove to be economical in some regions where smaller capacities are required and sufficient. Each desalinating system which uses solar, wind and tidal energy is designed based on the specific operation conditions of the region. In 1986, the first RO system with the capacity of 25 m^3 day^{-1} using a diesel-wind hybrid system was installed in the Middle East. In remote and coastal areas, the needed energy for desalinating systems is provided by wind turbines and proportionate to the wind blow and the power generated by the turbine, power control is achieved (Miranda and Infield, 2002).

In seawater desalinating units, it is possible to use tidal energy but this is much more costly than other renewable sources of energy. Thus a need for utilizing more advanced and efficient technologies is felt in these units. It is, therefore, concluded that demand for potable water in the region reveals the potential of tidal energy. Seawater desalinating units can use the generated electricity while connected to the national power grid or independently (without any connection to the national power grid) (Davies, 2005).

At the moment, more than 130,000 water desalinating units are operating worldwide producing some 38 million cubic meters of fresh water a part of which is consumed by industrial sector and the

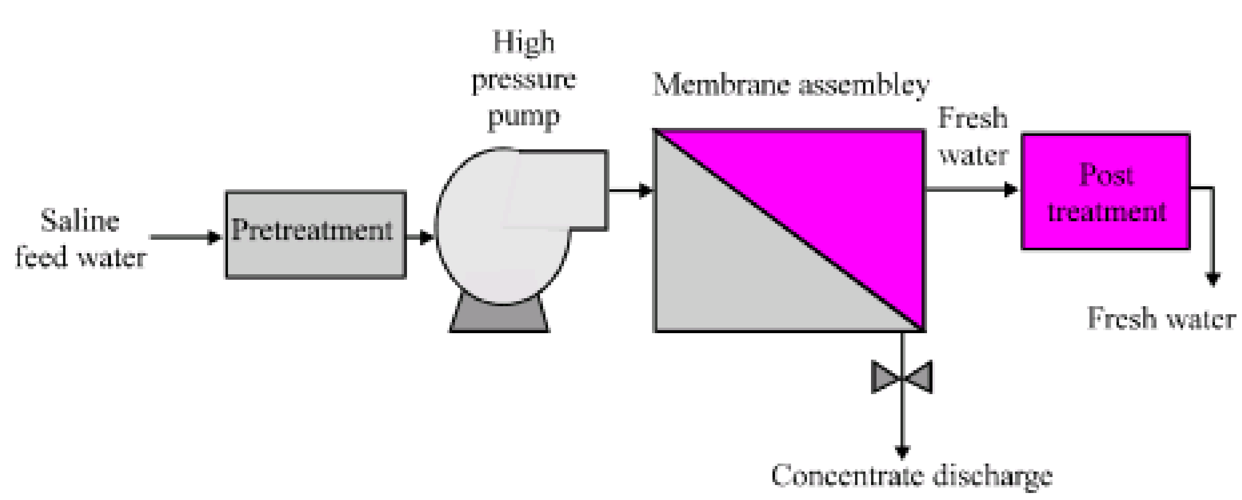

Fig. 1: Principle set-up of a RO desalination plant

Fig. 2: Portable PV-RO solar powered desalination system

remaining is used for agricultural purposes and drinking. RO, MSF, MED and VC types are among the most popular water desalinating units whose capacity is normally more than 100 cubic meters per day. Some types are capable of producing 100,000 cubic meters per day of drinking water (Rodriguez, 2002).

In reverse-osmosis desalination systems, solar energy is converted into electricity, using photovoltaic cells in RO systems. It is notable that the second method, due to its higher efficiency, adaptability with different climates, less capital costs, easier mobility, etc. is more popular (Fig. 2). In photovoltaic systems, solar energy is directly converted into electricity by means of solar cells (Essam *et al.*, 2008). In such systems, photo diodes are used in photovoltaic mode (zero bias). In some aspects, it is the best technology for small RO water desalinating units which merely need electricity for running. Therefore, RO is considered the best design for a solar powered water desalinating system where total demand for electricity is met through direct conversion of solar energy into alternative current electricity by solar cells. This study deals with modeling and design of a solar powered seawater desalinating unit which runs using RO technology. Such unit does not need batteries since uses photovoltaic energy (solar electricity). The capacity of the aforementioned unit is 1424 m^3 $year^{-1}$ of potable water according to the World Health Organization (WHO) international standards. Considering the fact that per capita demand for potable water is some 5 L day^{-1}, the designed water desalinating units is sufficient for providing daily needs of 156 families (with 5 persons). This system is designed for the regions that have no access to the national power grid thus photovoltaic cells are responsible for providing needed electricity and uninterrupted flow of water is maintained by water storage tanks.

