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Economic analysis of a stand-alone reverse osmosis desalination unit powered by photovoltaic for possible application in the northwest coast of Egypt

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ABSTRACT

The availability of fresh water and energy is the key factor for the development of many countries particularly those of over-populated arid areas. Potable water supply shortage and recent technological development have led to wider application of conventional, and yet advanced saline/brackish water desalination plants. Today, desalination methods require large amounts of energy, which is costly both in environmental pollution and in money terms. This study defines the main economic parameters used in estimation of desalination costs and limitation of the stand-alone, small size SWRO plants powered by photovoltaic (PV) at the northwest coast of Egypt. Moreover, a techno-economic study is made to estimate the actual cost of m^3/fresh water production on real field measurements. All cost estimates are based on the prevailing prices during 2012–2013. The average unit cost of desalted water with the desalination unit powered by PV battery is 9.3–5.6 LE/m^3, which is very high, but when using the unit with battery, the cost is reduced to 2.3–1.7 LE/m^3 by increasing working hours to 24 h. Economical strategies should be developed for more reduction in cost, taking into account all phases from site selection and design to operation and maintenance and most importantly increasing the local manufacturing.

Keywords: Production cost; Economic analysis; Stand-alone; Reverse osmosis; Photo voltaic; Desalination; Egypt

1. Introduction

Water is an abundant natural resource that covers three quarters of the Earth's surface. However, only about 3% of all water sources is potable. About 25% of worlds' population does not have access to satisfactory quality and/or quantity of freshwater and more than 80 countries face severe water problems. It is obvious that a considerable increase in the world population (over the next decade or so) will be concentrated mainly in most of the developing countries and particularly in Africa, causing severe water shortages [1]. Renewable energy provides a variable and environmentally friendly option, and national energy security at a time when decreasing global reserves of fossil fuels threatens the long-term sustainability of global economy. The integration of renewable resources in desalination and water purification is becoming increasingly attractive. This is justified by the fact that areas of fresh water shortages have plenty of solar energy and these technologies have low operating and maintenance costs [2]. In future, the use of nuclear or

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renewable energy for desalination may be cost-effective. The fast growing development in Egypt requires big movements of investments and people from the delta and Nile valley towards the east, with the fantastic Red Sea and Sinai coastal zones, and also towards the Western Desert that has promising brackish groundwater potentialities. In both cases, fresh water supply is essential and desalination is a feasible option that can cover the wide gap between the available capacities and the accelerating demands [3]. The cost of desalination is decreasing in recent time due to the development of desalination technologies and desalination is now able to successfully compete with conventional water resources for potable water supplies. However, the cost of desalination is site-specific. It is thus essential to select an appropriate desalination technology that produces desalinated water at a low cost for any site under consideration [4]. Many researchers analyzed actual and forecasted demands for industry, tourism, and urban planning. Their findings were directed towards recommendation of local manufacture of desalination units [5]. The suitability of renewable energy technologies, especially wind and photovoltaic (PV), for reverse osmosis (RO) desalination system is due to the fact that RO is suitable for desalination of small amounts of water for remote and isolated areas; it has low energy consumption and little need for maintenance [6]. This study defines the main economic parameters used in estimation of desalination costs and limitation of the stand-alone, small size SWRO plants powered by PV at the Northwest Coast of Egypt. Moreover, techno-economic study will be made to estimate the actual cost of m^3/fresh water production on real field measurements. All cost estimations will be based on the prevailing prices during 2012–2013 and with the exchange rate of about 6.75 Egyptian Pound (LE) for US$1.

