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Economic analysis of reverse osmosis desalination powered by the photovoltaic system for irrigation: a case study of the semi-arid irrigated area Dyiar-Al-Hujjej, Tunisia

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ABSTRACT

Several areas are experiencing local water shortages and are now using desalination devices to mitigate its effect. In this study, an equation is proposed to estimate the production unit cost of reverse osmosis (RO) powered by a photovoltaic (PV) system based on current PV-RO module prices used to determine the economic feasibility of the system. PV-RO for agriculture in the coastal area of Dyiar-Al-Hujjej. This study area suffers from seawater intrusion and is also threatened by the salinization of the soil due to irrigation. The results show as expected that the price increases from 1.02 to 2.12 US $/m^3 for 3,000 and 9,000 ppm respectively, as the salinity of the feed water increases. For crop selection, high-value crops and crops with low water requirements are the two main criteria to consider. Strawberry is the best choice with a positive return on investment of 237%, 120%, and 60%, respectively, for 3,000, 6,000 and 9,000 ppm, unlike other crops that still have a negative return on investment. Increasing needs to meet the demand for water in agriculture harms the economy of the PV-RO system.

Keywords: Water scarcity; Reverse osmosis; Photovoltaic; Solar desalination; Irrigation; Water Sustainability; Alternative water sources; Arid regions; Sustainable development

1. Introduction

According to the United Nations report [1], agriculture alone uses 70% of the world's water supply. Besides, global food demand is expected to increase by another 70% by 2050. However, according to the report, the main challenge facing the world today is not so much the increase of food production, but rather to provide good quality irrigation water to farmers in sufficient quantities. Shortage of water in arid zones has led to the usage of low-quality irrigation water in agriculture in most arid climate areas [2]. The water deficit is a problem present in many parts of the world, with lower rainfall and increased salinity of aquifers [3]. In semiarid and arid countries, the groundwater is usually the main resource used for irrigation [4]. in Tunisia, global water demand, according to estimates for the 2030 horizon, will stabilize at nearly 2,700 Mm^3/y on average, for a total population of 13 million inhabitants, knowing that the water resources can be regulated annually will be 3,100 Mm^3 [5]. However, the quality of irrigation water service is often lacking and crops irrigation is often not managed in an economic and environmentally sustainable way. Indeed, due to high salinities in these groundwater resources, salinization is becoming a common problem affecting irrigated areas [6]. In Tunisia, irrigation of diverse varieties of crops is increasing around shallow

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well having a salinity ranging from 1,800 to 5,400 ppm [7]. Irrigation with brackish aquifer is widely practiced in Tunisia causing low yields and crop choice is limited to halophyte crops.

Nowadays, desalination is a method to obtain good quality water. All desalination processes are energy-intensive and share the common minimum energy required to cause the saline solution to separate into pure water and concentrated brine. It is dependent on the detailed technology used, the exact mechanism or the number of process steps. Furthermore, the overall equivalent power consumption of a multi-stage flash unit is 20 to 30 kWh_{elec}/m^3, the overall equivalent power consumption of the multi-effect desalination unit also varies from 15 to 22 kWh_{elec}/m^3 [8,9]. These thermal processes are energy-intensive because there is a loss of energy efficiency due to phase changes (fossil to thermal or fossil to electric to thermal). According to the same author [10], for the reverse osmosis (RO) membrane process, the overall equivalent power consumption of the seawater reverse osmosis (SWRO) unit (seawater RO) reached the lowest specific energy consumption level of SWRO at 2.00 kWh_{elec}/m^3. The energy consumed by conventional desalination plants usually comes from combined cycle power plants. They are characterized by the highest efficiency of electricity generation technology from fossil fuels. These units are among the most developed, currently achieving yields above 60%. The CO_2 emission is equal to 330 kg CO_2/MWh [11].

In 2012, desalinated water reached 66 million m^3/d; in 2015, it is estimated at 100 million m^3/d [12]. Reverse osmosis (RO) represents about 60% of the global desalination capacity.