MATERIALS AND METHODS

Process Description

Reverse Osmosis (RO) is a pressure driven separation of water from a brine solution across a membrane the pressure being adequate to overcome osmotic pressure of the saline solution and to provide an economically acceptable flux (Fig. 3) (Mindler and Epstein, 1986).

The membrane is placed in a cylindrical pressure vessel which must be adequately protected against damage which would be caused by failure or power outage. The cost of membranes is about 25% of the total installations for brackish water and about 35% for seawater (Kuiper and Mendia, 1980). The feed water Fw with concentration Cf (ppm) enter the membrane-module with pressure P

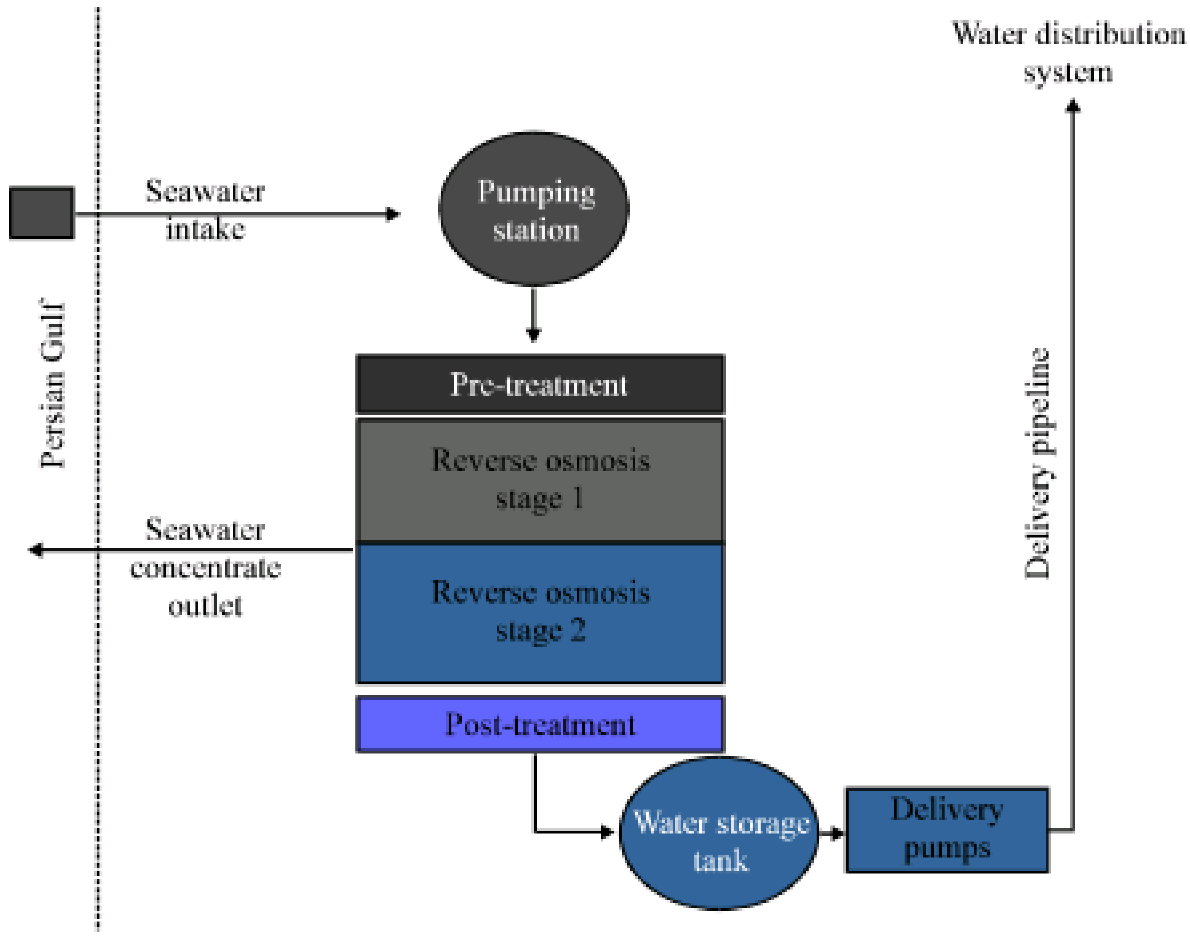

Fig. 3: Seawater Reverse-Osmosis (RO) desalination process

is split into a permeate flow or product water Pw with concentration Cp(ppm*)* and reject water Rw with concentration Cr(ppm).

