

## PERFORMANCE OF A WIND-SOLAR REVERSE OSMOSIS UNIT FOR BRACKISH WATER DESALINATION IN REMOTE AREA

Samira S. Kassem<sup>1</sup>, Abd El-Hamid Z. Shokr<sup>2</sup> and Suliman N. Suliman<sup>2</sup>, G. Papadakis<sup>3</sup>

### ABSTRACT

*In this study, the operation parameters of the developed brackish solar – wind reverses osmosis unit (BSWROU) were limited. As feed water pressure, feed water salinity and feed water pH were constant. The feed temperature was the only operation parameter changed due to ambient temperature changing. Thus, the effect of feed temperature on different parameters was considered. However, due to the huge data recorded for the unit, the performance was evaluated for some months of year 2012. These months were elected to represent winter, spring, summer, and autumn seasons. These months included January, April, July and October. Also, the performance was evaluated as average values for all criteria for all year. The performance of the unit was evaluated using different criteria. These criteria are energy consumption for producing fresh water (kWh/m<sup>3</sup>), recovery percent (%) and concentration factor (%). The average values of these criteria during operation in year of 2012 were 2.7 kWh/m<sup>3</sup>, 44.7% and 1.82 %, respectively. It is evident that these values demonstrated good operation of BSWROU.*

### 1. INTRODUCTION

**F**resh water is the most important source for life on the earth. However, Egypt, with the highest population in the area, is already considered to be in the water scarcity limit. Thus, there is an increasing need for desalted water to cope with the population growth and development (Al Bazedi et al., 2012). Furthermore, in the Egyptian deserts and rural areas, the supply of water and energy is the main

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<sup>1</sup> Agricultural Engineer, Agricultural Engineering Research Institute, Agriculture Research Centre, Egypt.

<sup>2</sup> Professor, Agricultural Engineering Department, Faculty of Agriculture, Alexandria University, Egypt.

<sup>3</sup> Professor, Agricultural Engineering Department, Faculty of Agriculture, Greece University, Athena, Greece.

problem where great part of the rural population does not have access to the general electrical grid and water resources.

In spite of presence of large sources of brackish water in such areas, there is a shortage in fresh water. On the other hand, solar energy is abundant in these remote areas of Egypt, where the amount of sunshine hours is around 3500 h per year (Ahmad and Schmidt, 2002).

The study of the potential interface between desalination and renewable energy technologies such as solar and wind energy has increased significantly in the last five years. Considering that the energy requirements for desalination continues to be a highly influential factor in system costs, the integration of renewable energy systems with desalination seems to be a natural and strategic coupling of technologies (Phuse and Shelke, 2012). Furthermore, the major advantage of a hybrid system is that when solar and wind power production is used together, the reliability of the system is enhanced (Mahmoudi et al., 2008).

The water available through desalination techniques like reverse osmosis can be used for domestic or industrial purposes. Reverse osmosis has the potential to provide high quality drinking water and water for household applications. It can put into use to supply small towns or large cities (Russel, 2009). Reverse osmosis such as a desalination unit could be powered by renewable energy systems (Hunter and Elliot, 1994).

The potential role of desalination of brackish water as a source of fresh water in Egypt was discussed in different research papers using solar cell as a source of energy (E1-Kady and E1-Shibini, 2001; Liu et al., 2002; Ismail et al., 2012), but little research is found on studying the use of hybrid renewable energy systems such as solar and wind to power desalination unit of brackish water. Also, the experience in these areas in Egypt is essential for next years as the source of water from Nile has major troubles.

Banat et al. (2012) mentioned that the alarming water and energy crisis in many regions of the world can be eased by combining renewable energy with desalination technologies. Goosen et al. (2011) reported that the renewable energy driven desalination systems fall into two categories. The first includes distillation processes driven by heat produced directly by the renewable energy system, while the second includes membrane and distillation processes driven by electricity or mechanical energy produced by

the renewable energy system. However, desalination refers to a water treatment process that separates salty water into a wastewater stream of high salt concentration and a fresh water stream of low concentration and is one of the principle alternative sources for fresh water available today (Abou Rayan et al., 2004).

RO is the one the widely used desalination technique in the world. It offers the distinct advantage over the other desalination techniques because it consumes low energy, provides a high quality final desalination process (Barron, 2006).

