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Economic efficiency of small mobile desalination system powered by renewable energy in Egypt

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ABSTRACT

Egypt is experiencing a fresh water crisis. Many large and small communities in Egypt are suffering an acute shortage of fresh water that complies with minimum health requirements. Many desert areas require high investment funds to provide them with pure, drinkable water. Some of these areas face a wide range of technical and administrative problems that hinder the achievement of this goal. This research focuses on the integration of saline water and RO water desalination and hybrid solar photovoltaic (PV) technology. Solar driven reverse osmosis desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. The research is based on an RO-PV driven prototype previously developed and successfully tested by the research team. The aim here is to determine the performance of the desalination unit, to measure their technical, allocative, and economic efficiencies. The data envelopment analysis (DEA) approach is used to estimate the technical, allocative, and economic efficiencies of desalination unit in the North West cost of Egypt. Overall technical, allocative and economic efficiency (EE) measures estimated from the DEA approach and their frequency distributions with constant return to scale (CRS) and variable return to scale (VRS) are presented. Under the CRS assumption, the estimated mean SE measure for desalination unit is 86%. With the VRS model the mean technical efficiency (TE) was estimated to be 94%. The mean allocative efficiency (AE) and EE measures estimated from the DEA frontier are 93%, 87% for CRS, and 96%, 94% for VRS, respectively, indicating that costs could be reduced by approximately 7%, if the unit was allocatively efficient. The mean TE estimated for the desalination unit for the CRS and VRS, DEA approaches are 93% and 98%. This result means that the small unit could produce the same level of output at approximately 7% less cost if the operation was technically efficient if CRS is assumed, or by 2% if VRS is assumed.

Keywords: Economic efficiency; Small mobile desalination system; Renewable energy; Egypt

1. Introduction

At present, there are significant challenges to water resources development and use in Egypt, beginning with a single source of water – The Nile – uncertainties in climate, developments upstream, and population growths. The current total water supply in Egypt is about 57.5 billion m^3/y from which there is a fixed 55.5 billion m^3/y from the River Nile. The per capita water share was 771 m^3/y in 2005, which is below the international standards of water poverty line of 1,000 m^3/y. Recent studies indicated that the estimated water need in 2010 is about 69 billion m^3/y that represents a shortage of about 19%. By the year 2025, this shortage will be severer; the total water demand will exceed 125 billion m^3/y resulting in a shortage of more than 30% [1].

Desert regions in Egypt constitute more than 94% of the total area of the country. The other 6% of the area includes mainly the cultivated lands in the Nile valley and Delta. On the other hand, the majority of Egyptian pop-

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ulation is concentrated within the area of the Nile valley and Delta whereas less than 5% of the population scattered in all desert areas. Such situation resulted in serious economic, social and environmental problems. The increasing of population in Egypt and the limitation of the fresh surface water resources (mainly Nile water) and, accordingly, the limitation of the cultivable lands in the Nile Valley and Delta urged the successive governments to draw various programs for land reclamation in desert areas. Such programs mostly depend totally or partially on exploitation in water reuse and desalination of brackish and saline water. Seawater and brackish water desalination are attracting more and more interest and attention, as they are the most important methods to solve the problem of water shortage [2]. Renewable energy provides a variable and environmental 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. Previous study defines the main economic parameters used to estimate desalination costs and limitation of the stand-alone, small size SWRO plants powered by photovoltaic (PV) at the North West cost of Egypt, it has shown that 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 North Western coastal, at a cost not far from that of water hauling [3].

Moreover, techno-economic study is made to estimate the actual cost of m^3/fresh water production on real field measurements. All cost estimations 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 be between 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. This paper aimed to achieve the most efficient use of economic resources available to produce desalinated water using solar energy, by measuring both the technical efficiency (TE), and economic efficiency (EE), determining the amount of resources that can achieve EE and estimate the surplus and deficit in the economic resources used in production, and assess the difference between the actual used quantities of resources and the optimum quantities that may achieve EE.