The relationship between product water and feed water is given by a recovery ratio Rr as: (Kuiper and Mendia, 1980):

$$Y = \frac{P_W}{F_W} \tag{1}$$

Also the relation between feed and product and reject water in the RO system is as:

$$F_W = P_W + R_W \tag{2}$$

The product water flow through a semi-permeable membrane can be expressed at design operating condition as following (Schmoldt *et al*., 1981):

$$P_W = (L_p)(P\text{-}\Delta\pi)(A) \tag{3}$$

Where:

Lp = The hydrodynamic permeability of the membrane (m^3/m^2. psi. hr)

P = The applied hydrostatic pressure (psi)

A = The area of the membrane (m^2)

$\Delta\pi$ = The difference between the osmotic pressure of the feed $\Delta\pi$ f and product $\Delta\pi$ p water where is calculated by the following relation (psi): (Kuiper and Mendia, 1980; Schmoldt *et al*., 1981; Halary *et al*., 1978)

$$\Delta\pi = \Delta\pi f\text{-}\Delta\pi p \tag{4}$$

The salt rejection R is defined by the relation: (Kuiper and Mendia, 1980; Schmoldt *et al*., 1981; Halary *et al*., 1978):

$$R = \frac{Cf - Cp}{Cf} \quad (5)$$

The osmotic pressure of feed water is established by the feed concentration Cf and temperature Tk it can be expressed by (Darwish *et al*., 1989):

$$\Delta\pi f = \frac{0.0384933(Cf)(Tk)}{\left[1000 - \left[\frac{Cf}{1000}\right]\right]} \quad (6)$$

And $\Delta\pi p$ is calculated as follows:

$$\Delta\pi p = \frac{0.0384933(Cp)(Tk)}{\left[1000 - \left[\frac{Cp}{1000}\right]\right]} \quad (7)$$

Flow Rate

A RO plant is usually designed to produce a certain flow of product water, low product rate is a sign of fouling and an indication that cleaning is necessary. A configuration must be operated above min. brine or reject flow rate to prevent concentration polarization, from occurring. Each stage of an RO plant is designed to operate at a particular recovery (Malik *et al*., 1987), if the recovery is more than the design value then the product water quality will be poorer because the salt concentration on the feed/reject side of the membrane increases. A higher salt concentration increases the salt flux also the increase of the osmotic pressure will reduce the water flux, both result in impaired product water quality (Mindler and Epstein, 1986). The range of recoveries which have been proposed for various systems has been between (20 and 45%), with the lower recoveries being used in smaller systems, in other words the reject brine water is between (80 and 55%) of feed water. Not any study deals with this quantity of Reject brine water. As economical problem of brine disposal where is not included in economical estimates (El-Nasher and Husseiny, 1980).

Effect of the Feed Concentration

In actual operating conditions the feed concentration changes frequently, it was found that R0 flux decreased with increased feed concentration, where when the feed concentration increased its osmotic pressure rose but the effective operating pressure decreases so the flux still decreased noticeably.

The salt flow is essentially independent of pressure and the permeate quality improves with applied pressure. The relationship between the water flux and salt flux characteristics of a membrane can have significant effect on the power requirements (Rodriguez, 2002) Salt rejection depend on the salt flux or on the quality in other word depends on the-recovery ratio.

Energy Consumption

The theoretical energy requirement to separate fresh water from sea water at law recovery is about 0.75 kWh m^{-3} this theoretical limit could be approached by an idealized reverse osmosis device having:

- Perfect membranes able to provide complete salt rejection at working pressure just slightly above the feed Osmosis pressure
- Zero concentration polarization
- No energy requirement for feed pretreatment and filtration
- Negligible brine side hydraulic losses
- 100% efficient feed pumping
- 100% efficient energy recovery from the reject brine

Real reverse osmosis system depart rather widely from the above idealizations, in order to achieve high membrane productivity and salt rejection, typical working pressures for sea water desalination are about 2.5 times the feed osmotic pressure.