Desalination using renewable energy sources does offer the potential of providing a sustainable source of potable water for some communities, particularly those in arid areas (Abou Rayan et al., 2004). The successful renewable energy systems/desalination applications prove that the coupling of the two technologies is technically mature and capable to provide fresh water at a reasonable cost. Charcosset (2009) showed that the renewable energies such as solar, wind, and wave could drive membrane processes include reverse osmosis, membrane distillation and electro-dialysis. Each type of renewable energy has its own advantages that make it suited to certain applications. Almost none of them release gaseous or liquid pollutants during operation.

The coupling of RO with solar energy is a promising field of development in the desalination sector, with the potential to (i) improve its sustainability by minimizing or completely eliminating the dependence on fossil fuels and (ii) significantly reduce the operational costs of desalination plants (Wilf and Klinko, 2001). Thomson and Infield (2005) simulated and implemented a PV-driven RO with variable flow that was able to operate without batteries, designed for Eritrea. They performed laboratory tests to validate the model and control of the system: 3 m<sup>3</sup>/day with a PV array of 2.4 kWp.

Ahmad and Schmid (2002) presented a design for a PV powered small-scale desalination system to be operated in remote areas of Egypt. It is estimated that the cost of producing 1 m<sup>3</sup> of fresh water from the PV-RO system is 3.73 \$.

Herold and Neskakis (2001) presented a small PV-driven reverse osmosis desalination plant on the island of Gran Canaria with an average daily drinking water production of 0.8- 3 m<sup>3</sup>/day. The plant was supplied by a stand-

alone 4.8 kW photovoltaic (PV) system with additional battery storage of 60 kWh. The specific energy consumption of this system was considered high with 16 \$/m<sup>3</sup> production cost.

Carvalho et al. (2004) presented the cost of PV-RO desalination plant with batteries installed in the community of Ceara, of Brazil. The specific energy consumption of produced water was around 3.03 kWh/m<sup>3</sup>.

Wilf and Klinko (2001) reported that the amount of freshwater that can be recovered from the feed is limited by membrane fouling and scaling. Overall water recovery rates are typically 45–50% for seawater RO systems, and they can be as high as 90% in brackish water desalination systems.

A small-scale wind powered RO system was tested by Robinson et al. (1992). Fresh water production by their system was 0.5 to 1 m<sup>3</sup>/day, which is the estimated volume needed by a typical remote community in Australia. A pressure vessel to store the feed water under pressure was included. There was no feedback control mechanism for the system operation, and when the available wind power was low, a small diesel or portable gasoline pump was used.

Miranda and Infield (2002) developed a system with a 2.2 kW wind turbine generator powering a variable-flow RO desalination unit. Operation at a variable flow allows the uncertainty and variability of the wind to be accommodated without need of energy storage. Batteries, which are common in stand-alone systems, are avoided and water production is dependent on the instantaneous wind speed.

The complementary features of wind and solar resources make the use of hybrid wind–solar systems to drive a desalination unit a possible alternative. RO and hybrid solar PV-wind power systems have been designed and implemented, e.g. in the rural areas of the Sultanate of Oman (Al Malki et al., 1998), in Israel (Weiner et al., 2001), in the northern part of Mexico, in a small island on the German coast of the North Sea (Petersen et al., 1981), and at the site of BorjCedria on the southern suburbs of Tunis city (Houcine et al., 1999).

A hybrid wind/photovoltaic power unit connected to a RO desalination plan was implemented on Libya's coast of the Mediterranean Sea (Kershman et al., 2005). The nominal production of the plant was intended to be 300 m<sup>3</sup>/day for the supply of a village with potable water.

The facility design was flexible for the integration of a diesel generator and electrochemical storage.

Mohamed and Papadakis (2004) presented the design of a stand-alone hybrid wind-PV system to power a seawater RO desalination unit, with energy recovery using a simplified spreadsheet model. A daily and monthly simulation and economic analysis were also performed. The calculated fresh water production cost was 5.2 €/m<sup>3</sup>, and the realized energy saving was close to 50% when a pressure-exchanger-type energy recovery unit was considered.

This study is a part of large project (HYARES) funded by Europe which was structured in the following phases: design of the desalination unit and the solar cells, wind turbine, study of infrastructures, hydraulic and civil engineering works, equipment transportation to the selected in Wadi EL-Natron region, Egypt, installation and starting-up of the whole system, complemented by the practical training of local technicians, and the follow-up and evaluation of the project. The study aim was to monitor the performance of a RO desalination unit for ground water in remote area powered by both PV and wind turbine. The benefits are the desalination units powered by renewable energy systems are uniquely suited to provide water and electricity in remote areas where water and electricity infrastructure is currently lacking.