2. Materials and methods

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 m to 104 m. The rate of water discharge from this area is 8,000 m^3/day. 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 [4]. The data are collected from daily observation sheet of the stand-alone, small size SWRO plants powered by PV during the period April 2014 to June 2015.

3. Methodology

In a pervious work, team work focused on the incorporation of brackish water and seawater RO desalination and solar PV technology in one system. A small Mobile PV driven RO desalination plant prototype without batteries was designed. Solar-driven reverse osmosis desalination can potentially break the dependence of conventional desalination on fossil fuels, reduce operational costs, and improve environmental sustainability. Overtime work, the innovative features incorporated in the newly designed PV-RO plant prototype are focusing on improving the EE, of producing drinkable water in remote areas. This was achieved by maximizing energy yield through an integrated automatic single axis PV tracking system with programmed tilting angle adjustment. An autonomous cleaning system for PV modules was adopted for maximizing energy generation efficiency. RO plant components were selected so as to produce 4–5 m^3/d of potable water. A basic criterion in the design of this PV-RO prototype was to produce a minimum amount of fresh water by running the plant during peak sun hours. Results show that feed groundwater of salinity 10,930 µs/cm desalinated to be 53.7 µs/cm permeate water with SEC 1.7 kwh/m^3 [5].

The most common concept of efficiency is "technical efficiency" (TE) which means if maximum output is not produced from a given bundle of inputs, production process is technically inefficient [6]. It implies that the firm specific TE varies over time because of the large number of observations involved.

The data in this study consist of three proxies for inputs and one proxy for output in the small mobile desalination system powered by renewable energy during the period April 2014 to June 2015. The output – based on Malmquist productivity index – requires only data for inputs and output(s): input data are monthly intermediate inputs such as labor cost, energy consumption, and temperature degree, and output data is represented by quantity of desalination water as output of SWRO plant [7].

Data envelopment analysis is one of the methods of non-parametric analysis, where the use of linear programming style to create a domain that contains the actual combinations of resources and puts the limits of efficiency according to the combination of the resources used in this area. There are two directions in the analysis of this type of data. The first trend is constant return to scale (CRS), meaning that the unit is operating at full output capacity, while the second direction, variable return to scale (VRS), which is supposed that the unit is operating at a lower level of the energy, allowing estimate TE and scale efficiency (SE).

3.1. CRS

Assume there are data on K inputs and M outputs on each of N firms or DMUs as they tend to be called in the data envelopment analysis (DEA) literature. For the *i*th DMU these are represented by the vectors x_i and y_i, respectively. The K × N input matrix, *X*, and the M × N output matrix, *Y*, represent the data of all *N* DMUs. The purpose of DEA is to construct a non-parametric envelopment frontier over the data points such that all observed points lie on or below the production frontier.

The basic ideas underlying the Farrell approach [8] to efficiency measurement are illustrated in Fig. 1. Consider a simple example of desalination unit producing potable water *y* using the inputs x_i. Fig. 1 shows the efficient unit "isoquant", point *P* represents the input units of three factors, per unit of output, that the unit is observed to use. Isoquant SS^- represents the various combinations of the three factors that a perfectly efficient unit might use to produce unit output. Now the point *Q* represents an efficient unit using three factors in the same ratio as *P*. It can be seen that it produces the same output as *P* using only a fraction OQ/OP as much of each factor. It could also be though of as producing OP/OQ times as much output from the same inputs. It thus seems natural to define OQ/OP as the TE of the firm. Alternatively, the DEA problem can be expressed using the dual form of the model.

$$\begin{aligned}
&\text{Min}_{\theta\,\lambda}\ \theta^{CRS} \\
&\text{S.t.} \\
&Y\lambda - y \geq 0 \\
&\theta x_i - X\lambda \geq 0 \\
&i = 1, 2, \ldots\ldots N \\
&\lambda \geq 0
\end{aligned} \qquad (1)$$

