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Techno-Economic Feasibility of Reverse Osmosis Desalination Scale Coupled with Solar Energy: Case of Algeria

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Abstract
Brackish water and seawater desalination have become important freshwater sources in arid and semi-arid regions suffering from water scarcity. Fortunately, the availability of solar energy provides an excellent opportunity to replace conventional energy with renewable energy for desalination system power. However, technical and economic feasibility studies must be carried out according to the characteristics of each region to assess its economic feasibility. This study assessed the techno-economic feasibility of a solar-powered desalination small-scale BWRO with a capacity of 2.016 m^3/day. Two scenarios were proposed: a desalination station powered by a public network without a solar energy system (On-Grid) and a second powered by photovoltaic panels (Off-Grid). The result shows that the water production cost of the Off-Grid system (0.33 \$/m^3) was about 1.14 times lower than the water production cost of the On-Grid system (0.38 \$/m^3). The economic analysis result shows that the reverse osmosis desalination system coupled with a photovoltaic system (Off-Grid) is an economically suitable option for satisfying the increasing freshwater product demand compared to the grid-powered system (On-Grid), especially in arid areas.
Keywords: Brackish water desalination. Cost analysis. Levelized water cost. Photovoltaic system. Reverse osmosis.

Nomenclature

A_i	Annual operating cost ($/y)
C	Initial capital cost ($/y)
$C_{O\&M}$	Operating and maintenance cost ($/y)
i	Interest rate
IRR	Interest rate return (%)
LWC	Levelized water cost ($/m^3)
n	Number of years
NPV	Net present value ($)
P_{des}	Energy required by desalination (Kwh)
$P_{pv.tot}$	Energy required by photovoltaic(Kwh)
Q_f	Feed water flow rate (m^3/day)
t_{hd}	Average hours of daylight (h)
y	Water recovery ratio (%)
ΔP	Pumping pressure (bar)
η_{pump}	Hydraulic pump efficiency
α_{BCH}	Charging efficiency of the battery
α_{BDCH}	Discharging efficiency of the battery

1. Introduction

Population growth, climate change and industrialization, a variety of factors explain the continuous increase in the world's need for potable water. However, the resource remains unevenly distributed on the planet. By 2050, the world's population is expected to reach 9.6 billion (Islam and Karim 2019), which will lead to an even more rapid increase in water demand. Today, between 1.5 and 2 billion people live in regions where, during part of the year, the available of freshwater is not sufficient to meet the growing demand. Many solutions have been proposed to help meet the growing demand for water, including better water resource management, increased water reuse, and desalination (Kim *et al.* 2020, Adda *et al.* 2020).

In order to meet their growing need for drinking water, many countries are increasingly relying on seawater/brackish water desalination. Reverse osmosis membrane system has been widely used as a main technique in desalination plant. The main advantages of RO systems compared to other desalination methods are their low energy consumption, modularity, and simplicity in installation and operation (Gorjian *et al.* 2014, Hchaichi *et al.* 2014). Moreover, the small-scale reverse osmosis desalination system with solar-powered is suitable process for the remote areas. On the other hand, renewable energies preserve and protect the environment from the harmful effects of toxic emissions of carbon dioxide through conventional desalination plants (El-Sayed 2003).

Today, desalination based on renewable energy sources is an emerging technology to produce freshwater without carbon emissions (Abdoelatef *et al.* 2016). In particular, it is a promising technology for remote areas, where connection to the public power grid is costly or not available.

