Pilot-scale reverse osmosis for brackish and seawater desalination coupled with renewable energy

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Abstract: - Reverse osmosis membrane technology is used in a large range of applications namely the wastewater treatment and brackish and seawater desalination. It is considered an alternative clean water source to overcome water scarcity and ensure a good water quality in many Middle East and North Africa (MENA) regions. Water is an important factor for economic and social development of a country. For domestic, agricultural and industrial purposes, several membrane separation technologies were implanted in large scale for water production. The reverse osmosis (RO) desalination process is the prevailing technology to produce drinking water from salt water for many domestic and industrial applications. In the present work, we provide an experimental analysis of reverse osmosis pilot for small capacity designed for desalination and water treatment. In this preliminary study, we use brackish well water of UDES for experiments test. The pilot scale reverse osmosis is applied to the desalination and treatment of raw water to produce water of quality appropriate for potable purposes. The bacteriological analysis of raw water shows that the water contains total coliform and pathogenic bacteria. The main goal is to explore the effect of the pressure on the permeat and reject water flow rate in order to control system production and operation between various parameters that can directly affect the process. Design and optimization of a stand-alone renewable energy generator for powering a small scale reverse osmosis desalination system with battery storage is studied. The objective of the pilot study is to demonstrate the feasibility of brackish and seawater desalination generated with renewable energy. The effects of operating conditions on conversion rate behavior of spiraled membrane are evaluated.

Key-Words: - Desalination, Membrane, Reverse osmosis, Seawater, Energy

1 Introduction

Many attempts and experiments have been conducted to find appropriate coupling processes between the RO desalination processes with PV as renewable energy resources. Several studies focused on this type of configuration by carrying experimental small plant. With support from the Canadian government, B.G. Keefer et al, [1] developed two small reverse osmosis systems powered by photovoltaic energy in Vancouver, British Columbia, to demonstrate the use and optimization of solar energy consumed with storage batteries (panels have a power of 480 W). To produce demineralized water 0.5 to 1 m^3/d, they examined the differences between the direct connections of PV reverse osmosis system, the maximum power tracking and storage battery. Using a positive displacement pump with variable speed, with energy recovery of the rejected brine, they claim to be able to reduce life cycle costs by 50% compared to RO/PV conventional systems. Others investigations illustrated that power consumption can be achieved 0.89 kWh/m3, [2, 3] and modelling this type of coupling without using batteries as given by Thomson [4]. A. Hanafi, [5] studied the different desalination technologies associated with renewable energy, mainly solar, wind, tidal and geothermal. He presented some control limits for the use of energy sources including wind that is recommended more than RO / PV. A systematic approach for renewable energy powered desalination by considering all the alternatives was presented by M. Rodriguez et al. [6].Following the studied combinations, they concluded that RO powered by PV is interesting in very specific cases, such as in sunny remote sites.

A small reverse osmosis system (RO) powered by photovoltaic (PV) has been installed and tested at the island of Grand Canada by D. Herold et al. [7]. A feasibility study of this small PV system RO of $1m^3$/d was presented. The pilot plant, with an average production capacity of 3.2 m^3/d of fresh water, is coupled to a standalone PV system and storage batteries. The rated power consumption is 2.35 kW.