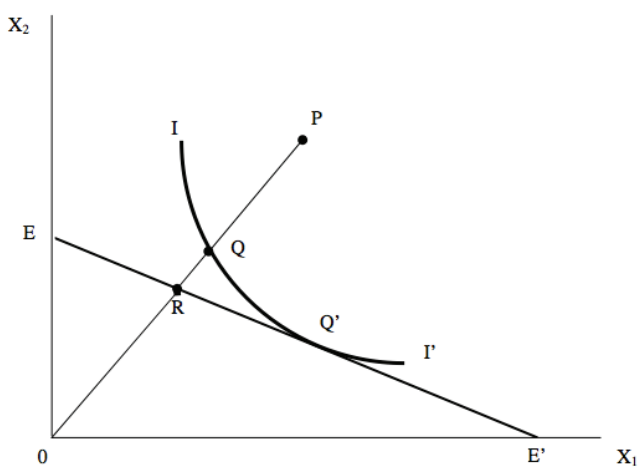

Fig. 1. Farrell's measure of efficiency.

where θ^{CRS} is a scalar that measures the TE of the *desalination unit* and λ is an *N* * 1vector of constants or weights attached to each of the efficient unit [9]. The estimated value of θ is the efficiency score for the *unit*. This estimate will satisfy the restriction θ ≤ 1. If θ = 1 the unit is technically efficient, and on the frontier. If θ^{CRS} <1, then the unit is not on the frontier and is technically inefficient.

To estimate the overall EE, we can solve the cost-minimizing DEA model as follows:

$$\begin{aligned}
&\text{Min}\ \theta^{CRS}{}_{\lambda}\ W^{-}{}_{i} X^{*}{}_{i} \\
&\text{S.t.} \\
&Y\lambda - y \geq 0 \\
&X^{*}{}_{i} \geq X\lambda \\
&\lambda \geq 0
\end{aligned} \qquad (2)$$

where X_i^* is the cost minimizing vector for the *unit*, given its input price vector, W_i, and output level Y_i, and this equation accounts for input slacks not captured by Eq. (1), and attributes any input slacks to allocative inefficiency [10]. The *EE* can be determined as the ratio of the minimum cost to the observed cost:

$$EE_I = W^{-}{}_{i}^{*} X^{-}{}_{i} / W_{i}^{*} X_{i} \qquad (3)$$

The allocative efficiency (AE) can be derived from Eq. (1) and Eq. (3) as follows:

$$AE_I = EE_i / \theta_i^{CRS} \qquad (4)$$

3.2. VRS

The CRS assumption can be relaxed and the DEA model can be easily modified to incorporate VRS [11]. While choice of orientation does not affect efficiencies under CRS, it does under the assumption of VRS [12], although it has been shown only to have a slight influence in many cases. In an input orientation, outputs are assumed to be fixed and the possibility of proportional reduction in inputs is explored; whereas, in an output orientation, it is inputs that are fixed while the possibility of a proportional expansion of outputs is explored. The latter orientation is deemed the more

Fig. 2. Small mobile desalination system powered by renewable energy.

appropriate in this study where the quantity and quality of the inputs are fixed. In an output-oriented framework and under the assumption of VRS, the following linear programming model needs to be solved for each DMU in the data set in order to calculate DEA efficiencies. The VRS mathematical programming formulation is as follows:

$$\begin{aligned} &\text{Min}_{\theta\lambda}\ \theta^{VRS} \\ &\text{S.t.} \\ &Y\lambda - y \geq 0 \\ &\theta_{xi} - X\lambda \geq 0 \\ &i = 1, 2, \ldots\ldots N \\ &N'\lambda = 1 \\ &\lambda \geq 0 \end{aligned} \quad (5)$$

where N is an N*1 vector of ones. The inclusion of the convexity constraint means that the data are enveloped more closely than with the CRS model. This means that the TE scores derived under a VRS are greater than or equal to those obtained under CRS. The constraint, $N'\ \lambda = 1$, ensures that a unit is only compared with other unit of a similar size.