The potential combination of solar photovoltaic (PV) energy with reverse osmosis has generated increasing interest due to the inherent simplicity of both technologies. Many plants have been installed around the world, especially in rural areas with small desalination capacity. The studies conducted so far mainly indicate the possibility of using PV technology for salt-water treatment with RO processes (PV-RO). PV-powered reverse osmosis (RO) desalination unit can provide fresh water to remote, arid areas and isolated regions with high solar energy potential and access to salt water sources (such as the sea or brackish water) (Hosseini *et al.* 2018) . Significant work has been done on conceptualizing and designing potential technology combinations, observing laboratory, pilot, and full-scale applications, and simulating projected operational and economic conditions. Throughout the world, brackish water desalination with renewable energy was the subject of many papers. In Egyptian desert, Ahmad and Schmid (2002) estimated the cost of the produced freshwater is about 3.73\$/m^3 from a small-scale brackish water desalination system. Ahmed (2006) presented a socio economic study of a small-scale off grid PV-RO desalination unit with capacity of 1.0 to 5.0 m3/day to produce freshwater in remote areas. They concluded that in remote sites with high potentials of solar energy the small-scale desalination system is suitable. In Iraq, Al karaghouli and kasmerski (2010) used HOMER software to analyse the economic viability of a small-scale. PV-BWRO unit with capacity of 5.0 m^3/day and 4000 ppm salinity of feed water installed in Babylon, the results show that the lowest cost of produced freshwater was 3.98 \$/m^3. In Iran, Gorjian*et al.* (2014) evaluated a small-scale BWRO unit desalination unit integrated with a stand-alone hybrid photovoltaic-thermal (PVT), installed in Tehran. From the results, the maximum average productivity of the BWRO unit was obtained as 13.98 L/h when temperature values of the PV module, soft water, and brackish feed water (BFW) were recorded as 52.94 °C, 28.97 °C and 36.60 °C respectively. In addition, it was found that the temperature of brackish water feed (BFW) positively affects the PVT module's thermal performance and improves the whole unit's productivity. The economic analysis of the system revealed that the cost of the produced freshwater for the BFW's salinity of 15,000 ppm is 18.96% higher in comparison with 5000 ppm for all cases. However, Mostafaeipour*et al.* (2019) studied the technical and economic feasibility of PV-BWRO units in Iran. They noted that realizing PV-BWRO units is technically feasible and showed that at least 148 m^3 and up to 228 m^3 of potable water can be produced per day for 1.96to 3.02 \$/m^3. Alghoul*et al*. (2016) established and evaluated a six-month ongoing PV-BWRO desalination system. They observed that the high temperature of PV which exceeds 45°C and the temperature of the battery room above 35 °C negatively influence the operation of the modules, the output power and the autonomy of the battery. BaghaeiLakeh *et al.* (2017) evaluated a decentralized off-grid PV-BWRO desalination system that was capable of desalinating Brackish Water at a salt rejection rate of more than 97.5% and a recovery rate of up to 80%. Alsarayreh *et al.* (2017) studied the feasibility of integrating a BWRO desalination system with a PV system in Jordan Valley. The PVSOL software was used for the design of PV system while the economic feasibility was carried out using Average Incremental Cost of Water (AICOW) for different scenarios. The results indicated that for farmers using the PV-BWRO desalination system at their electricity tariff is not economically feasible.

Algeria is classified in the category of countries that suffer from water stress, due its geographical location in the semi-arid and arid region. In this case, to ensure a lower cost and permanent power consumption in the brackish water desalination plant, an economic feasibility study of RO/PV small scale is designed for the solar equipment development unit of Algeria (UDES) with 2.06 m3/d capacity. Therefore, in this study, we have used two scenarios, the first scenario is a public power grid (On-Grid) used to power the RO plant, and the second scenario is the RO plant fully powered by solar panels PV-RO with 200Wp (Off-Grid).

2. The reality of the Algeria water desalination

In Algeria, water resources threatened by human activities, industrial and agricultural, and global warming, have become a major issue. Consequently, the World Bank classifies Algeria in the category of the "poorest countries in terms of water potential". For this reason, the recourse towards the desalination of seawater/brackish water has become the alternative solution to face the water stress; it allows supplying freshwater to large coastal cities and isolated localities. The capacity of Algeria in desalination of seawater is more than 2 110 000 m3/day and brackish water about 3 554 433 m3/day. (Water Resource Ministry 2021)

According to Table 1, the water cost is a sensitive economic parameter that varies from station to other and from region to region, influenced by several independent factors such as membrane costs, transportation, location and energy consumption…. etc. Therefore, sustainable water management is crucial for the environment and our future, but its cost is often hard to measure accurately. However, investing in sustainable solutions can bring long-term benefits and savings in terms of environmental impact and financial sustainability.

Table 1 – Algeria Desalination plants operated and their characteristics.

Plant	Capacity(m^3/day)	Water produced Cost (\$/m^3)
Kahrama	90 000	0.87
El Hamma	200 000	0.82
Skikda	100 000	0.74
BeniSaf	200 000	0.69
Souk Tleta	200 000	0.76
Honaine	200 000	0.76
Mostaganem	200 000	0.72
Cap Djinet	100 000	0.72
Fouka	120 000	0.75
Magtaa	500 000	0.56
Tenes	200 000	0.59

Algeria's ideal location grants it enormous solar potential, boasting one of the highest deposits of solar energy in the world. The PV powered reverse osmosis (RO) desalination units located in remote areas and isolated sites is a suitable option for freshwater production. The main problem with these technologies remains their high costs and the availability of photovoltaic cells. Renewable energy desalination offers a cost-effective alternative to fossil fuel-based desalination. The high solar potentials make people’s life easier with lots of environmentally friendly products. Solar PV has become an effective way of producing electricity in terms of cost and cleanliness (Kaya *et al.* 2019).