2. Materials and methods

Northwestern coastal zone is one of the promising parts of Egypt for sustainable development, the planning for the development of such coastal zone needs integrated studies in numerous scientific fields, such as geology, pedology, hydrogeology, hydrogeochemistry, and socio-economy. The study area stretches westwards from Abo Laho in the east to Marsa Mattroh and west of El-Negela basin (about 80 km length and 20 km average width) is considered one of the most promising regions for development. This selected area have a population of about 300,000 and can possess a good agricultural expansion, due to its favorable soil and water potentials, in addition to its mild weather. The area depends mainly on groundwater whose salinity ranges from 2,000 to 25,000 ppm and the water type is brackish to extremely saline. The water samples in the promising area of investigation are more than 100 water points and the depth to water is 4.22–104 m. The rate of water discharge from this area is 8,000 m^3/d. This area is characterized by breadth localities prone to solar energy for the length of days of the year. Temperatures range from 22° to 43° in summer and from 0 to 17 in winter. Sunshine periods range between 6.5 and 12 h/d [7]. Therefore, using the proper desalination process can make this quantity of water useful for different purposes and extended the crowded population to another places far from the Nile delta and valley.

Renewable solar energy sources in Egypt can play a very effective role to combat energy shortage. The Supreme Council of Energy has announced an ambitious plan aiming at generating 20% of total energy demands of Egypt by 2020 from these renewable sources. The use of solar energy for seawater desalination to obtain potable water is the subject of many investigations done during recent years. Potentially, solar desalination offers an ecologically advantageous means of renewable energy utilization at a minimum cost. Solar water evaporation plants use collected solar energy for direct heating and evaporating of salty water to gain distilled water. In other cases, solar energy has been used to heat seawater and later to inject warm water into air to humidify it. The subsequent cooling of the humid air delivers the needed water free of salt. In all of these processes, the salty water is directly heated by the sun [8]. The advantage of using "free" energy is partly offset by increased amortization costs; however, distillation with solar energy remains one of the most favorable processes for small capacity water desalting for remote regions where there is substantial solar radiation, and a lack of skilled personnel and erection and maintenance facilities. A comparison between solar desalination and conventional systems (RO and multi stage flash) is presented (as a percentage of the total costs (MSF)) by Heschl and Sizmann [9], and is highlighted in Table 1. It is worth noting that the data presented in Table 1 is almost 20 years old and some of it may not be valid any more. The comparison shows that investment costs are the highest, but energy costs are the lowest in the case of renewable energy powered desalination systems. In countries with abundant solar energy, solar desalination could be one of the most successful applications of solar energy. The estimation or stipulation of an economic price is essential for poor small communities lacking fresh water [10]. Although market prices for renewable energies are high, they could gradually become lower in the future

Table 1
Distribution of costs for conventional (RO and MSF) plants and for plants driven with renewable energy

Type of process	Investment costs (%)	Operational costs (%)	Energy costs (%)
Conventional (RO)	22–27	14–15	59–63
Conventional (MSF)	25–30	38–40	33–35
Renewable	30–90	10–30	0−10

and would be competitive with conventional energy sources.

Buros [11] made it clear that there is a relationship between the different methods of water desalination, as shown in Table 2, that, of the 100% desalted water produced around the globe annually, RO (42%) and MSF (44%) are the most widely used technologies. In the US, the primary desalination method currently utilized is RO, while the majority of large seawater desalination facilities in the Middle East utilize MSF and other distillation technologies. Mesa et al. [12] claim that desalinating groundwater at 2,000–3,000 ppm TDS by RO requires between 1.4 and 1.7 kWh for every cubic meter of product water (5–6 kWh/1,000 gal), which is significantly lower than the energy required to treat seawater (5.6 kWh/m^3 for 30,000–40,000 ppm TDS). Distillation processes, on the other hand, utilize little electricity relative to their heat energy intake. Distillation requires 1.3 kWh/m^3 electricity (5 kWh/1,000 gal) and 48.5 kWh/m^3 heat (0.66 GJ/1,000 gal) independent of feed water salinity. Thus, we see that distillation is more energy intensive than RO. Peterson [13] states that the energy requirements for both RO and distillation are proportional to the volume of product water. However, because of the high cost of membrane replacement, membrane methods are less suitable for desalinating seawater. But technological advancement has also allowed some reduction in the total desalination cost, by improving energy efficiency (multi flash distillation or hybrid systems), by facilitating transfer processes or by energy recycling (process of cogeneration) [14].