In Algeria, A. Sadi et al [8] have conducted experiment studies, on a reverse osmosis desalination plant, with a capacity of 0.85 l/h, installed in Hassi Khebi (Southeastern Algeria) coupled to a photovoltaic generator. The plant was acquired as part of the collaboration between the CDER (Algeria) and the Commissariat à l'Energie Atomique (CEA, France). They presented the evolution of power and pressure versus a time; the results were encouraging during the experimentation period, giving a conversion rate of 40.7%. Subsequently, the rate dropped to 24% due to neglect and lack of skilled technicians. Unfortunately, the membranes were clogged, causing a loss of production. D. Andesselem Dehmas et al, [9] have provided a detailed analysis of wind energy resources for seawater reverse osmosis desalination (SWRO), coupled to wind energy, in Algeria. An economic analysis using five wind turbines of type Bonus 2 MW and details about financial investment hazards and CO_2 emissions reduction was performed. It was found that wind energy could successfully power a SWRO desalination plant in some windiest regions of Algeria. E. Badreddine et al. [10] were able to build a prototype of a reverse osmosis desalination unit with 100 l/h at the laboratory scale powered by a photovoltaic energy source (550W-4.2A). This innovative concept AAST was installed in Egypt in the framework of a cooperation project with PROAUT UASZ and supported by SwissContact. The plant is intended for educational and research purposes. This preliminary operation experience shows that skilled personnel is required for operating and maintaining this kind of desalination systems. They briefly discussed some of the issues of research that can be studied at laboratory scale, by modelling the system to optimize energy consumption, system availability and production of water under variable weather conditions. In Jordan, S. Abdallah et al [11] have presented an experimental study, which aims to investigate the potential for water desalination development using a solar powered system. The results have shown that the reverse osmosis system powered by photovoltaic energy can be easily applied. They conclude that a gain of 25 and 15% of electrical energy and the flow of desalinated water, respectively, using the tracking system an East-West axis with flat fixed plate. The results are presented in curve form namely the electric current, voltage, electric power and the production rate for a fixed surface and a PV tracking system versus time. Furthermore, the production rate for a fixed surface and a PV tracking system according to electric current was introduced. They reported that more experimental work must be done to study the continues performance of the system and further investigation should be carried out on the membrane fouling and system recovery.

Different possibilities of coupling RO with the most appropriate sources of renewable energy as hybrid systems (photovoltaic and wind) are presented by K. Bourouni et al. [12] using a new model based on the Genetic Algorithms to minimize the total water cost. The village of Ksar Ghilène located in the South of Tunisia was chosen as case study using solar reverse osmosis unit (PV/RO) installed since 2007.A comparative analysis with reference software (ROSA for the RO unit and HOMER for the PV modules) was validated. Numerical simulations on a small-scale, stand-alone, solar-PV powered (RO) system, with or without battery storage was reported by P. Daniel et al. [13]. They noted that the system scalability influences the sensitivity of simulations and the type of I-V characteristics used. The results confirm that including batteries to store excess renewable energy have a significant impact on the performance of smaller systems compared to larger ones. Various alternative systems can be used for desalination technology integrating the RO desalination process. M. Ibarra et al [14] analyzed the performance of a specific solar desalination Organic Rankine Cycle (ORC) system at part load operation. They tried to understand its behavior from a thermodynamic perspective and predict the total water production with changing operation conditions. The main purpose of the present work is to integrate a sustainable energy source in the water desalination process by reverse osmosis technology. This project demonstrates the coupling between renewable energy with water desalination and leads in developing the infrastructure of Algerian water authority that supports scientific activities in the fields of water desalination automation using solar energy sources. Our objective was that desalination industry that has a strong future would benefit directly from the project experience by developing new equipment’s and technologies, which meet the specific requirements of remote and arid area development. The effects of operating conditions on conversion rate behavior of membrane are evaluated and different physicochemical and bacteriological analyses of water before and after treatment are presented.

2 Reverse Osmosis Pilot description

Reverse Osmosis (RO) EUROS-MM-M-25-22 was designed in France by DFM group to UDES Center in order to operate a desalination Reverse Osmosis plant with solar energy using photovoltaic array system cells.

The considered activities include operation of the membrane process, control, monitoring, fault detection, design and dimensioning a PV structure and coupled system optimization of the PV-RO pilot plant shown in figure 1.

By definition, reverse osmosis is a membrane separation process in which pure water passes from the high-pressure seawater side of a semi permeable membrane to the low pressure permeate side of the membrane. We acquired a reverse osmosis pilot laboratory low capacity 84l/h.