In Algeria, since 2002 modest attempts to replace fossil energy with renewable energy are not enough despite its enormous solar potential, such as the brackish water desalination unit localized in Hassi-khebi region of Tindouf. This small reverse osmosis unit powered by a solar generator produces approximately 950 L/h of drinking water for about 1000 inhabitants of this village, and it has worked more or less regularly for 12 years under very specific conditions (Othenio&awange 2016). Recently, the N'Goussa step, a 100% green station used renewable energy since 2010. The N'GOUSSA wastewater treatment plant was built as part of the mega project to fight against the rising waters of Ouargla. This system is designed to treat urban wastewater in the region using planted reed filters; it is one of the extensive devices that use macrophytes for the biological treatment (ONA. 2021). This process has a low environmental impact and requires minimal energy while still producing excellent purification results. (Nassrullah *et al.* 2020).

3. Presentation of the RO/PV desalination unit

In this study, a small-scale BWRO desalination unit with a capacity of 2.016 m3 / day powered with a solar PV module was developed. The main characteristics and operating of the RO module used in this work are presented in Table 2. The experiments were carried out in the Solar Equipment Development Unit (UDES), in Tipaza, Algeria Figure 1. The experimental setup consists of a BWRO desalination unit and a PV unit with battery and accessories. Note that a PV system consists of PV arrays, batteries, regulator, inverter, transformer and several types of load. In our case, this PV system is connected to BWRO desalination unit Figure 2. The energy required by the RO system is only the electric power consumed mainly by the high-pressure pumps.

Table 2 – Characteristics and operating parameters of reverse osmosis unit

	Brackish water characteristics	
(Zioui *et al.* 2018)	Temperature (°C)	17.8
	Ph	8.05
	Salinity (g/L)	7.7
	Conductivity (ms/cm)	13.36
	MES (mg/L)	12.6
	Reverse osmosis unit	
(Abbas *et al.* 2018)	Type of membrane	SW30HR380 Filmtec
	Feed flow	3.96 m^3/day
	Rejection	99%
	Pump efficiency HPP	75%
	Consumption energy	2 kWh