According to Mohammed Ramadane et al. [13], water scarcity can be solved by the use of desalination coupled with solar energy. Depending on the amount of energy received on the Tunisian coasts for a year, these areas are conductive to the installation of solar power plants. The desalination potential over one year can reach more than 85 billion m^3/y in certain areas when the direct normal irradiance (DNI) exceeds 1800 kWh/m^2/y (Fig. 1). The x-axis represents the DNI and the y-axis represents the quantity of desalinated water obtained (in billions of m^3/y). It is the distribution of surfaces according to the radiation expressed in the production of desalinated water.

These processes are energy-intensive, so water desalination systems coupled with photovoltaic (PV) systems have recently been studied, providing promising alternatives for agriculture. The main objective of this article is to investigate whether it is possible to consider desalination of saline water by PV-RO desalination system for irrigation water supply to the coastal agricultural area of Dyiar-Al-Hujjej in Tunisia. This coastal area aquifer suffers from seawater intrusion due to excessive pumping.

An empirical equation is proposed to calculate the unit cost of reverse osmosis powered by the photovoltaic system based on the feedwater salinity and the capacity of the facility to compare the unit water cost concerning agronomic income. This study aimed to develop a decision support system for the water-food and energy nexus approach in arid countries such as Tunisia.

2. Material and methods

2.1. Study area and data

Dyiar-Al-Hujjej, a northeast city of Tunisia (latitude 36°61′N; longitude 10°81′E), borders the Mediterranean Sea (Fig. 2). The bioclimate in this site is Mediterranean semi-arid, with temperate winters and with large interannual and interseasonal variations of precipitation.

As for rainfall, having the same climate as the capital Tunis (67.3 km as the crow flies from Tunis), the region received about 456 mm/y [15] and the evapotranspiration which represents the water losses resulting from soil evaporation and plant transpiration in this region is 1,166 mm.

Seawater intrusion and generalized salinization were observed in this 800 ha agricultural area. The number of abandoned wells, due to seawater intrusion, has increased from 1,268 in 1980 to 3,200 in 2005 [16]. The salinity

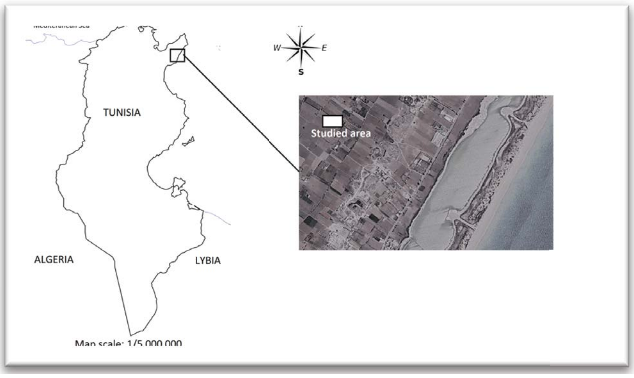

Fig. 2. Geographical location of the studied area.

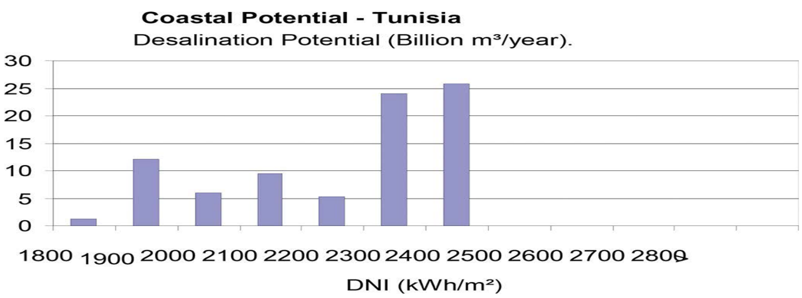

Fig. 1. Statistical analysis of the direct normal irradiance (DNI) map for CSP-desalination in Tunisia, (20 m above sea level) [14].

aquifer map prepared in 1963 shows the presence of salinities varying between 2,100 and 3,430 ppm. In 2007, the salinity varied between 2,800 and 10,000 ppm with an average of 6,300 ppm.

This area was put under the direct control of the Tunisian government because of the very high salinity that is in the aquifer. The piezometer of this aquifer is always under monitoring. The prediction of the groundwater level of an aquifer is one of the most important tasks in hydrogeology [17]. Such forecasts are essential for developing better strategies for the exploitation of water resources and the up-to-date monitoring of groundwater.