This experimental reverse osmosis consists of a high-pressure pump (PHP) stainless steel model with variable pressure (plunger pump), which provides a pressure of up to 105 bar. This pump is placed on a stainless steel base 304 connected to a valve that controls the inlet pressure. The installation contains two spiral wound membranes (1000 psi (70 bar) membrane sheet resistant FRP) placed in a series casing as the concentrate from the first membrane is received by the second. A flow meter placed at the output of the membrane allows controlling the permeation rate and therefore the conversion rate. The various electric power cables are grouped in an electrical box with a switch on / off. The high-pressure ducts are made of 316L stainless steel by low pressure against the conduits are PVC polyvinyl chloride. Two cartridge filtration units to filter water to 5 microns are behind the frame 304 stainless steel bearing all components and other equipment (conductivity meter on the production chain, flush valve, automated panel ... ect).

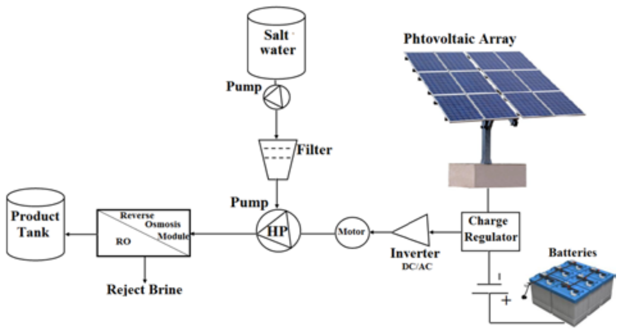


Fig. 1.: Schematic diagram of the PV powered RO system

This system is easy to operate it without using a full-time operator characterized by an automatic flushing and start-up, a LCD screen and an indicator of the state of the system on the automated panel (stop, danger): A system of automatic cleaning has been programmed in the algorithm. It is provided to protect the membranes from scaling and fouling. The cleaning system operation depends on the running time of the RO plant, which will be started directly after a shut-down of the device. As considering the pilot is used for laboratory experiments demonstration with control algorithms, supervision and error or stop detection, it does not actually have to pre-treatment and post-treatment program. The reverse osmosis equipment for desalination and softening of seawater and brackish water consists of following components listed on table 1. Figure 2 shows the installation of reverse osmosis plant on laboratory. In the system of reverse osmosis, water is forced under pressure across a membrane element with a part of the feed permeating the membrane and the balance of the feed water along the membrane surface and exiting without passing through the membrane.

Table 1. Technical operating data for pilot

TECHNICAL DATA	
Permeate flow	84 l/h
Operating pressure	55 bars
Raw water consumption	1651/h
Raw water pressure	3-5 bars
Rejection	99%
Current	230V/50 Hz
Power installed	3 kW/500 A
Pipe connection	Raw water : DN 15 Permeate : DN 15 concentrate : 15 DN
Dimensions	H*W*D=179*90*44 cm^3
DESIGN CRITERIA	
TDS	<35000 ppm
Nominal temperature.	18 ° C
Inlet pressure of Need	At least 3 bar

Operating pressure requirement	67 bar max
Flow	16 L / m² / h
SDI	<3
Iron	<0.01mg / lt
Manganese / Aluminium	<0.025 mg / lt
Barium Strontium	very little
Bore	no
Silica	<20
Free Cl, oxidizing materials	none
Oil, grease and oil	no
Hydrogen sulfide	none
BOI, KOI	none

Fig. 2: Reverse osmosis plant installed on the site of UDES laboratory

The membrane will let pass water but will reject most of the dissolved minerals as well as any small particles. The membrane characteristics used in this work are shown in Table 2. Conservation of the membranes is assured in a sodium metabisulfite solution.