Energy losses due to hydraulic friction and pump inefficiencies are substantial. Reverse osmosis process is reversible and the minimum work is required for separation when the applied pressure approaches the osmotic pressure. Thus for a typical seawater system with an osmotic pressure of 24.8 atm the energy required to separate one liter of water would be 24800 cc-atm in more familiar units this amounts to 0.595 kWh m^{-3} in this is at an infinitely low permeation rate (Riedinger and Hickman, 1982).

The energy consumed by the P.O. process will be mainly used to drive the following pumps (El-Nasher and Husseiny, 1980):

- High pressure pump
- Reject water pump
- Feed water pump
- Product water pump
- Miscellaneous pumps for chemical injection

The following relations are used to calculate the consumed energy (wh) in PO:

- High pressure pump is:

$$EO = \left[\frac{(c)(P)}{ep}\right]\left(\frac{1}{Y}\right)(Fw) \tag{8}$$

- Reject water pump is:

$$ERP = \left[\frac{(c)(PR)}{ep}\right]\left(\frac{1}{Y}-1\right)(Rw) \tag{9}$$

- Feed water pump is:

$$EFP = \left[\frac{(c)(PF)}{ep}\right]\left(\frac{1}{Y}\right)(Fw) \tag{10}$$

- Product water pump is:

$$EPP = \left[\frac{(c)(PP)}{ep}\right](Pw) \tag{11}$$

where, c is conversion factor, P, PR, PF, PP are the applied pressure by high, reject, feed, product, pumps, respectively (psi) and ep is the efficiency of the pump.

Miscellaneous pumps for treatment will be not considered for simplicity and unknown specific parameters The load EL(wh) in the model is:

$$EL = EO+ERP+EFP+EPP \tag{12}$$

The specific energy SPE(kWh/m) of product water is:

$$SPE = \left(\frac{(EL)(10)^{-3}}{Pw}\right) \tag{13}$$

Solar Energy

The rising energy costs have motivated many countries to turn to renewable energy sources for desalination purposes. And particular attention is being paid to the consumption of various desalting processes it also results in an increased research effort on the use of renewable energies. A lot of effort is devoted to find competitive alternative energy source. Among possible alternative energy sources, the solar energy is the most inexpensive, pollution-free and limitless. The application of solar energy in different uses has found its way successfully in many purposes. The knowledge of the available solar irradiation is valuable for the design and assessment of solar energy system. Extensive work has been done for determining the total solar insulation on a flat plate surface at any orientation and their optimum tilt in different ways (Buros, 1981; Karagianuis and Soldatos, 2008).

The world's first solar-powered sea water reverse osmosis system has been installed and was operating in Jeddah, Saudi Arabia on the eastern shore of the red sea. A design concept for a solar desalination plant couples a solar power generation system with a reverse osmosis membrane filtration system. A photovoltaic powered reverse osmosis seawater desalination plant with a fresh water production of 150 (m^3/day) was carried out in Tarifa Cadiz Spain.

Solar Radiation

The solar radiation consists of direct and diffused radiation and the hourly values of global radiation incident on a tilted surface are calculated as follows: (Keefer *et al*., 1985):

$$H_t = H_{bt}+H_{dt}+H_{rt} \tag{14}$$

Where:

H_{bt} = Hourly values of direct radiation incident on a tilted surface
H_{dt} = Hourly values of diffuse radiation incident on a tilted surface
H_{rt} = Hourly values of reflected component incident on a tilted surface

The direct component on a tilted surface is calculated as the following:

$$H_{dt} = 0.5(H_d)(1+\cos(t)) \tag{15}$$

$$H_{rt} = 0.5(H)(rg)(1+\cos(t)) \tag{16}$$

Where:
H = The hourly value of the global radiation on a horizontal plane
rg = The ground reflectance
t = The tilt angle of the surface toward the horizontal plane

$$H_{bt} = (H\text{-}H_d)(R_b) \tag{17}$$

where, Rb is the hourly mean tilt factor and defined by the relation:

$$R_b = \frac{\cos(z)}{\cos(i)} \tag{18}$$

Where:
z = The angle between the incident direct radiation and the normal to the horizontal surface at the mid-point of the hour considered
i = The angle between the incident direct radiation and the normal to the tilted plane at the mid-point of the hour considered

The Photovoltaic Solar Cells

The growth of research development and production during the last decade in the area of medium and large-scale photovoltaic power generation, is phenomenal and several factors have emerged during the recent years that place the photovoltaic in a more favorable economic position (Keefer *et al*., 1985). The silicon is the most widely used and the best characterized semiconductor material.

