Energy Efficient Reverse Osmosis Desalination Process

Reza Dashtpour and Sarim N. Al-Zubaidy

***Abstract*—It is well known that water scarcity and global warming are the two most important concerns of the 21st century. Fresh water resources are limited and while desalination can potentially provide unlimited supply of fresh water produced from infinite oceans, high energy consumption and associated environmental impacts are major drawbacks. This paper presents a practical scheme for providing freshwater by utilizing hydrostatic pressure in conjunction with wave energy. While in a typical seawater reverse osmosis plant, 3 to 10 kWh of electric energy is required to produce one cubic meter of freshwater, in the proposed approach, since only the product water needs to be pumped to the surface the specific energy consumption can be reduced to 2.46 kWh.**

***Index Terms*—Desalination, hydrostatic pressure, reverse osmosis, submerged system.**

I. Introduction

The idea of using renewable energies to operate desalination plants with the aim of both meeting the future water demand and satisfying the CO_2 emission reduction is becoming increasingly attractive. Solar powered desalination plant in Egypt (Ahmad GE and Schmid J., 2002), Jordan (Gocht W et al, 1998) and Australia (Richards BS and Scha ̈ fer AI., 2002) as well as wind powered reverse osmosis plants in Croatia (Vujcˇic´ R and Krneta M., 2000), Norway (Paulsen K, Hensel F., 2005; Paulsen K., Hensel F., 2007) and Australia (Robinson R. et al, 1992) are few examples of such systems. In addition to renewable energies, hydrostatic pressure of the water has also been investigated as an option to improve the efficiency of reverse osmosis desalination plants (Drude BC., 1967). In recent years water scarcity and global warming have led to intensification in research in this area by many researchers including (Reali M. et al, 1997; Colombo D. et al, 1999; Al Kharabsheh S., 2006; Piccari FM, Hardy A., 1999; Raether RJ., 1999; Grassi G et al, 2000).

One of the major factors affecting the total cost of water production by any type of desalination process is the energy cost. Typically in a reverse osmosis plant, 3 to 10 kWh of electric energy is required to produce one cubic meter of freshwater from seawater. Fig. 1 shows the process stages of a typical reverse osmosis plant, another major factor contributing to the total cost in a typical reverse osmosis desalination plant are the fixed cost. Fixed cost depends on many parameters such as location of the plant and implemented technology. The major fragment of energy consumed in a typical reverse osmosis plant is used to pressurize the feed water. Operating pressure depends on the degree of feed water salinity and varies between 15 to 30 bars for brackish water and 55 to 70 bars for seawater desalination. As freshwater extracted from the feed, concentration of salt increases behind the membrane which could lead to fouling of the membranes and other components. Therefore the amount of freshwater that can be recovered is limited to as low as 25% to 45% for seawater and as high as 90% for brackish water (Charcosset C., 2009). At these percentages, a 25% increase in energy cost would increase the cost of produced water by 11%. Unless another alternative solution is found that can reduce the energy used in desalination processes, the share of desalination costs attributable to energy will rise as energy prices rise (Cooley H. et al, 2006).

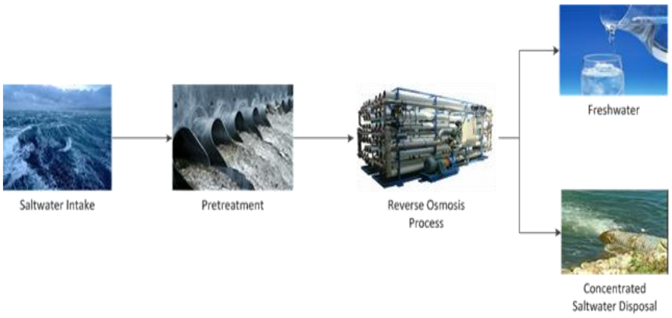


Fig. 1. Reverse osmosis process stages

Since cost of renewable energy is generally independent of fossil fuel prices, the cost fluctuations due to energy cost instabilities can be avoided if the system is operated with renewable energy technologies. Furthermore the energy required for pressuring feed water can be significantly reduced if deep-sea hydrostatic pressure is used. In a conventional seawater reverse osmosis plant with typical recovery ratio of around 25%, for each unit of freshwater four units of feed water has to be pressurized up to between 60~70 bars. Even though it is possible to operate reverse osmosis units at higher recovery ratio, this will result in shorter membranes lifetime and increases overall operational cost. In contrast, in the proposed submerged reverse osmosis system, units are relocated at sufficient depth and potable water is produced using the natural hydrostatic pressure of the water. As a result only produced potable water has to be pumped up to the sea level which, if recovery ratio remains the same, in theory suggests reduction of shaft power to one fourth of what is currently needed. Fig. 2 shows the effectiveness of the proposed approach in terms of the elimination of condense brine rejection and operation sequence.