## **2. MATERIALS AND METHODS**

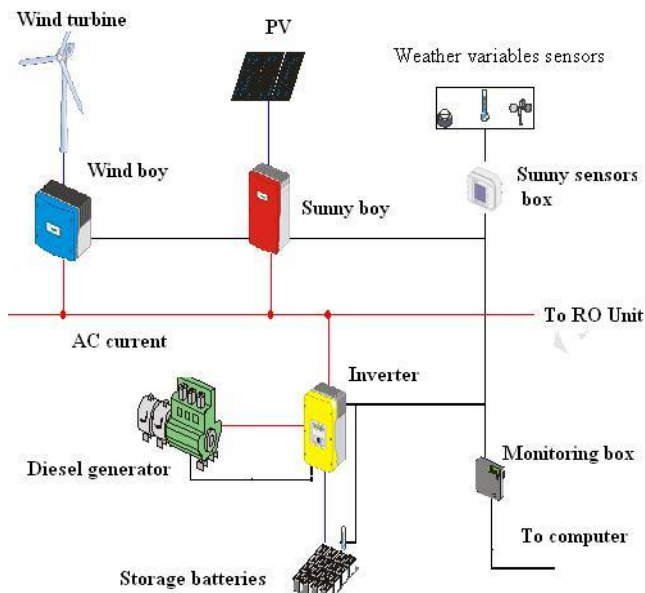
### **2.1 Site selection**

The main criteria for site selection were availability of solar energy, sunshine hours and wind speed. The East of EL-Gaar Village at Wadi EL-Natron, El-Beheara Government, Egypt was selected to install the renewable energy desalination unit due to this site has both predictable wind energy as well as an abundance of sunlight. Wadi EL-Natron Depression lies at the Western Desert margin of the Delta at latitudes of 30° 15' 29'' and 30°33' 23'' °N and between longitudes of 29° 59' 17'' and 30° 30' 50'' °E. (Metwally, 2008).

### **2.2 System components**

The hybrid renewable energy system in this study was consisted of solar cells (PV), one wind turbine, commercial RO desalination unit, diesel generator, storage batteries and others. The PVs were a thin-film solar cell with a total number of 40 cells grouped in two modules connected in parallel and the

two modules were connected in series. The PVs were tilted to 25° faced to south direction. The total power from PVs was 7.2 kW. The wind turbine used in this project is produced about 5 kW. Besides, there was a diesel generator for generating electricity if needed, sunny boy, windy boy and battery inverter were also used. The experimental setup as RO unit was commercial one with capacity of 30 m<sup>3</sup>/day. Constructing of the whole system was addressed by expert men according to our design. Figure (1) illustrates the flow diagram of hybrid renewable energy system.



**Figure (1). Components of the hybrid renewable energy system for water desalination.**

**2.3 PV panel**

The daily energy demand, (kWh/day), from the solar panel is given as (Assad, 2010):

$$E_L = \frac{E_s}{\eta_{overall}} = \frac{W_f H}{\eta_{overall}} \dots\dots\dots(1)$$

Where *E<sub>s</sub>* (kWh/day) is the estimated daily energy demand;  $\eta_{overall}$  is the overall system efficiency, which is the product of component efficiencies; *W<sub>f</sub>* (kW) is the power rating of the facility; and *H* (h/day) is the number of hours the facility is in use per day. The overall system efficiency is given as (Bayod- Rújula and Martínez -Gracia, 2009):

$$\eta_{overall} = \eta_{PV} \eta_B \eta_{INV} \dots\dots\dots(2)$$

Where  $\eta_{PV}$  is the PV module efficiency;  $\eta_B$  is the battery efficiency; and  $\eta_{INV}$  is the inverter efficiency. The PV floor area,  $A_{PV}$  ( $m^2$ ), can be calculated by the following equation (Abd El-Shafy, 2009):

$$A_{PV} = \frac{E_L}{I_{ave} T_{CF}} \dots\dots\dots(3)$$

Where  $I_{ave}$  ( $kWh/m^2/day$ ) is the average daily energy (solar isolation) input over the year and  $T_{CF}$  is the temperature correction factor. The PV peak power,  $W_{PVP}$  ( $kW$ ), at peak solar isolation (PSI,  $kW/m^2$ ) is given as (Alamsyah et al., 2003):

$$W_{PVP} = APV \times PSI \times \eta_{PV} \dots\dots\dots(4)$$

The total system direct current,  $I_{DC,sym}$  [Ah], needed can be calculated as follows (Assad, 2010):

$$I_{DC,sym} = \frac{W_{PVP}}{V_{DC,bus}} \dots\dots\dots(5)$$

Where  $V_{DC,bus}$  (V) is the DC bus voltage.