It is dominating among the semiconductor materials used for photovoltaic energy conversion and it looks like it will keep this position for many years to come. Although there materials with better photovoltaic properties exist, silicon is out performing them either because of economic reasons or because of the mastering of its cell technology (Keefer *et al*., 1985; Thomson, 2003).

The design and simulation steps of a PV-RO solar powered desalination system is expressed through a practical sample that was carried out in south of Iran as a case study.

RESULTS AND DISCUSSION

Design and Modeling of a PV-RO System for Persian Gulf Water Solar Desalination

The data regarding the feed of the system is the foremost prerequisite for designing such system. In this system, feed is the seawater with TDS of 40,000 ppm (according to the analyses carried on the waters in the south of Iran), temperature of 25°C (maximum 40°C and minimum 15°C), pH equal to 7.6. If the (potable) water with the flow rate of 3.9 m^3/day outflows from the system, where the efficiency of the membranes is 10%, the flow rate of feed will be 39 m^3/day.

The system is mono-membrane with SW 30-4040 membranes (manufactured by the Filmtech Company) which is designed using ROSA 6.1 software.

It is notable that, according to standard No. 1053 developed by the Institute of Standards and Industrial Research of Iran, the required TDS for potable water is 500 ppm while the maximum allowed TDS is 1500. Therefore, the system is designed is to produce potable water with the TDS of 400 ppm. In the Fig. 4, the flow rate of the PV-RO solar water desalinating unit is shown.

Design of Photovoltaic System

The most important factor in designing appropriate solar powered units in any given region is having an access to sufficient data and statistics regarding the radiation and position of the sun in that