Table 2 Maximum operating limits of the membrane

Tested membrane	**OI Model SEA5-4040**
Maximum pressure	69 bar
Pressure drop	0.7 bar
active area	7.9 m^2
pH be tolerated during treatment	3 à 10
Temperature	45 °C
Chlorine concentration	ppm<0.1
Feedwate tubidity	1.0NTU
Feedwater SDI	15mns
Minimum ratio of concentrate to permeate flow for any element	5:1

3 Results and discussions

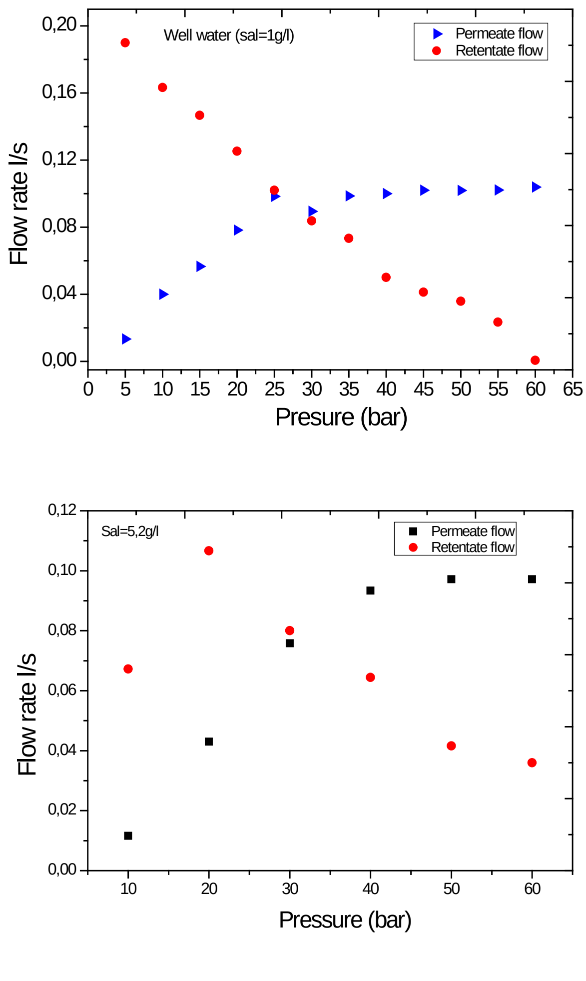
3.1 Membrane performance

Table 3 contains the physicochemical and microbiological characteristics of brackish water to be treated for constant salinity 5.2g/l. High hardness, bicarbonate and rich in chloride and sodium ions characterize this water. In the first part, the pilot is generated by conventional energy for characterizing different parameters that affect the production rate and mastering technology.

Figure.3 depicts the evolution of flow rate of permeate and retentate versus pressure for brackish water with low salinity 1g/l. For low pressure values, we note that the permeate flow rate gradually increases as the pressure increases in the range p≤30 bar for a salinity of 1 g / l and p≤40 for a salinity of 5.2 g / l beyond these values permeate remains constant regardless of the pressure applied. By cons, the retentate flow decreases with increasing pressure in a decreasing manner until zero (1g / l).

Table 3 Results of physicochemical and microbiological analysis of Bou-Ismail well water (UDES)

Parameter	Results
Temperature	17.8OC
pH	8.05
Dissolved oxygen	3.60mg/l
Salinity	5.2‰
Conductivity	13.36 ms/cm
M.E.S	12.6 mg/l
Ammonium	8.0876 mg/l
Nitrites	0.0751 mg/l
Nitrates	202.56 mg/l
Phosphates	0.0086 mg/l
Chlorides	1762.57 mg/l
Carbonates	0.1065 mg/l
Calcium	438.12 mg/l
Sulfates	0 mg/l
Total coliform bacteria	4
Fecal coliforms	4
E-coli	0



(a)

Fig. 3 Flow of permeate and retentate as a function of pressure for brackish water with low salinity of well water (a) sal=1g/l and (b) sal=5.2g/l

This means that the membrane passing whole quantity of water to be desalinated and that this value of salinity is negligible compared to the permeability of the membrane. Indeed, it reveals that the desalination of brackish water requires a pressure value less than 35 bars.