Modules are connected in series and parallel according to the system usage as follows:

The number of PV module in series,  $N_{ms}$ , is obtained as (Bayod-Rújula and Martínez-Gracia, 2009):

$$N_{ms} = \frac{V_{DC,bus}}{V_{DC,mod}} \dots\dots\dots(6)$$

Where  $V_{DC,mod}$  (V) is the PV module rated voltage . However, the string number of modules in parallel,  $N_{mp}$  (each containing  $N_{ms}$ ), is given as (Bayod-Rújula and Martínez -Gracia, 2009):

$$N_{mp} = \frac{I_{DC,sym}}{I_{DC,mod}} \dots\dots\dots(7)$$

Where  $I_{DC,mod}$  (A) is the module rated current. Therefore, the total number of modules that make up the panel is given as (Bayod- Rújula and Martínez -Gracia, 2009):

$$N_m = N_{ms} \times N_{mp} \dots\dots\dots(8)$$

According to Oko and Ogoloma (2011) The optimal tilt angle,  $s^*$  (o), for a south facing fixed flat plate collector for the geographical location under consideration is given as:

$$S^* = 2.9489 + 1.405 \phi - 0.019 \phi^2, \dots\dots\dots(9)$$

for  $4.858 < \phi < 13.0107$  [ $^{\circ}$ ]

Where  $\phi$  ( $^{\circ}$ ) is the latitude of the location.

**2.4 Wind turbines**

Wind turbine is machine which harness the kinetic energy of the wind to do useful work such as pumping water or generating electricity. A wind turbine absorbs power according to the following equation:

$$P = 0.5 \rho A C_p V^3 \dots\dots\dots(10)$$

Where  $P$  = power generated by the wind turbine (W),  $\rho$  = air density,  $\text{kg/m}^3$ ,

$V$  = wind speed (m/s),  $A$  = rotor swept area ( $\text{m}^2$ ) and  $C_p$  = power coefficient.

**2.5 Storage batteries**

Both wind energy and solar energy were considered as renewable energy sources for the RO unit. The power system would have to include electricity storage, and lead-acid batteries were chosen over nickel-cadmium due to lower cost. The storage capacity,  $S_{BC}$  (kWh), of the battery can be estimated according to the following relation (Mahmoud and Ibrik, 2006):

$$S_{BC} = \frac{N_c E_s}{DOD \times \eta_B} \dots\dots\dots(11)$$

Where  $N_c$  (day) is the largest number of continuous cloudy days of the location and DOD is the maximum permissible depth of discharge of the battery. If the total number of batteries,  $N_B$ , is obtained as: e dc bus voltage,  $V_{DC,bus}$  is known, then one can present the storage capacity in Ampere-hour,  $S_{BC}$  (Ah), as:

$$S'_{BC} = \frac{1000 S_{BC}}{V_{DC,bus}} \dots\dots\dots(12)$$

Where  $S'_{1,BC}$  (Ah) is the capacity of one of the batteries selected for the system. With the knowledge of the number of batteries, the connection of the battery bank can then be easily obtained. The number of batteries in series,  $N_{BS}$ , is given as:

$$N_B = \frac{S'_{BC}}{S'_{1,BC}} \dots\dots\dots(13)$$

Where  $V_{DC,1B}$  (V) is the voltage rating of one of the batteries selected for



the system. The number of batteries in parallel,  $N_{BP}$ , in string of  $N_{BS}$  is given as:

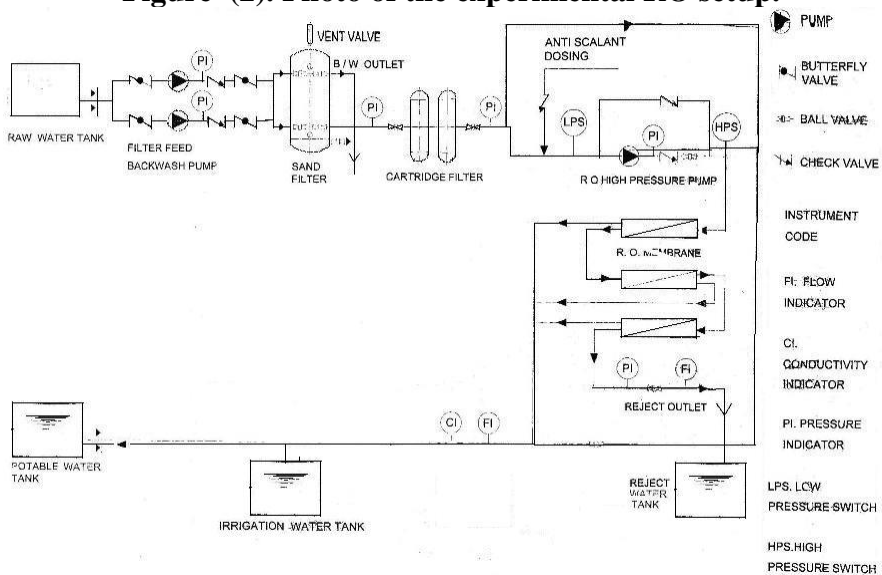
$$N_{BP} = \frac{N_B}{N_{BS}} \dots\dots\dots(14)$$