2.2. Agricultural data

In Tunisia, farms are generally very small in size (53% of Tunisian farms have an area of less than 5 ha). Also in Dyiar-Al-Hujjej, farms with a size smaller than 5 ha are the most repurposed in this area.

The existing study on the average net revenue from Dyiar-Al-Hujjej agricultural area was used for the case study economics. Table 1 summarizes net revenue ($/ha/y) and daily water requirement (m^3/ha/d) from three crops. Strawberry was shown to have the highest ratio of profits and was used for the optimistic case study in the Dyiar-Al-Hujjej area. Tomato is relatively a profitable crop but has a large water requirement that was used for the basic scenario in the Dyiar-Al-Hujjej area. Pepper represents a marginal crop with low profits and high-water requirements. It was also considered in the case study of the Dyiar-Al-Hujjej area. Water requirements were calculated by CropWat.

2.3. PV-RO desalination unit production cost and economic evaluation for the agriculture

RO desalination is the principal desalination technology in Tunisia using natural gas or oil for power generation. The low expenses of conventional energies in Tunisia discourage the use of solar energy. On the other hand, as Tunisia has joined the Kyoto agreement, it is committed to reducing its carbon footprint by reducing its greenhouse gas emissions. In this paper, the focus was on RO powered by PV system for power generation (Fig. 3). For small-scale applications, PV is suitable with RO since PV panels are designed in a modular way to facilitate assembly if the will to build up solar stations for agricultural purposes.

In this paper, a multiple linear regression analysis was performed to derive an empirical cost Eq. (1) (US$) for PV-RO desalination plants as a function of feed water salinity and plant capacity. Data were obtained from modeling performed for PV-RO [19] and data from PV + RO systems in Middle East North Africa for brackish water [20] from a salinity higher than 3,000 ppm. Eq. (1) is only valid for values Q less than 50,000 m^3/d. The PV system is composed of 64 monocrystalline Si modules (ATERSA, Model A-75) with a total power of 4.8 KW_{elec}, a DC/AC inverter (TRACE, Model SW4548E) of the nominal power of 4.5 KW_{elec} and batteries (TUDOR, Model 10TSE80) of nominal capacity 1,240 Ah, 48 V. The RO desalination unit consists of a spiral-wound membrane (Filmtec HR3040) of 3 m^3/d capacity. For the pressure of the feedwater is 45 bar, the plant must be operated for 6.5 h to achieve the minimum required production of 0.8 m^3/d with salinity 450 ppm and specific energy consumption of 16.3 kWh_{elec}/m^3.

$$\mathrm{Cu} = 0.148S - 4.173\times10^{-7}Q + 0.447 \quad (1)$$

Cu: desalinated cubic meter cost ($/$m^3$); S: feedwater salinity (ppm) and Q is the plant capacity (m^3/d)

The constant 0.447 simply indicates if all the explanatory variables, which are feed water salinity (ppm) and plant capacity (m^3/d), included in Eq. (1) are zero at a certain period, then the value of the dependent variable which is the cubic meter desalinated the cost ($/$m^3$) will be equal to the constant term.

Table 1
Crops net revenue ($/ha/y) and annual water requirement (m^3/ha/y)

Locational parameters	Strawberry	Tomato	Pepper
Net revenue ($/ha/y)	12,391	2,800	659
Annual water requirement (m^3/ha/d)	9.86	17.71	16.44