3. RO & membrane desalination

The coupling of a membrane distillation system to a solar-driven multi-effect or MSF distillation units increases the overall performance ratio. Other hybrid desalination processes also have interesting potentials. RO desalination driven by solar-assisted power cycles provides the electricity consumption of the RO plant as well as the low-grade thermal energy consumption of the membrane distillation process in order to distil the blow down of the RO plant. None of these hybrid desalination processes have ever been implemented. In stand-alone solar desalination systems, the connection of a salinity gradient solar pond to a membrane distillation process has never been implemented. It could however be one of the most economic systems since a given membrane distillation system is able to operate at varying top brine temperature provided by the solar pond during the year. This fact guaranties the continuous and trouble free operation of the desalination system along the year, according to solar pond behavior [15]. Only a slight decrease in the performance ratio should be exhibited in winter since the decreasing ambient temperature partially overcomes the decreasing temperature of the heat storage zone. If a conventional thermal input is available as energy backup, an absorption heat pump provides a higher

Table 2
Installed desalination capacity

Desalination method	Abbreviation	Installed desalination capacity (%)	Typical parameters
Multi-stage flash	MSF	44	4,000–60,000 m^3/d production, operate at top brine temperature of 90–110℃
Reverse osmosis	RO	42	70–90% recovery
Electrodialysis	ED	6	70–90% recovery
Multi-effect distillation	MED	4	2,000–20,000 m^3/d, operate at lower temperatures than MSF, as low as 70℃ 500–20,000 m^3/d, operate at a temperatures as low as 50℃
Va or com ression	VC	4	500–2,000 m^3/d, operate at a temperatures as low as 50℃

Note: Adapted from Buros [11].

energetic performance for the fossil fuel since the temperature of the required heat input is higher than that of the membrane distillation process. The coupling of a heat pump would also lower the temperature of the coolant below ambient temperature, thus increasing the performance of the membrane distillation process.

4. Small autonomous RO systems powered by PV

Stand-alone PV systems are used in areas that are not easily accessible or have no access to electricity (Fig. 1). A stand-alone system is independent of the electricity grid, with the energy produced normally, being stored in batteries. A typical stand-alone system would consist of PV modules, batteries, and charge controller. An inverter may also be included in the system to convert the direct current (DC) generated by the PV modules to the alternating current form (AC) required by normal appliances [16]. Small capacity desalination units utilizing the RO technology and powered by PV cells, represent an ideal solution for providing freshwater to small communities in isolated arid areas with high solar irradiation and having access to the sea or brackish water. Usually, such communities have no access, neither to the local power grid nor to the fresh water network [17].

4.1. Description of system operation

A major hurdle in determining the cost of desalinated water from solar-powered systems is the limited data available for economic evaluation and cost estimation of these processes. Solar energy-based plants are capital-intensive and as prices for the construction materials are location specific, there is difference in cost of fresh water produced between regions. Some investigators have conducted cost estimation studies on solar-powered desalination processes in general. A few researchers have also studied a combination of solar energy with conventional desalination techniques and the costs of these processes have also been presented in this study. The aim of this economic analysis is estimating the cost of autonomous desalination systems, as usually each system cost is determined using different parameters, the interest rate is considered as 9%, and the economic duration of the desalination system is assumed 30 years Table 3. Under these identical conditions (Tables 4 and 5) the prices for total investment cost and maintenance (O&M) cost have been derived directly from the contractors who are supervising the plant operation.

Fig. 1. Small autonomous RO systems powered by PV.

Table 3
Detailed system configuration

Item	Unit	Result
Depreciation time	Year	30 years
Interest rat	%/Y	8
Quantity of water produced per year	$3\,m^3/6\,h$	1,095
Quantity of water produced per year	$5\,m^3/6\,h$	1,825
Annual operating time	h	2,190
Water cost $3\,m^3/d$	LE	9.3 LE/m^3
Water cost $5\,m^3/d$	LE	5.6 LE/m^3

Source: Collected and calculated data from questionnaires sample field study.