**2.6 Experimental work**

The experimental setup as RO unit is designed and constructed in the selected site. Figure (2) illustrates the photo of the experimental RO setup. However, the flow diagram of the experimental RO setup is shown in Figure (3).



**Figure (2). Photo of the experimental RO setup.**



**Figure (3). Flow diagram of the experimental setup**

It consists mainly of water tank, feed water pump, sand filter, cartridge water filter, high pressure water pump, RO membrane element assembled unit, piping and control valves. The water tank which is made from polyethylene (capacity 5 m<sup>3</sup>) is open to the atmosphere. The tank is normally full of brackish water that is used as a feed water source to the system. Other tank (capacity 5 m<sup>3</sup>) is used to collect the permeate and the brine is collected in open area.

The raw water flows first through the sand carbon filter to remove any odor. The water is then flows through a cartridge filter to remove solid particles. The high pressure pump is used to supply the membrane element assembled (RO) unit with high pressure feed water. The setup is equipped with a number of valves to control the flow rate through the membrane RO unit. The permeate and drain flow rates are measured with the flow meters. Six membrane elements assembled RO unit. The element is Model WAVE-300 E-4 and maximum operating pressure 21 bar. The pressure is measured by high precision and accurate pressure gauges, while the temperature is measured by a digital thermometer. The brackish water which had concentration of 2291 ppm was fed by the well pump in to the raw water storage tank. Before entering the desalination system, the raw water passes a sand filter and cartridge filter to remove excess turbidity or suspended solids, which may cause problems in pump operation and instrumentation if they enter the RO System. The RO- modules are served by high pressure pump. The feed water is distributed across the membranes by means of transverse stream filtration and by this apart of the water is desalinated as it permeates the membranes. The remaining brine is drained off. The pure water flows from the modules to a storage tank. For further analysis, a data processing a data acquisition system was used to record all variables in Excel sheets. Weather data and solar cell temperature was recorded.

## **4. RESULTS AND DISCUSSION**

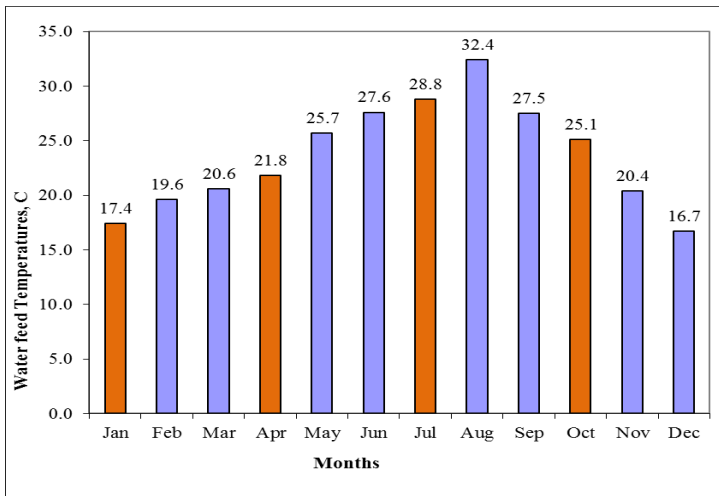
### **4.1 Performance analysis of (BSWROU)**