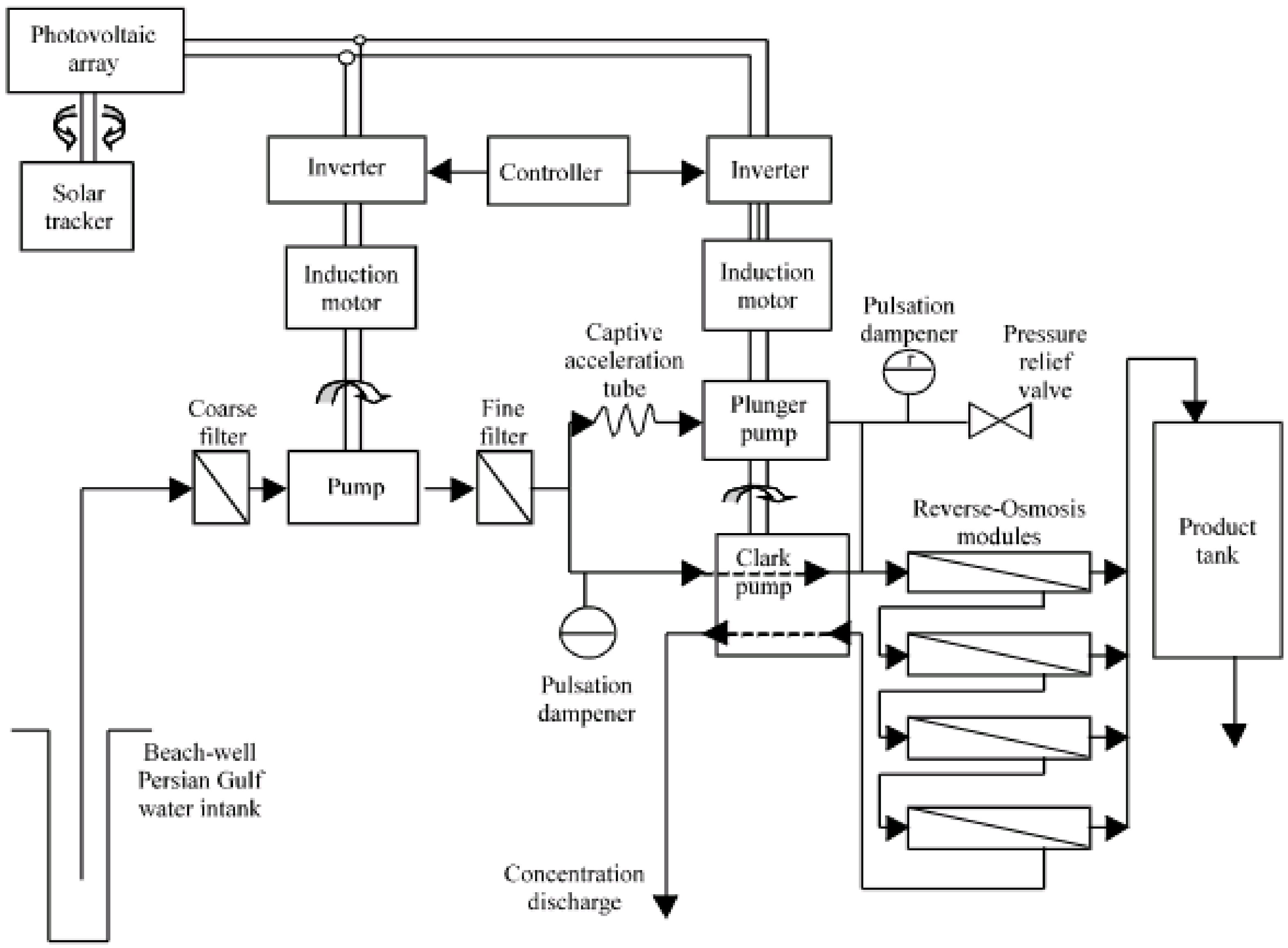

Fig. 4: Process flow diagram of the proposed PV-RO solar powered water desalination system

Table 1: Specifications of the selected module for the proposed PV-RO Solar powered seawater desalinating system

Model	NT-185UI
Type	Mono-Si
Open circuit voltage (V)	44.90
Short circuit current (A)	5.75
Voltage in maximum power (V)	36.20
Current in maximum power (A)	5.11
Area of the module (square meter)	1.30
Module efficiency (%)	14.20
η_r (%)	13.00
β_p (%/°C)	0.40

area (Thomson, 2003). In this study, calculations and statistics are carried out using average solar radiation data. In the proposed PV-RO system, the model NT-185UI manufactured by the Sharp Company was selected (Table 1).

In this design, the number of modules is determined considering the minimum radiation of the sun (which occurs in December) so that this number of modules would be sufficient for other months of the year (Fig. 5).

The amount of radiation based on the regions latitude is estimated at 5.272 kWh m^{-2}. In independent systems (not connected to the national power grid), direct voltage of the system is 24 or 48 V and considering the voltage of the system, the array of the modules series and type of inverter can be determined. Considering the fact that the selected modules at their maximum power can supply a voltage of 36.2, a two module series is needed to provide a direct current of 48 V. Considering the direct current of 48 V and maximum power of the pump, an inverter with the power of 5.5-6 kW is needed. Thus a 6 kW inverter (6.48 PSI Pars) is convenient for the system. Some fixtures are needed to fix the modules (Fig. 6).

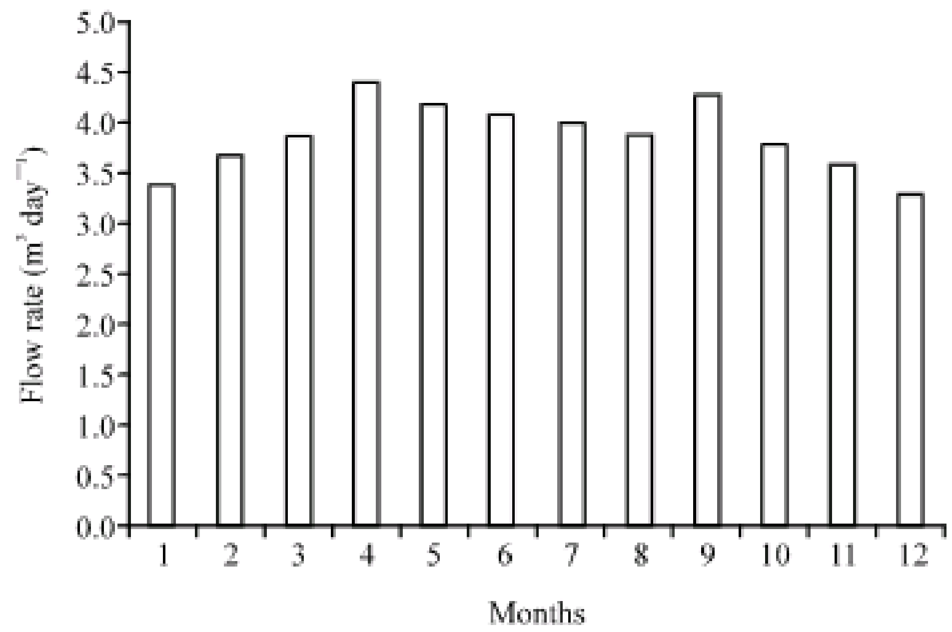

Fig. 5: Average flow rate of produced potable water per month by the solar powered water