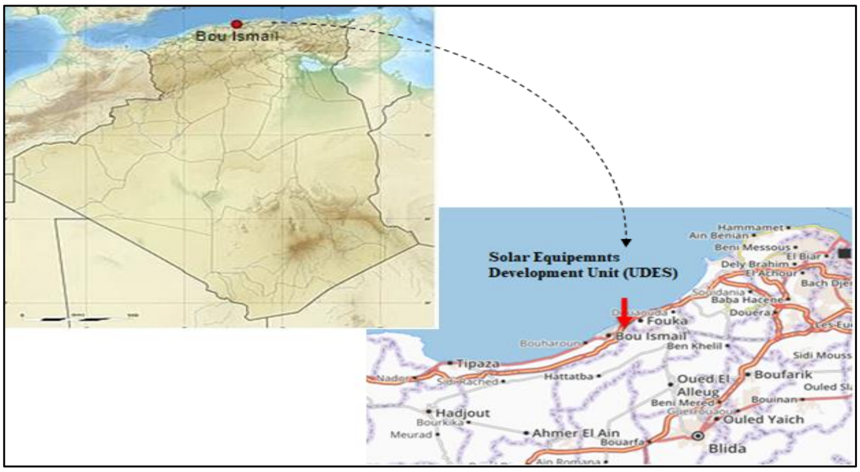


Figure 1 – Location of BWRO Desalination

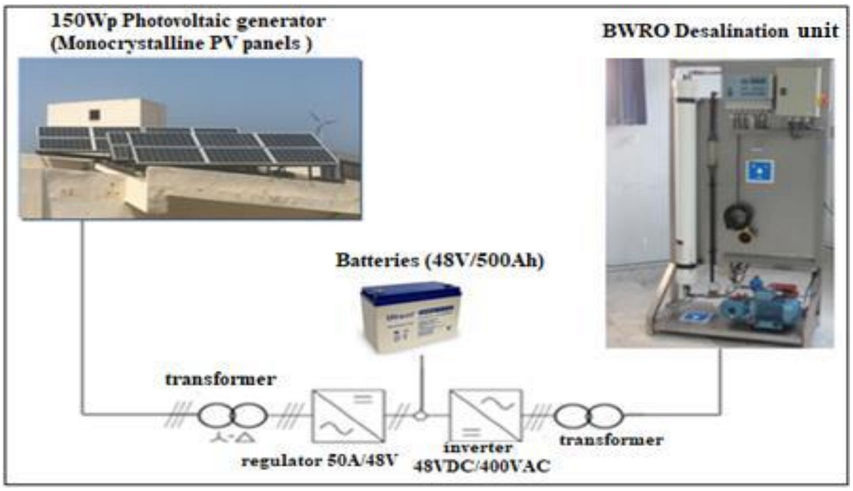
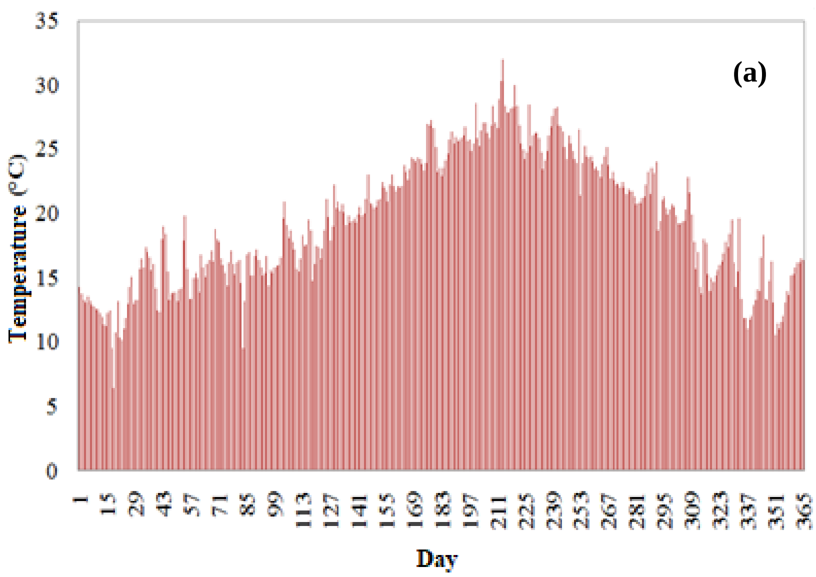


Figure 2 – Schematic diagram of BWRO Desalination unit powered by Solar PV

2.1 Potential of site

The measurement station installed within the Solar Equipment Development Unit (UDES) in Bou Ismail, allows to measure and record meteorological data as well as solar radiation. Figure 3show the variation of the meteorological data concerning the average monthly global solar radiation, ambient temperature over one year. The atmospheric temperature during the year with a variation between 13 and 33°C over the year and an average daily difference between the maximum and minimum temperatures of around 8°C throughout the year. The monthly solar radiation received on an inclined plane in the site of Bou Ismail was determined from measurements of illumination on an inclined plane every 10 minutes. The maximum monthly average solar radiation is shown in July and it is around 485 W/m^2. We can note that a large solar deposit characterizes this region. However, the sizing of the PV system to power the reverse osmosis unit is based on the characteristics of the pump and the sizing assumptions.

Therefore, using the solar radiation data, we have sized an autonomous photovoltaic solar field with a power of 2.8 kW/day, which can operate the high-pressure pump.



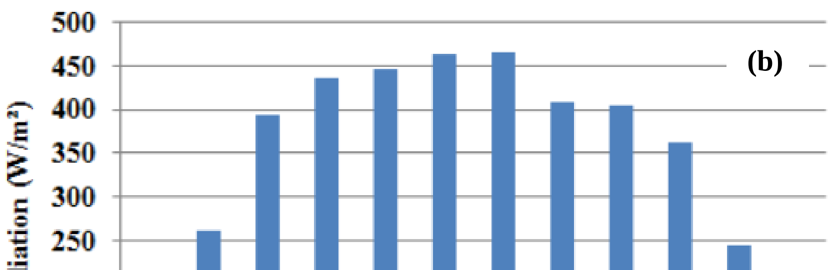


Figure 3 – Meteorological data of Bou Ismail region : (a) Temperature and (b) Solar radiation

2.2 BWRO/PV desalination system modelling

In Brackish water desalination system; the energy from the pressurized can be recovered by energy exchanger systems, thus reducing the required pumping energy by about 30 to 50% (Nassrullah *et al.* 2020).

The high-pressure pump acts as an energy recovery and must ensure a flow of water at a given pressure while absorbing the minimum amount of energy. However, the energy required for the pressurization of the feed water in the reverse osmosis desalination system $_{des}$ (kWh) was calculated using Eq. (1):

$$P_{des} = \frac{Q_f \times \Delta P}{36.6 \times y \times \eta_{pump}} \qquad (1)$$

Where

- Qf is the feed water flow;
- ΔP the pumping pressure;
- η_{pump} being a datum corresponding to the hydraulic efficiency of the pump, around 80-90 %, depending on the dimension of the RO system;
- y the desalination system recovery.