#### **4.1.1 Effect of feed temperature**

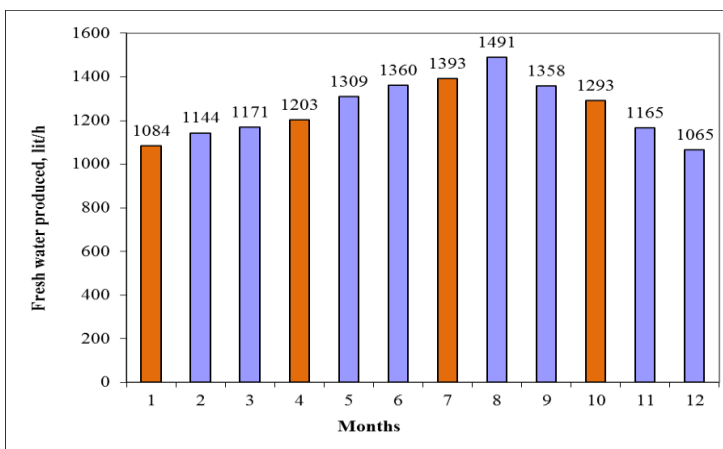
##### **4.1.1.1 Fresh water produced**

Temperature of the feed water has a great impact on the fresh water produced. The temperature was varied due to variation of ambient

temperature in the location. Figure (4) illustrates average of feed temperature during months of year 2012. Meanwhile, Figure (5) shows average of fresh water produced for months of year 2012. The feed temperature varied from about 16.7°C (in winter, December) to 32.4°C (in summer, August) as depicted in Figure (4). The water temperatures were 17.4, 21.8, 28.8 and 25.1 °C in January April, July and October months, respectively as representative for winter, spring, summer and autumn seasons. The percent increase through these selected months were 25.3, 65.5 and 44.4%.



**Figure (4). Average of water feed temperature for months of year 2012.**



**Figure (5). Average of fresh water produced for months of year 2012.**

As a result, the fresh water produced increased from 1065 to 1491 lit/h in December and August, respectively. Meanwhile they were 1084, 1203,

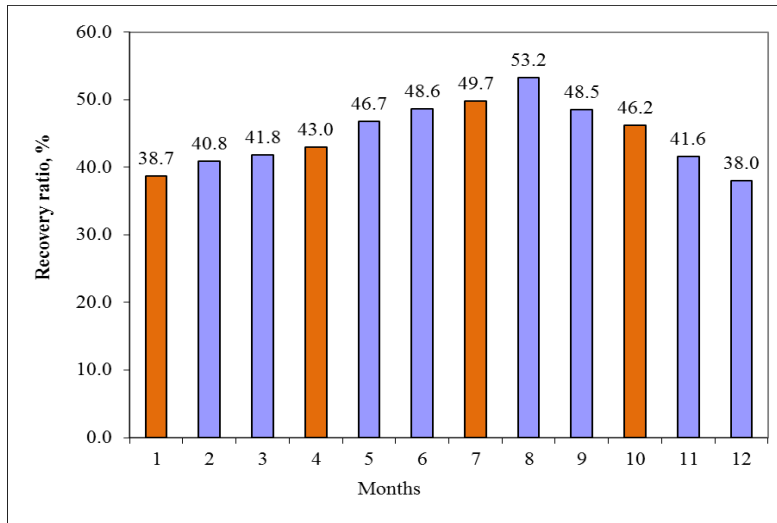
1393 and 1293 in the selected moths, respectively. The increases of percent in fresh water produced over January month were 10.9, 28.5 and 19.3% due to the increase in water temperature at April, July and October, respectively. It is evident that fresh water produced increase with feed water temperature for the monitored range of temperature recorded in this work. This is attributed to the effect of the temperature of the feed water. As this temperature increases (Hawladar et al., 2001), this will decrease the net driving pressure due to the increase in osmotic pressure and, on the other hand, will lead to increasing in water permeability coefficient due to the decrease in both viscosity and density and the later one will overcome the effect of net driving pressure thus the fresh water produced is increased as reported by Al-Bastaki and Al-Qahtani (1994). Goosen et al. (2002) reported that increasing in the rate of fresh water produced through the membrane as the feed water temperature increases since the viscosity of the solution is reduced and higher diffusion rate of water through the membrane is obtained. There was up to a 60 % increase in the permeate flux when the feed temperature was increased from 20 to 40°C.