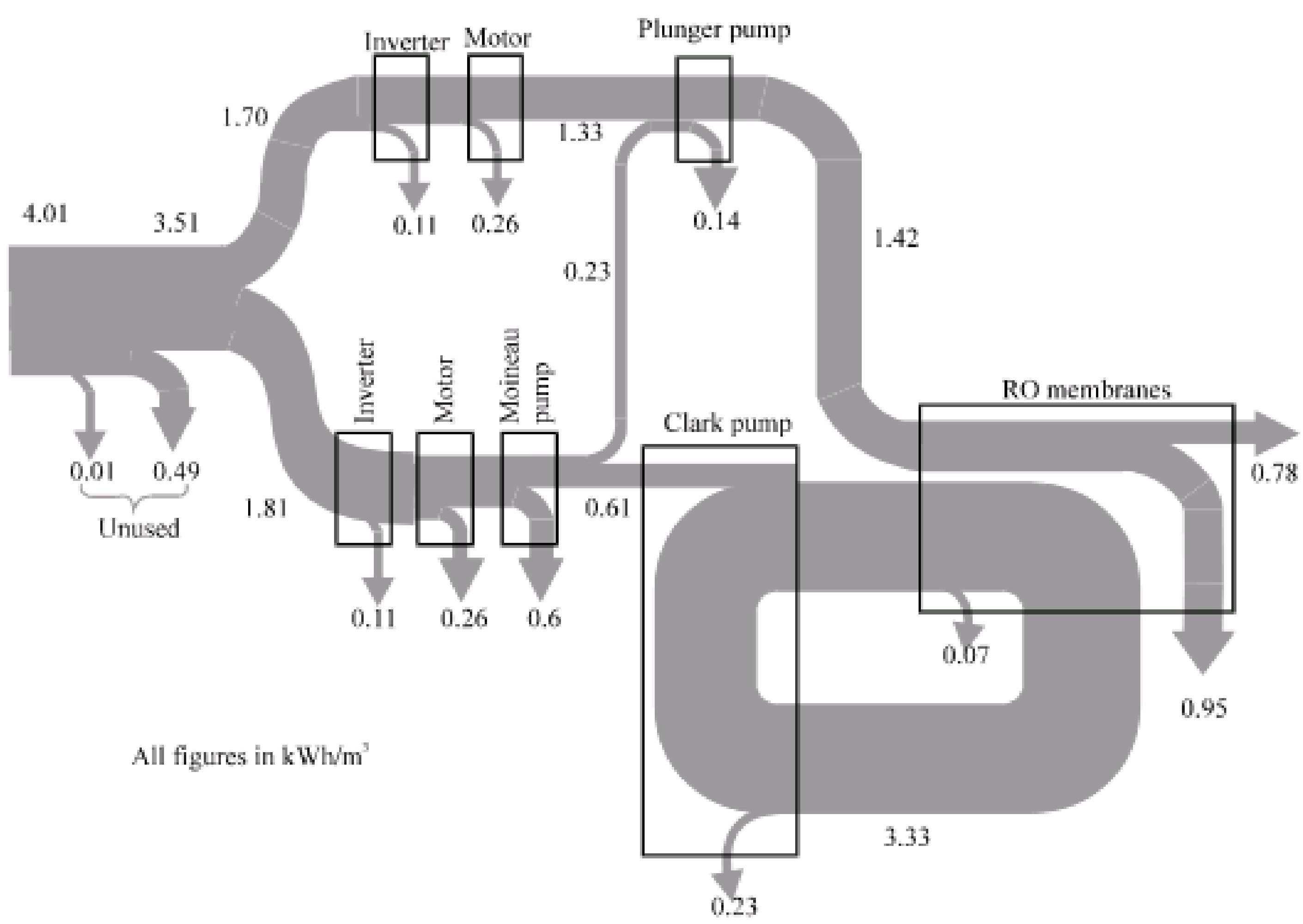

Fig. 6: Energy balance of the solar powered water desalination unit

For the modules manufactured by the Sharp Company, the TTRGM and DPandW fixtures capable of fixing at least 4 modules are used.