To evaluate the performance of the RO/PV system proposed, a global model of the system is divided into two models, the first is for RO unit water drinking and the second dedicated for photovoltaic system. The two models are performed in MATLAB software. On the other hand, the required energy production from photovoltaic system to feed the desalination system (kWh/day), is given by the Equation 2:

$$P_{PV,tot} = \frac{P_{des}}{t_{hd}/24 + (1 - t_{hd}/24)\alpha_{BCH}\alpha_{BDCH}} \qquad (2)$$

It presents the main link between PV and RO, where $Pdes$, from equation (1) is the energy required by desalination unit and thd (h) is the average hours of daylight. $\alpha BCH$is the charging efficiency of the battery, and $\alpha BDCH$ is the discharging efficiency. In our case we took αBCH = 0.2and $\alpha BDCH$ = 0.8.

The PV module connects directly the RO system along 8 hours a day. The stand-alone photovoltaic system consist of twenty PV modules of 150 Wp (monocrystalline), two50A/48V regulators, 3kW inverter (48VDC/400VAC), solar batteries (250Ah x8) and mounting accessories and protection (wiring, electromagnetic circuit breaker, electrical box).). The role of the solar controller is to ensure and regulate the charge of the battery. It optimizes the power of the panels and prevents deep discharges/ overcharges that are harmful to the good life of the batteries. It improves the battery charge/discharge. To complete the full charge of the battery, it separates the current supplied by the panels and sends it to the batteries in the form of pulses. Accurate reading of these pulses from the regulator at the battery terminals allows knowing the charge level. Taking into account of the annual irradiation of the UDES site, the PV field provide approximately 500 kWh of annual energy to the RO pilot left.

4. Economic aspects of PV/RO system

4.1 Economic assessment

Proposed capital desalination system costs can be assessed by an economic feasibility study including an economic analysis of the project. The purpose of economic analysis is to determine an economic justification for the investment decision. Water cost is an economic parameter that incorporates all project capital and annual O&M expenditures associated with water production. It is typically presented as monetary units per unit volume of desalinated water. The Levelized Water Cost per unit LWC ($/m3) is affected by various factors including recovery ratio, energy source (fuel or renewable energy), cost of equipment (membrane and solar system), interest rate, subsidy given by government, labor cost etc. The Levelized Water Cost (LWC) is expressed by the Equation 3 :

$$LWC = \frac{C_{inv}+C_r+C_{O\&M}}{Q_p} \tag{3}$$

Where inv is the initial capital cost, $CO\&M$ is the operation and maintenance cost and Qp is the permeate flow rate (m3/h). The total capital recovery factor Cr is given by the following Equation 4. The profitability indicators identified are used to measure the financial and economic feasibility of the solar photovoltaic desalination project through the net present value (NPV) and the internal rate of return (IRR), where are the objective functions to be minimized in the optimization process of the Levelized water cost LWC.

However, the costs can be compared to the costs of existing fossil-fuel desalination plants to assess the cost-effectiveness.

$$C_r = \frac{i\times(1+i)^n}{(1+i)^n-1} \tag{4}$$

The Net Present Value is one of the most important tools applied in the analyses of water projects given its versatility, and it is the difference between the discounted cash flow capacity generated by investment and the initial amount of investment. NPV summarizes the values of relevant economic costs and benefits over the lifetime of a project (Molinos- Senante *et al*. 2015). The net present value (NPV) is presented by the Equation 5 following:

$$NPV(n) = \sum_{i=1}^{n} \frac{A_i}{(1+i)^n} - C \tag{5}$$

Where C is the initial capital cost, Ai is the annual operating cost, i is the interest rate, and n is the economic lifetime in year (Shatat *et al*. 2013).

The IRR is based on a discount technique such as net present value. In this technique, future cash inflows are discounted so that their total present value is just equal to the present value of the total cash outflows. It is assumed that management has knowledge of the timing of the realization of future cash flows but not of the discount rate. The internal rate of return IRR is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash flow analysis. It is given by the following equation:

$$0 = NPV = \sum_{i=1}^{n} \frac{A_i}{(1+IRR)^n} - C \tag{6}$$

The annual cost of the SWRO plant is estimated over a lifetime of 25 years, which is the same duration for the PV system (Table 3). The benefits of the project were estimated based on the sale price and the water produced from the station.

Table 3 – Global system RO/PV cost analysis

Investment installation cost		
Parameter	**Cost ($)**	**Lifetime (y)**
Photovoltaic panel	139.35/module	25
Inverter/Regulator	800.16	20
BWRO desalination unit	22608.98	20
Membrane module	452.18/module	5
Tank	65.26	30
Batteries	534.52	6

4.2 Power supply cases

The modelling approach developed aims at analysing the interrelations between the cost of desalinated water and the cost of energy in small-scale desalination with 95% availability. To evaluate the impact of the technology on the desalinated water cost rigorously, it is mandatory to have an accurate description of the technical choices made for building the desalination plant. The net present value (NPV) was used as an economic indicator. In this paper, we have taken into account two scenarios of supplying the system with the electrical energy required for its operation.