#### 4.1.1.2 Recovery ratio

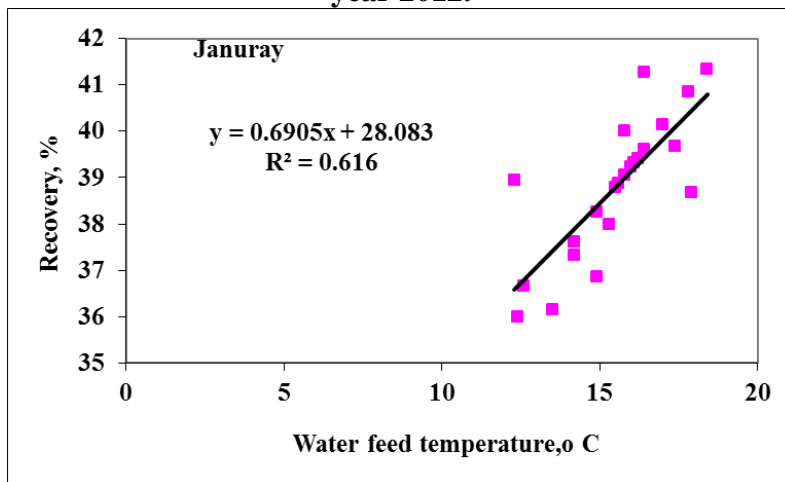
The ratio of the amount of permeate produced by the RO relative to the amount of feed going to the RO is called the recovery ratio (RR) or system efficiency. Recovery ratio is extremely important in regard to RO performance (Gabr, 2007). However, the permeate recovery is important parameter in the design and operation of the RO systems. Recovery ratio is the ratio of conversion of the feed water,  $Q_f$ , to product or (permeate),  $Q_w$ , and is defined as:

$$RR = \frac{Q_w}{Q_f} \times 100 \dots\dots\dots(15)$$

The effect of temperature of the feed water on recovery ratio was depicted in Figure (6) for the all months and average of recovery ratio for January was depicted in Figure (7). It is evident that recovery ratio increase with feed water temperature for the monitored range of temperature recorded in this work.



**Figure (6). Effect of feed temperature on recovery ratio for months of year 2012.**



**Figure (7). Average of recovery ratio for January month of year 2012.**

The recovery ratio ranged from 38.0 to 53.2% in December and August months. While, they were 38.7, 43.0, 49.7 and 46.2% through the selected months, respectively. The percent increases in the recovery ratio over January month due to increasing the water feed temperature were 11.1, 28.4 and 19.2%, at April, July and October months, respectively. The effect of feed water temperature on recovery was also seen by Joshia et al. (2012). As the temperature of feed water increases, the net driving pressure decreases due to an increase in osmotic pressure and this leading

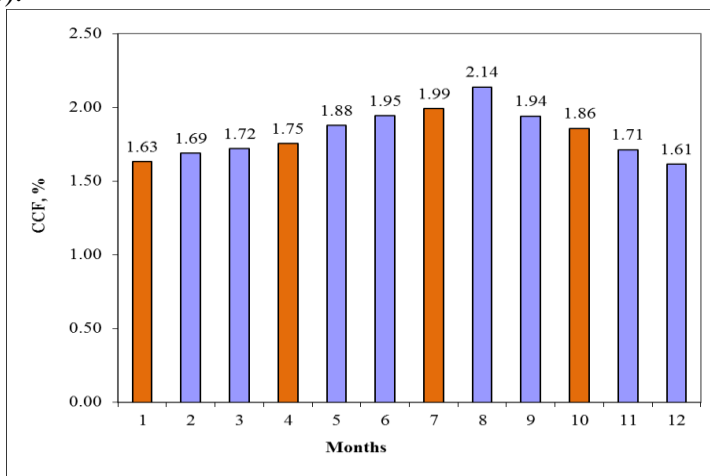
to overall increase in recovery ratio (Al-Bastaki and Al-Qahtani, 1994; Hawlader et al., 2000 and 2001).

**4.1.1.3 Concentration factor**

Recovery ratio can be used to get concentration factor. However, the concentration factor is related to the RO system recovery and is an important equation for RO system design. The more water you recover as permeate (the higher the recovery percent), the more concentrated salts and contaminants you collect in the concentrate stream. This can lead to higher potential for scaling on the surface of the RO membrane when the concentration factor is too high for the system design and feed water composition. The concentration factor (CF) could be calculated as follows:

$$CCF\% = \frac{100}{100 - RR} \dots\dots\dots(16)$$

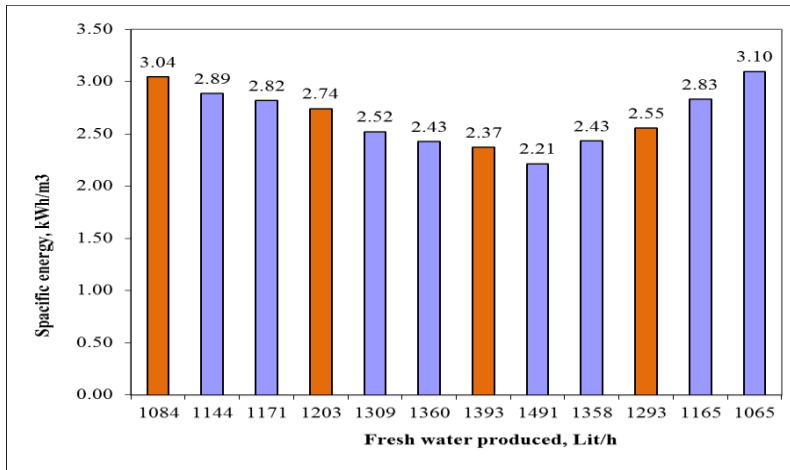
The average of concentration factor for months of year 2012 is shown in Figure (8).



**Figure (8). The average of concentration factor for months of year 2012**

**4.1.2 Relationship between fresh water produced and specific energy consumption during desalination process**

The specific energy consumption for the all months of year 2012 is illustrated in Figure (9). The specific energy consumption is typically ranged between 2.21 and 3.10 kWh/m<sup>3</sup> throughout the year of experiment with an average of 2.7 kWh/m<sup>3</sup>.



**Figure (9). The specific energy consumption for the all months of year 2012.**

In previous study, energy consumption of common desalination processes such as Thomson (2003) who reported that specific energy consumption (photovoltaic-electricity) was between 3.2 and 3.7 kWh/m<sup>3</sup> for the desalination of sea water depending on the solar irradiance and feed water temperature.

### **5.CONCLUSION**

Performance of a wind-solar reverse osmosis unit for brackish water desalination in remote area of Wadi EL-Natron region in Egypt was investigated. However, the operation parameters of the developed brackish solar –wind reverses osmosis unit were limited. The performance of the unit was evaluated using energy consumption for producing fresh water (kWh/m<sup>3</sup>), percent recovery (%) and concentration factor (%). The average values of these criteria during operation in year of 2012 were 2.7 kWh/m<sup>3</sup>, 44.7% and 1.82 %, respectively. It is evident that these values demonstrated good operation of the developed unit.

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### الملخص العربي

## أداء وحدة تناضح عكسي لتحلية مياه الأبار تدار بالطاقة الشمسية وطاقة الرياح في منطقة نائية

سميرة شلبي قاسم<sup>١</sup> عبد الحميد زكريا شكر<sup>٢</sup> سليمان نصيف سليمان<sup>٢</sup> جورج باباداكس<sup>٣</sup>

تهدف هذه الدراسة إلى رصد أداء وحدة تناضح عكسي لتحلية مياه جوفية قليلة الملوحة تعتمد في تشغيلها على الطاقة الكهربائية المنتجة من الخلايا الشمسية وتوربينات الرياح في منطقة نائية من مصر، مع اعتبار أن هذه الدراسة هي جزء من مشروع كبير يسمى HYARES تمويله من المفوضية الأوروبية. في هذه الدراسة متغيرات التشغيل لوحدة التناضح العكسي كانت محدودة حيث ضغط التشغيل، وملوحة المياه ودرجة الحموضة ثوابت. وبسبب ضخامة البيانات المسجلة أثناء التشغيل، تم تقييم الأداء لأربعة أشهر من العام ٢٠١٢ م، حيث تم اختيار أشهر يناير وأبريل ويوليو وأكتوبر لتمثيل فصل الشتاء، الربيع، الصيف، الخريف على الترتيب. تم تقييم أداء الوحدة باستخدام معايير مختلفة. وهذه المعايير هي استهلاك الطاقة لإنتاج المياه، ونسبة استعادة المياه العذبة ومعامل التركيز. وكان متوسط قيم هذه المعايير خلال عام ٢٠١٢ م هي ٢,٧ كيلو وات ساعة/ متر مكعب و ٤٤,٧% و ١,٨٢%، على التوالي. وهذه القيم أظهرت أن وحدة التناضح العكسي المدارة بالشمسية وطاقة الرياح معا جيدة التشغيل في منطقة التجارب بوادي النطرون بمصر.

<sup>١</sup> مهندس زراعي، معهد بحوث الهندسة لزراعية، مركز البحوث الزراعية، مصر  
<sup>٢</sup> أستاذ، قسم الهندسة الزراعية، كلية الزراعة، جامعة الإسكندرية، مصر  
<sup>٣</sup> أستاذ، قسم الهندسة الزراعية، كلية الزراعة، جامعة اليونان، أثينا، اليونان