3.3. SE

The SE measure may be used to determine the nature of returns to scale for any decision-making units and the main reason for this method is that scale economies can be determined directly both for efficient as well as for inefficient decision making units. Calculation of SE assumes the calculation of TE measures. TE scores can be obtained by running constant returns to scale (CRS) DEA model to achieve total or overall TE (TE_{CRS}) and VRS DEA model to achieve pure TE (TE_{VRS}). If there is a difference between the scores of TE under CRS and VRS for a certain farm, the difference indicates that a farm is scale-inefficient. SE measure can be calculated by dividing the total TE by pure TE:

$$SE = TE_{CRS}/TE_{VRS} \quad (6)$$

If SE = 1, then a farm is scale-efficient, its combination of inputs and outputs is efficient both under CRS and VRS and the farm is operating under increasing returns to scale. If SE < 1, then the combination of inputs and outputs is not scale-efficient and the farm is operating under decreasing returns to scale [13].

4. Results and discussion

4.1. SE of desalination system

Research estimated SE of small mobile desalination system powered by renewable energy and estimate TE under constant and VRS, estimate EE and optimum use of the economic resources of the unit. Data collected from desalination unit record were divided into four periods; the first period from March/2014 to June/2014, second period from July/2014 to October/2014, third period from November/2014 to February/2015 and fourth period from March/2015 to June/2015.

In the first period, where temperatures ranging between 23 and 27 on average, the TE under fixed return ranged between 90% and 100%, an average of 94%, so it could be argued in this case that it can provide 6% of the resources involved in the production process to produce the same amount of desalinated water. The average VRS achieved about 100% and the average capacity efficiency reached about 94% which required increase production to achieve full TE.

In the second period, where temperatures rise and increase the intervals of sunshine per day, the TE under fixed return ranged between 81% and 100%, an average of 90%, so it could be argued in this season that it can provide 10% of the resources involved in the production process. The average VRS achieved about 93% and the average capacity efficiency reached about 96%, which required increase in the unit production to achieve full TE.

In the third period, where temperatures drops and decrease the periods of sunshine per day, the TE under fixed return ranged between 66% and 81%, an average of 75%, so it could be argued in this period that it can provide 25% of the resources involved in producing the same amount of desalinated water. The average VRS achieved about 94% and the average capacity efficiency reached about 78%, which required to increasing the unit production to achieve full TE.

In the last and fourth period, where temperatures recording an improvement, the TE under fixed return ranged between 81% and 95%, an average of 87%, so it could be argued in this period that it can provide 13% of the resources involved in producing the same amount of desalinated water. The average VRS achieved about 92% and the average capacity efficiency reached about 95%, which required to change in the combination quantity of input and output to achieve full TE.

From the above, it is clear that the second period was the best in using the resources, compared with the other periods, where the average efficiency of capacity for the second period was 96%, while on average about 94%, 95% and 78% for the first, third and fourth period, respectively, which requires more resources to raise the efficiency. These results are due to higher solar cell efficiency due to rising temperatures, long periods of sunshine and low wind power in summer season.

4.2. AE for desalination system

AE of the resources used in the desalination process under the costs and production resources prices was estimated by using a DEA model. Table 2 showed that the average AE for the total sample reached about 94% under fixed return to scale. This means that reallocating the economic resources will save 6% of the production costs. Under VRS the average AE was 97% which means reallocating the economic resources will save 3% of the production costs.

AE of resources used for the first period ranged between 1.00 and 0.98 with average 0.99 under the fixed return to scale which means reallocating the economic resources will save 1% of the production costs in this period; on the other hand, the average AE reached about 0.99 under VRS, which means reallocating the economic resources will save 1% of the production costs.