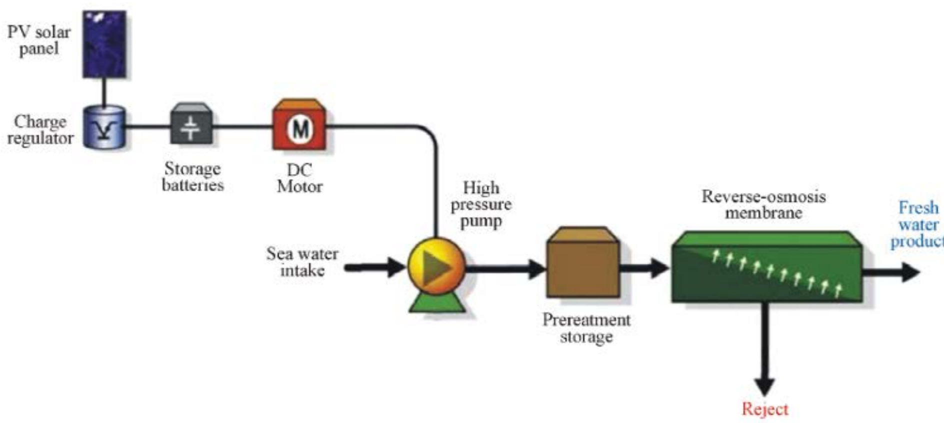

Fig. 3. Schematic diagram of PV-RO system [18].

Also, the return on investment formula which is an economic indicator [21] is used to evaluate the sustainability of alternative projects. The return on investment (ROI) formula is as follows [22]:

$$\text{ROI}(\%) = \frac{\text{Gain from investment} - \text{Cost of investment}}{\text{Cost of investment}} \quad (2)$$

where ROI is a measure of cash engendered or lost due to the investment and may be calculated by the ratio of net profit from investment which is the sale of the agricultural goods to the amount of money invested in the PV-RO unit [23].

3. Results and discussion

Desalination cost is considerably affected by feed water salinity as projected (Table 2). The empirical equation was used to identify the best crop for different situations based on the feedwater salinity, water requirements and net profits. Results are presented for salinity fluctuating from 3,000 to 9,000 ppm. The agricultural area of Dyiar-Al-Hujjej was designated for case study evaluation for farmers with plots less than 5 ha with the will to implement PV-RO stations.

For the first case which is the strawberry crop, the system is lucrative with an ROI of 237%, 120%, and 60% for 3,000, 6,000 and 9000 ppm respectively. For all this range of salinities that also have been measured in the aquifer of Korba where Dyiar-Al-Hujjej belongs (Section 2 – Materials and Methods), strawberry is the best choice for desalination for agriculture in Dyiar-Al-Hujjej agricultural area, due to the high profits and relatively low water requirements. Strawberry is grown from September to May where the climate is relatively moderate and rain is relatively heavy. This crop takes advantage of the rain to meet these water needs and for the leaching of salts in the soil.

The second case study, illustrates that although tomato induces relatively good profits; the high-water requirements equal to 88.5 m^3/d compared to 49.3 m^3/d for strawberry, necessitate an expensive desalination system of 32.8, 50.7 and 68.5 $ thousand for 3,000, 6,000 and 9,000 ppm respectively. This system results in an ROI of –60%, –72%, and –80% for 3,000, 6,000 and 9,000 ppm respectively. Tomato is a summer crop where the climate is very hot and rain is scarce. Evapotranspiration is highest in this period. This crop doesn't take advantage of the rain to meet these water needs and for salts leaching. It needs complementary irrigation for both growth and salts leaching in the soil. Economic profit has decreased significantly in comparison with the first case. As projected, the third case study shows the poor crop choice and results engenders an unbeneficial system. Pepper is also a summer crop like that tomato and evapotranspiration is highest in this period.

Brackish desalination water may be a solution for irrigated agriculture in the coastal area of Dyiar-Al-Hujjej faced with persistent water scarcity and growing low-yielding rain-fed crops where there is a lack of alternative water resources. Indeed, brackish desalinated water is considered an untapped and unrestricted source of water. Indeed, a study was conducted in Sydney on the use of alternative water sources for irrigation and the replacement of traditional sources of drinking water with alternative sources. According to Paul et al. [24], this option can be considered to regulate water consumption that is at critical levels whether it is drinking or agricultural. Heavy droughts and population increases have put pressure on existing water sources, resulting in restrictions that affect the community. However, the economic cost of brackish desalination water is so high for most field crops in irrigated areas. The use of brackish desalinated water in agriculture is considerably limited by its high price measured at the cost of other conventional sources of water. A work done by Helmi et al. [25] emphasized the prospect of renewable energies compared to conventional energies and its competitiveness and profitability on the price of electricity. Renewables energies sources can provide clean and sustainable electricity but more expensive than conventional power if the state subsidy is existing.