The Results of the Proposed PV-RO Water Desalinating System Simulation

The results of the simulation of the system's function are shown in the following diagrams.

Cost Assessment of the Proposed Solar Powered Water Desalination Unit

Total annual capital cost of implementing the project of a PV-RO solar powered water desalinating unit producing 1424 cubic meters per annum in the Persian Gulf region (without batteries) are shown in the following Table 2.

Table 2: Assessment of annual cost of implementing a pilot project

Items	Cost($)
Photovoltaic (PV) array	9515
Reverse osmosis elements and pressure vessels	3635
Pumps (all three)	2977
Motors and inverters	1048
Miscellaneous	3298
Total components and materials	20473
Manufacture's make-up on components and materials	4095
Manufacture's labour at cost including overheads	3778
Make-up on labour	1134
Total	29480

Table 3: Cost of producing a cubic meter of potable water by the PV-RO Unit

Life cycle cost based on 20 years of operation	Values
Annual product volume (m^3)	1424
Total amount of water produced (m^3)	28480
Initial hardware cost	29972$
Estimated shipping and installation costs	7150$
NPV of maintenance costs	36980$
NPV of total investment	74102$
Cost per cubic meter	2.6$

It is notable that the cabling and its installation cost for the proposed system is considered about 195 $/kWh.

Surveys have revealed that annual cost of replacing worn out parts is 2134$ and human resources cost was some 381$ considering the wage of each labor 4 $ h^{-1}. Given the interest rate of 8% and financial aids from the Iranian Fuel Consumption Optimization Company (IFCO), cost of producing a cubic meter of potable water by the PV-RO unit in the Persian Gulf region are worked out as shown in Table 3.

As mentioned earlier, surveys indicate that total annual cost of constructing a PV-RO solar powered seawater desalinating unit with the capacity of 1424 m^3 $year^{-1}$ of potable water is 29480$. It is worth mentioning that the proposed pilot project does not incur any cost regarding fuel and electricity since it does not use any batteries so total cost of producing a cubic meter of potable water has decreased in this solar powered unit. Total cost of producing a cubic meter of potable water by the proposed solar powered unit, including all other cost, namely maintenance cost, are estimated at as low as 2.6 $. Similar cost in conventional systems are 1.3 $ m^{-3} of potable water. Therefore, the proposed design is much more cost-effective and economically attractive than other solar powered water desalinating units which can produce potable water at 6.5 $ m^{-3}.

The modeling carried out based on the leading software, the consumption of photovoltaic energy in this design, depending on different positions of the sun and water temperature in different seasons and day time is estimated at 3.2-3.7 kWh m^{-3}.

CONCLUSIONS

In this study, the design and modeling of a PV-RO solar powered according to the WHO standards was dealt with. In RO water desalinating systems, needed energy is totally in the form of electricity which is provided by solar cells using photovoltaic technology where solar energy is directly converted into electricity (alternative current). This water desalinating unit is capable of desalinating seawater and producing 1424 cubic meters of potable water per annum with the TDS of 40,000 ppm. The main feature of this system is that it does not include any batteries. It is notable that to run RO solar powered water desalinating units round the clock (even in nights); they are equipped with lead-acid batteries (Essam *et al.*, 2008). These batteries are charged by solar cells in the daytime and in the following 19 h into the night they provide the needed electricity. However, using such batteries is not free from technical problems and they may threaten the economics of the systems. Therefore, a solar powered water desalinating unit without using batteries was designed. In this design, the flow rate of potable water was not constant in different hours due varying light conditions but the problem was solved by including a potable water storage tank to the system. In other words, in this system, potable water instead of electricity is stored.

Surveys indicate that total annual cost of constructing a PV-RO solar powered seawater desalinating unit with the capacity of 1424 m^3 $year^{-1}$ of potable water is 29480 \$. It is worth mentioning that the proposed pilot project does not incur any cost regarding fuel and electricity since it does not use any batteries so total cost of producing a cubic meter of potable water has decreased in this solar powered unit. Total cost of producing a cubic meter of potable water by the proposed solar powered unit, including all other cost, namely maintenance cost, are estimated at as low as 2.6 \$. Similar cost in conventional systems are 1.3 \$ m^{-3} of potable water. Therefore, the proposed design is much more cost effective and attractive than other solar powered water desalinating units which can produce potable water at 6.5 \$ m^{-3}.

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