Table 1
Technical standards of efficiency and return on capacity of small mobile desalination system

Season	Return to scale	TE_{CRS}	TE_{VRS}	Scale	Number of months
First season	Irs	0.918	1.00	0.918	
	Irs	0.903	1.00	0.903	
	Constant	1.00	1.00	1.00	
	Average	0.940	1.00	0.940	
	Max	1.00	1.00	1.00	
	Min	0.903	1.00	0.903	
Second season	Irs	0.900	0.930	0.968	
	Irs	0.815	0.873	0.932	
	Constant	1.00	1.00	1.00	
	Average	0.905	0.934	0.966	
	Max	1.00	1.00	1.00	
	Min	0.815	0.873	0.932	
Third season	Irs	0.766	1.00	0.766	
	Irs	0.817	0.824	0.922	
	Irs	0.667	1.00	0.667	
	Average	0.75	0.941	0.785	
	Max	0.817	1.00	0.922	
	Min	0.667	0.824	0.667	
Forth season	Irs	0.819	0.873	0.938	
	Irs	0.838	0.887	0.945	
	Irs	0.953	0.993	0.961	
	Average	0.870	0.918	0.948	
	Max	0.953	0.993	0.961	
	Min	0.819	0.873	0.938	
Total		0.866	0.942	0.920	12

Source: Calculated from Data Record Book 2014/2015.

The second period ranged between 1.00 and 0.98 with average 0.99 under the fixed return to scale which means reallocating the economic resources will save 1% of the production costs; meanwhile, the average AE reached about 1.00 under VRS, which means there is no saving of the production costs.

The third period ranged between 0.73 and 0.86 with average 0.83 under the fixed return to scale which means reallocating the economic resources will save 7% of the production costs; meanwhile, the average AE reached about 0.98 under VRS, which means there is 2% saving of the production costs.

The last period, AE of resources ranged between 0.93 and 0.96 with average 0.96 under the fixed return to scale which means reallocating the economic resources will save 4% of the production costs in this period. On the other hand, the average AE reached about 0.90 under VRS which means reallocating the economic resources will save 10% of the production costs.

4.3. EE for desalination system

Table 2 showed that the average EE for the total sample reached about 0.87 under fixed return to scale where the same level of production could be achieved under reducing the costs by 13% from the production costs, under VRS, the average EE was 0.94 where the same level of production could be achieved by reducing the costs 6%.

Average of EE of resources used for the first period under the fixed return to scale was 95%, which means the same level of production could be achieved by reducing the costs by 5%. On the other hand, the average EE reached about 0.96% under VRS, which means it can save 2% from the production costs.

The second period average was 0.99 under the fixed return to scale which means the same level of production could be achieved by reducing the costs by 1%. Meanwhile,

Table 2
Economic efficiency of small mobile desalination system

Season		TE		AE		EE	
		CRS	VRS	CRS	VRS	CRS	VRS
First season	Average	0.962	0.970	0.987	0.986	0.949	0.958
	Max	1.00	1.00	1.00	1.00	1.00	1.00
	Min	0.962	0.971	0.980	0.965	0.905	0.907
Second season	Average	1.00	1.00	0.994	1.00	0.994	1.00
	Max	1.00	1.00	1.00	1.00	1.00	1.00
	Min	1.00	1.00	0.982	1.00	0.982	1.00
Third season	Average	0.918	1.00	0.803	0.983	0.734	0.983
	Max	1.00	1.00	0.855	1.00	0.758	1.00
	Min	0.838	1.00	0.729	0.950	0.716	0.950
Forth season	Average	0.863	0.960	0.966	0.897	0.836	0.858
	Max	1.00	1.00	0.996	1.00	0.968	1.00
	Min	0.667	0.880	0.935	0.729	0.623	0.729
Total	Average	0.935	0.982	0.937	0.966	0.878	0.949

Source: Calculated from Data Record Book 2014/2015.

the average EE reached about 1.00 under VRS, which means there is no saving of the production costs.

The third period average was 0.73 under the fixed return to scale, which means reallocating the economic resources will save 27% of the production costs. Meanwhile, the average EE reached about 0.98 under VRS, which means there is 2% saving of the production costs.

The last period, EE of resources average was 0.83 under the fixed return to scale, which means the same level of production could be achieved by reducing the costs by 17%. On the other hand, the average EE reached about 0.86 under VRS, which means reallocating the economic resources will save 14% of the production costs.

From the above, it is clear that the third period was the best in using the desalination resources economic efficiently compared with the first, second and fourth periods under fixed and VRS.

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