Based on the results of the comparative case study of Dyiar-Al-Hujjej, it showed that applying PV-powered RO to a high-yielding crop such as strawberry can result in a

Table 2
Water cost ($/$m^3$), total investment ($/m^3) and return on investment (%) for 5 ha

		Locational parameters		PV + RO results			
Crops	Area (ha)	Net revenue for 5 ha ($)	Annual water requirement for 5 ha (m^3/d)	Feed water salinity (ppm)	Water unit cost ($1	Investment, O&M and insurance costs for 5 ha ($)	ROI (%)
First case: Strawberry	5	61,958	49.3	3,000	1.02	18,354	237
				6,000	1.57	28,251	120
				9,000	2.12	38,148	60
Second case: Tomato	5	14,000	88.5	3,000	1.01	36,225	–60
				6,000	1.56	50,392	–72
				9,000	2.12	68,481	–80
Third case: Pepper	5	3,301.2	82.2	3,000	1.01	30,303	–89
				6,000	1.57	47,105	–93
				9,000	2.12	63,606	–95

positive return on investment. The two important factors observed on which the ROI depends are the feedwater salinity and the unit capacity. If applied to the salinities measured in this study, the best value is for strawberries. It would provide a ratio of 237% for the return on investment for a feedwater salinity of 3,000 ppm. In Tunisia, A study presented the performance of a pilot solar irrigation system under arid climatic conditions [26]. The objective of this study was to study the potential of this combined solar system to produce freshwater as an alternative source for irrigation in the greenhouse used for tomato growth. Preliminary performance tests showed that 15% of tomato water requirements were provided by this system. Solar energy can be considered an alternative source for desalination.

Furthermore, a study in Iran [27] was made to examine all kinds of desalination technologies for water desalination. Iran with an annual average daily irradiation of 5.6 kWh_{elec}/m^2 has an inherent potential for the application of solar desalination. By applying simulation software, the result of the investigation showed that in all cases, the reverse osmosis coupled to the photovoltaic system had the best performance in terms of energy consumption and water cost production. Typically, the reverse osmosis process powered by photovoltaics needs to be adjusted to meet agricultural water quality requirements by:

- Choosing a place with a high normal direct irradiance to provide the energy needed for this process;
- Introduce high value-added crops to increase with generally small water requirements.

Despite the growing number of experiments using brackish desalination water to provide irrigated agriculture, much more experience and research are needed to determine when, where and how it could be a profitable source of irrigation water.

In the future, if the problem of soil salinization will affect large agricultural areas, MENA countries may consider thermal desalination plants which are better suited for the long-term and that can be coupled directly with solar thermal energy like concentrating solar power (CSP). A large number of CSP projects have currently been developed or proposed in many countries, particularly in China, Spain, and the USA [28].

Concentrating solar power (CSP) systems are deemed as the potential alternatives to current fossil fuel-based generating systems for the large-scale mining industry [29]. Indeed, many studies propose new simulation tools to facilitate the optical design of CSP technology [30].

Furthermore, In Algeria which is a neighboring country of Tunisia, a state program aims to achieve a renewable power installation of about 22,000 (MW) between 2011 and 2030, of which 12,000 (MW) will be oriented to cover the national demand and 10,000 (MW) for export. So, renewable energies are placed at the center of the economic and energy policy awareness of the country [31]. On a small or large scale, it appears that solutions are existing for desalination for agricultural purposes. Additionally, with the advancement of technology, these desalination methods will be even more suitable for agriculture. Renewable energies are in particular a privileged vector of the fight against global warming.

4. Conclusions

In this study, an empirical equation was developed to calculate the unit production cost of RO powered by a PV system depending on feed water salinity and plant capacity. The use of PV-RO in the Dyiar-Al-Hujjej agricultural area is currently found to be viable only for crops with high profits and low water requirements. However, its usage is limited to small-scale applications in locations with high solar insolation. On a large scale, thermal desalination by CSP can be a solution for irrigation water supply. In Tunisia, state subsidies will also influence the rate of adoption of solar energy.

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