Table 4
Parameters for estimating cost of investment and operation

Parameter	%
Cost of power energy (6 unit)	7.5
Cost of RO unit	60.6
DC/AC inverter	10.1
Structure	3.9
Tracking system control panel	2.4
UPS	1.44
Mechanical drive	0.92
Electronic motor	1.2
Trailer	4.5
Assembly	7.5
Total	100

Source: Collected and calculated data from questionnaires sample field study.

Table 5
Parameters for estimating cost of operation and maintenance (O&M)

Parameter	%
Membrane replacement	4.8
Maintenance people	11.9
Operational people	11.9
Other maintenance cost including spare parts	71.4

Source: Collected and calculated data from questionnaires sample field study.

Finally, as shown in Table 6, the case that the RO/PV system battery less, has production of 1,095–1,825 m^3/year. So, the cost of the desalinated water becomes 9.3–5.6 LE/m^3, while the RO/PV system with battery has production of 4,380–7,300 m^3/year. So, the cost of the desalinated water becomes (2.3–1.7 LE/m^3). The RO/PV desalination systems examined in this paper are not quite large as they can produce around quarter a ton of potable water per year. However, it could be a viable solution for a small zone like north-west coast. Taking into account that the daily human requirements of potable water are approximately 3 l of fresh water, a suitable water desalination capacity, it can be easily understood why this system not only form a solution but at the same time is very useful as it is based on renewable energy sources which do not harm the environment and the natural beauty of this zone.

5. Economic and social effects

5.1. Economic effects

Table 6 explains some measures of economic efficiency calculated from the obtained data to reveal:

(1) The average production amounted to about (1,095–1,825 m^3/year) of potable water.
(2) The value of total production (10,183–10,220 LE/year).
(3) The standard ratio of benefits to costs amounted to about 0.98–1.2, this indicates that the project is economically feasible, But the project does not bring economic profits.
(4) The cost of water unit (battery less) is about (9.3–5.6 LE/m^3), while the cost of water unit (with battery) is about (2.3–1.7 LE/m^3) when the desalination unit is used for the whole day.

5.2. Social effects

The fact that water is necessary for human life magnifies of the value of water. Where water is sufficiently scarce, that fact would be reacted in a private or national willingness to pay large sums for small amounts of water. Where water is somewhat more abundant (although still scarce), the value of water will be lower. But, no matter how scarce water is, every person requires and is entitled to at least the minimal amount of water consistent with human life and dignity. To find out how important this project is one must identify the factors that encourage the establishment of this project despite the high costs, and study the proportion of individuals deprived North-West Coast to enjoy a glass of clean water measuring poverty in its various dimensions and call for a qualitative approach: index measures of poverty in crescendo multiple dimensions of denial at the individual level in the areas of health, education, and standard of living, which is a measure based on a sample of accurate data that taken by the research group of families. This methodology is based measure to split the three indicators to 10 reference points, dividing the dimensions of education and health to four reference points and the standard of living index which includes six points. Fig. 2 shows reference points that divided them into three indicators. Sample survey has been taking randomly of 35 families with 4–9 members. The analysis of data by poverty measurement equations reveals the following:

The proportion of people who suffer from multidimensional poverty [18] equal,

Table 6
Measures of economic efficiency of the desalination project

Standard	3 m^3/d Battery less	12 m^3/d With battery	5 m^3/d Battery less	20 m^3/d With battery
Average amount of production/year	1,095 m^3	4,380	1,825 m^3	7,300
The value of total production	10,183 LE/year	10,074 LE/year	10,220 LE/year	12,410 LE/year
Standard ratio of benefits to costs	0.99	0.98	0.99	1.2
Cost of product unit	9.3 LE	2.3 LE	5.6 LE	1.7 LE

Source: Collected and calculated data from questionnaires sample field study.