Scenario 1/ System powered by public electricity network (On Grid)

The Figure 4 represents the first scenario of the proposed system, which depends on the local conditions of the electrical network. The energy required by the desalination unit is 2.8 kWh/day, while the commercial price of electricity is estimated at 0.08 $/kWh.

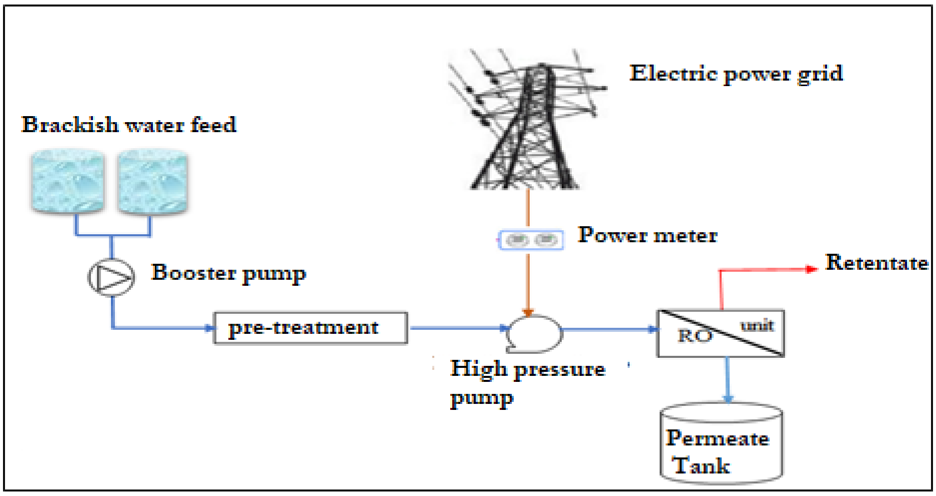


Figure 4 – RO desalination system powered by public electricity network (On Grid).

Scenario 2/ System Powered by a photovoltaic solar array and batteries for storage (Off-Grid)

Figure 5 shows the second scenario of the proposed power plant, which depends on a solar power system only known as (an off-grid system). The output of the off-grid system is entirely dependent on the intensity of the sun. The more exposure to the sun greater the yield.

Table 4 depicts the main parameters required for the economic analysis of both scenarios.

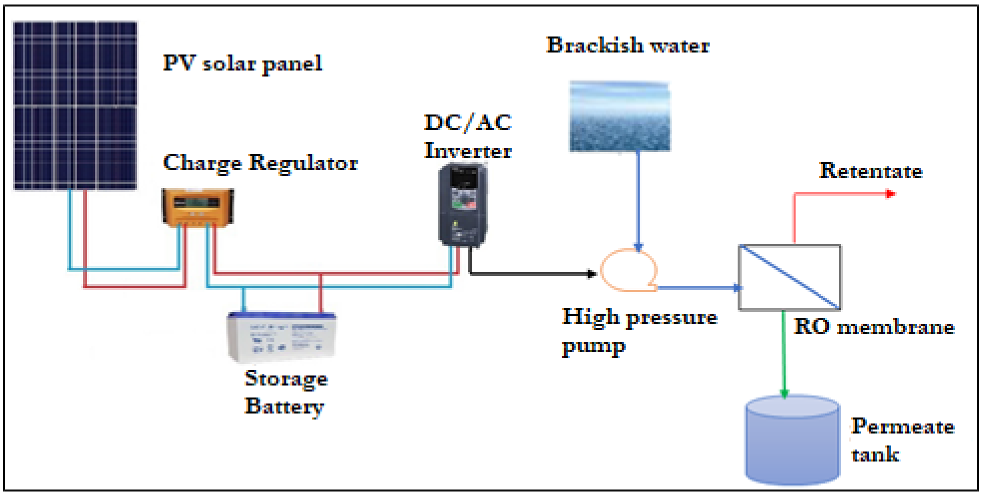


Figure 5 – System powered by a photovoltaic solar array and batteries for storage (Off-Grid)

Table 4 – The annual cost for On and Off Grid

Elements	On -Grid	Off - Grid
BWRO desalination unit	22608.98	274296.74
Land	0	0
energy	221.57	221.57
Operating & Maintenance	31.0575	35.8575
Replacement	556.08	556.08

5. RESULTS AND DISCUSSION

5.1 Effect of permeation flow on permeate TDS and rejection rate

It appears that, from a TDS concentration of 50 g/L in the feed water, the amount of TDS in the produced water becomes decreasing. This is not consistent with the fact that the amount of permeate TDS must be proportional to that in the feed water recovery. Therefore, it can be concluded that starting from 50 g/L of salinity, the RO system used here is not adequate. We determined the effect of the permeate flow Jeon the amount of the permeate TDS and on the rejection rate Figure 6.