To study the salinity effect on membrane production, the water to be desalinated is obtained by enriching well water conductivity between 1900 and 2011µS/cm, by sodium chloride NaCl in order to achieve a total salinity from 5.2 to 30.2 g/l.

Figue.4 shows the permeate flow rate variation as a function of pressure for different salinity. It is noted that salinity has a significant influence on the permeate flow of the reverse osmosis membrane.

It is found that when the salinity increases the minimum operating pressure increases as shown in figure 4 and 5. Especially for high salinity 30.2g / l the minimum pressure to desalinate salt water starts at 40 bar.

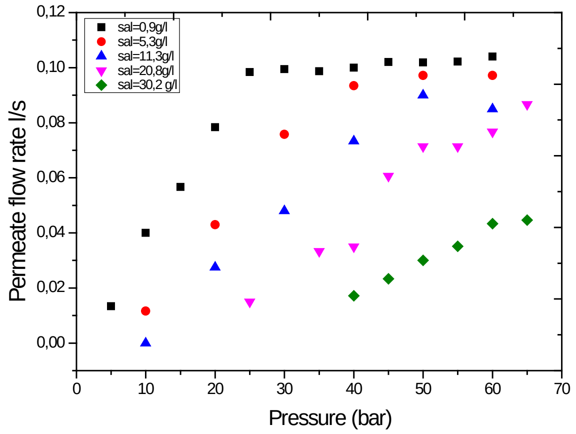


Fig.4 Variation of permeate flow as a function of pressure various salinity

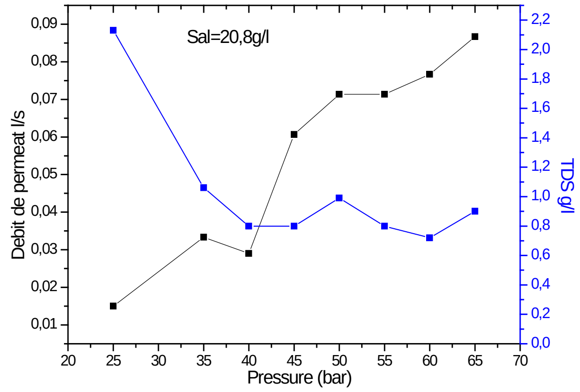


Fig. 5 evolution of permeate flow for salinity 20.8g/land Total Dissolved Solids (TDS) versus pressure.

3.2 RO and PV coupling

To link desalination with renewable energy, we studied the case of coupling the RO pilot with a photovoltaic system. The choice of this technology is related to the priority given by the renewable energy program implemented by the Algerian government, to install a capacity of around 13575 MWp of photovoltaic in 2030 (Figure 6), [15].

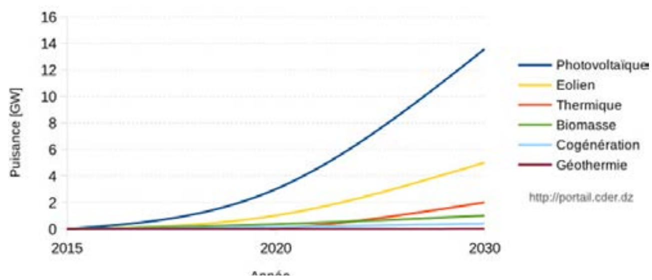


Fig. 6 Installed capacity by sector in 2030, [15]

Monthly solar radiation received on a tilted plan in the latitude of Bou-Ismail site was determined from the illuminance measurements on a tilted plan every 10 minutes on the Bou-Ismail site. Figure 7 shows the evolution of the monthly irradiation of Bou-Ismail site of 2015.We noticed that the monthly radiation is maximum on summer where it reaches 71.35 kWh/m^2. However, the sizing of the PV system for powering the reverse osmosis is based on the characteristics of the pump and the sizing assumptions. So using the solar radiation data, we sized autonomous solar PV field with a power of 2.8 kW that can operate the high-pressure pump of the osmosis.