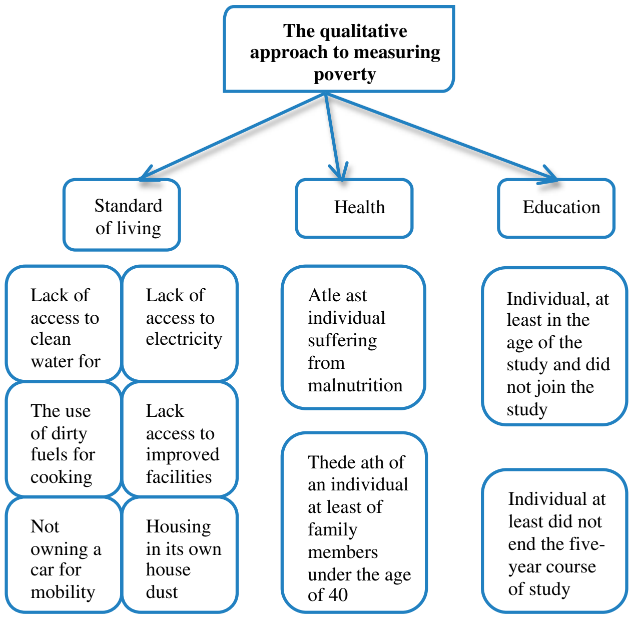

Fig. 2. The qualitative approach to measuring poverty.

$$H = \frac{Q}{N} \tag{1}$$

where H = the proportion of people who suffer from poverty dimensional, Q = the number of people who suffer from poverty dimensional, N = the total population. The results indicate that 83% of the total sample households suffer from poverty in many areas, therefore, the severity of poverty was measured by the following equation [13]:

$$A = \frac{\sum_i C}{Q} \tag{2}$$

where A = severity of poverty, C = total disadvantages suffered by the poor, Q = the number of people who suffer from poverty dimensional.

Computation of the equation dictates that the severity of poverty rate is 74% of the total number of households those recording suffer from multi-dimensional poverty and this figure indicates that a poor person is deprived of 74% of the previous indicators. It is already clear that the project could cover its cost, but not economically profitable in the short-term, but may bring economic profits in the long-term if some components are produce it locally. The greatest benefit from this project is helping poor people in this region and improving the standard of its living.

6. Conclusions

There is an increasing need for renewable energy powered desalination systems, as this seems to be the sole environmentally friendly alternative to the conventional fossil fuel powered systems. RO seems to be particularly suitable for combining either direct electricity producing technologies (such as PV and wind turbines) or indirect such as solar collectors. This paper focuses on an efficient cost-effective battery less mobile PV powered groundwater reverse osmosis (PV/RO) desalinating unit, This unit is capable of desalinating brackish and saline groundwater with TDS up to 25,000 ppm and produces 3–5 m^3/d of potable water per day that complies with international standards. Northwestern coastal zone have good solar resources that recommend the use of PV power. On the other hand avoiding the use of batteries is based upon their poor performance due to deep discharging problems and improper maintenance practices, maximizing electric energy yield is provided in the unit by incorporating single axis tracking system as well as PV cleaning and cooling. These features can increase energy yield by 30–35%. In practice however, small-scale PV/RO presents two technical challenges. Firstly, solar power is intermittent and variable, batteries are often used to allow RO units to run continuously and at constant flow, yet batteries are very problematic especially at remote areas. The cost of desalination using the PV/RO system battery less is 9.3–5.6 LE/m^3. The investment cost present 87.9% of the total project cost; the operation and maintenance cost present 12% of the total project cost. The cost of water unit can decrease dramatically if we use conventional sources of energy; however, even at this level of cost, the PV/RO system could provide the necessary quantities for potable water for a small zone, like the area selected in the northwestern coastal, at a cost not far from that of water hauling.

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