We can notice that the permeation flow must be as high as possible in order to obtain a high rejection flow and a low amount of TDS permeate. It is important to consider the external pressure when choosing an RO system, and opting for one with a high working pressure can be a wise decision. This can help ensure that the system operates efficiently and effectively, ultimately leading to better results.

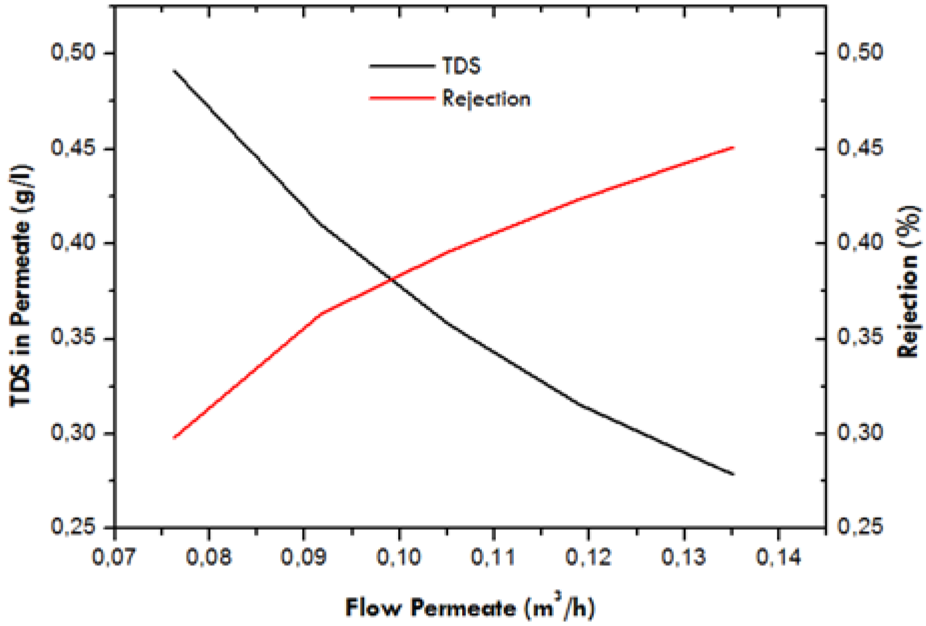


Figure 6 – Permeate flow effect on permeate TDS and rejection rate

5.2 Effect of permeate TDS on the RO and PV energies required

In fact, on Figure 7, we notice that the energy required by the RO pump and the required by the PV, decrease as a function of the permeate TDS amount variation. Then, to have a produced water with the minimum of TDS (about 0.27 g/L), we need an energy of 35 Kwh/day from PV to supply a RO pump of 15.6 Kwh.