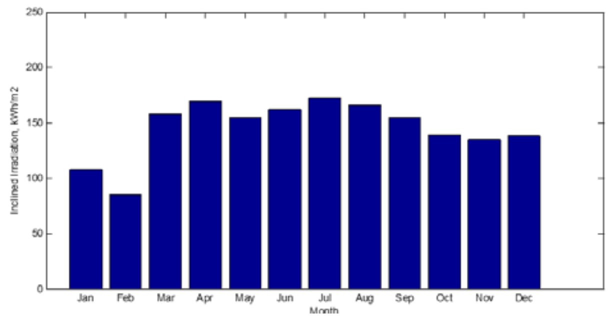


Fig. 7 Estimated Monthly Irradiation on the site of Bou Ismail

These characteristics allows us to determine the various elements of the autonomous photovoltaic chain namely the number of modules required which provides real generator size and its storage capacity according to the daily demand for electricity.
In the present conception, we are consider that the number of operating hours per day is 4 hours / day and the number of operating days per week is 5 days where the operating battery is 3 days. Therefore, the maximum monthly water production is supposed to be 8m^3.The energy consumption of reverse osmosis desalination was estimated in the MENA region from 3.5 to 5 kWh per m^3, depending on the size of the facility [16]. Consequently, the average annual consumption of the RO pilot is amounted to 40 kWh per month if we consider 5 kWh/m^3 of distilled water product. Pump high-pressure features are presented in the Table.4.

Table 4: Features of pump high pressure PHP

Pump efficiency (pump unit)	11.5 liters minute (1420 RPM)
Voltage and current	400v-3.7Amp
Pump speed	1700t / m
Nominal mechanical power	1kW
Power factor (Cos)	0.77
Electrical power	1.8KW≈2KW

This autonomous photovoltaic conversion chain (see table 5) should consists of twenty PV modules of 150 Wp (monocrystalline), two regulators 50A/48V, inverter 3kW (48VDC/400VAC), solar batteries (250Ahx8) and mounting and protection accessories (Wiring, electromagnetic circuit breaker, electrical box). The role of the solar controller is to ensure and regulate battery charge. It optimizes the power of the panels and prevents landfills / harmful deep overload the good life of the batteries. They improve battery charging. To complete the full charge, it separates the current provided by the panels and sends it to the batteries in the form of pulses. The accurate reading of the regulator to the battery terminals modulates these pulses. This allows it to know its charge level.
However, considering the annual irradiance of Bous mail site, the sizing of PV field without batteries, decreases the number of PV modules from 20 to 3 modules with 200 Wp each to supplies the about 500kWh of annual consummation of RO pilot.

Table 5 PV-RO system components

Item no	Description	Quantity
1	Modules	20
2	Pv source conductor	1
3	Pv disconected	1
4	Pv output conductor	1
5	Inverter	3.0 kW
7	RO cable	1
9	Charge controller	1 (100 A)
10	Battery bank	24 (500 Ah 48V)
11	Data acquisition system	1
12	Modem	1
13	Battery	1 (48 V/500 Ah)

4 Conclusion
A pilot-scale reverse osmosis desalination system powered by solar panels with battery storage has been designed and realised according to the climatic conditions of Bou-Ismail town. The considered system average specific energy consumption is the order of 3 kWh which requiring 20 monocrystalline PV panel of 150 Watt.As the treatment by osmosis, is an energy intensive technique and in arid and semi-arid regions with abundant solar radiation as Algeria, photovoltaic panels may be a sustainable alternative energy for water desalination.
The estimated monthly irradiation on the Bou-Ismail site is calculated during 2015.It has been concluded that a RO plant powered by PV panels with battery storage is a promising solution for small monobloc

of Bou-ismail to overcome high-energy costs. The performance of the reverse osmosis system is evaluated for different pressure conditions and various available brackish feed waters using conventional energy. The system demonstrated that the brackish water desalination requires a pressure value less than 35 bar.

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