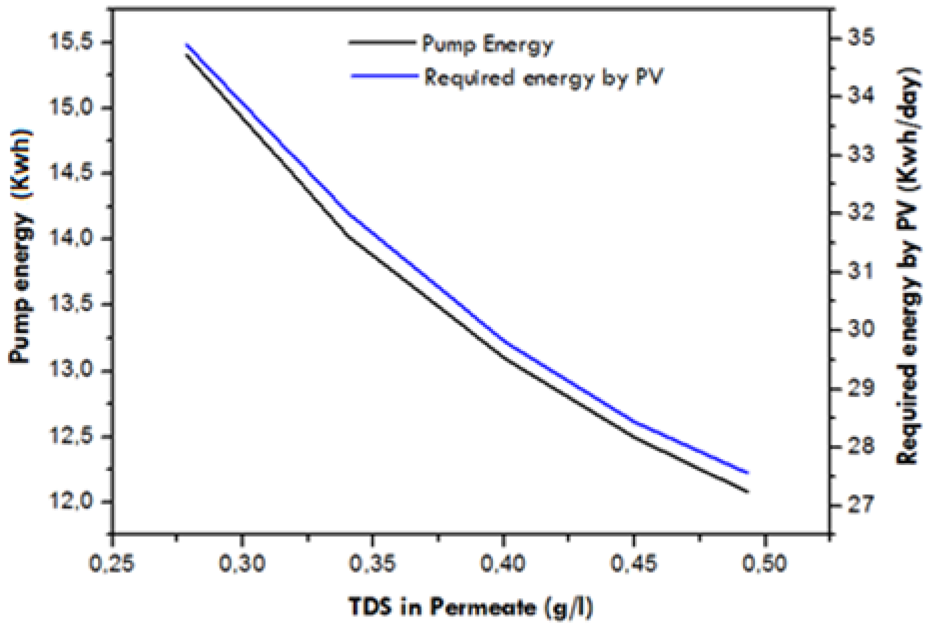


Figure 7 – Effect of permeate TDS on the RO and PV energies required

5.3 The cost analysis

The Levelized water cost (LWC) was calculated on the base of the information presented in the previous Table 4. These have been presented in Figure 8, which shows the results of calculations of water costs in relation to various interest rates. With the increase of the interest rate from 4% to 8% for both scenarios, considering a variation of water cost with the average interest rate value of 4%. In addition, the water production cost of the Off-grid system was about 1.14 times lower than that of the On-grid system. The Levelized water cost Off-grid scenario that depends on photovoltaic as an energy source was the lowest cost compared to On-grid system. This is reflected positively according to the economic indicators.

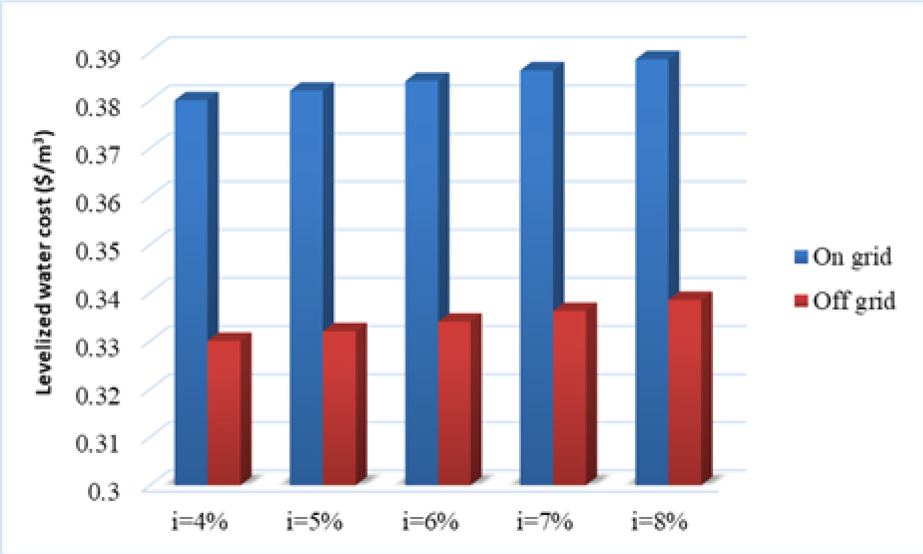


Figure 8 – Effect of interest rate on water cost

The values of NPV and IRR are estimated for an interest rate of 4% recommended by the government (Abbas *et al.* 2018). The detailed economic analysis of the PV-RO system is shown in Table 5. From these results, we see that the on-grid scenario yields the same electrical energy produced in the off-grid scenario, but the "NPV" revenues are positive due to the high initial investment cost of the off-grid compared to the on-grid. The project is profitable when NPV is positive. Indeed, the off-grid scenario is profitable for the investment because the IRR is the higher.

Table 5 – Economic analysis results

	On-Grid	**Off-Grid**
LWC($/m^3)	0.38	0.33
NPV($)	-16163.09	383730.47
IRR(%)	11.43	11.72

6. Conclusion

Desalination is one of the solutions chosen by Algeria and around the world to solve the emergency water problem. This process is limited to the energy and operating costs of these stations and therefore to the cost price per cubic meter of water produced. Renewable energy-powered reverse osmosis desalination systems are promising technologies for seawater and brackish water desalination in remote areas as they exhibit low energy consumption and can be designed according to potable water requirements and available energy resources. In this study, an economic analysis was carried out for a reverse osmosis desalination plant of capacity of 2.016 m3/day. Several techniques and economic approaches are proposed in order to assess the economic feasibility of the project. Two scenarios were proposed, the first scenario being a desalination station powered by a public network without a solar energy system (On-Grid) and the second scenario a station powered by photovoltaic panels. The economic analysis show that the levelized water cost of the Off-Grid system (0.33 $/m3) was about 1.14 times lower than of the On-Grid system (0.38 $/m3). We can notice that the second scenario was chosen as the best economic option to optimize the cost of the desalination unit at UDES. It depends on the solar power system and electrical power known as (Off-Grid).

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