Manuscript received June 5, 2012; revised June 30, 2012.

Authors are with School of Engineering, Nazarbayev University, Kazakhstan, Astana, Australia (e-mail: dashtpour56@yahoo.co.uk; sal-zubaidy@nu.edu.kz).

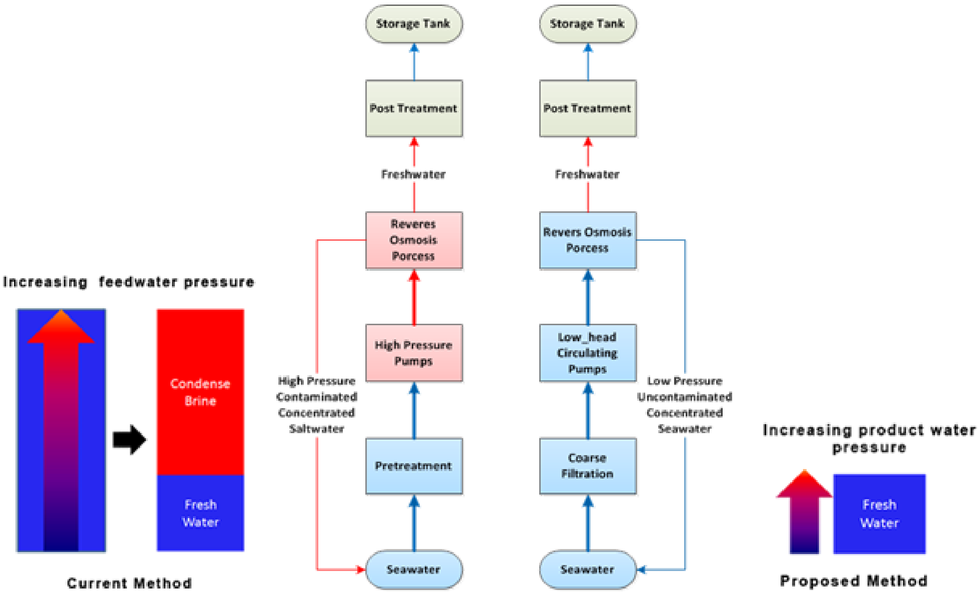


Fig. 2. Comparisons between the submerged reverse osmosis system current schemes

II. Implementation Requirements

In order to evaluate the technical, social and economic benefits and limitations of the proposed scheme it is essential to select an area where the following conditions could be met:

- There is a need for fresh water for municipalities and agricultural proposes.
- Access to sufficient depth within the 10 kilometre from the cost.
- Sufficient Wave energy production capabilities at the location.

Fig. 3 shows global map of suitable agricultural land while Fig. 4 highlights fresh water availability in the world, in addition wave power resources are presented in the Fig. 5.

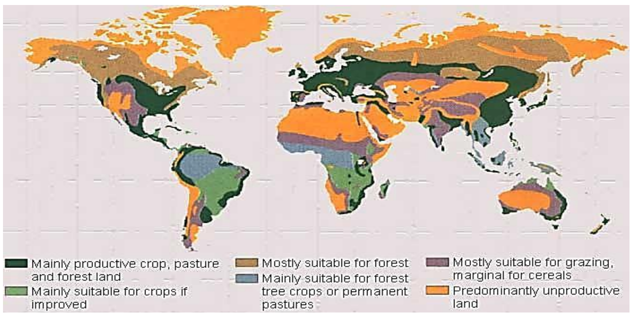


Fig. 3. World potential land use capabilities (FAO, 2012)

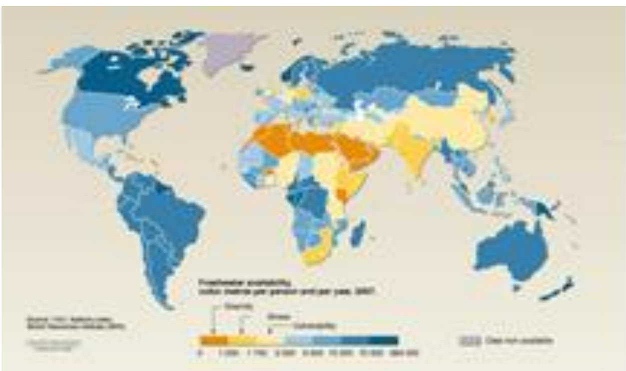


Fig. 4. Global Fresh water availability UN (2012)

Fig. 5. Global wave power resources (Global wave 2012)

With reference to the above figures, several sites can be identified as the suitable candidates for closer evaluation of the project. West coast of the United States, South part of Oman, coasts of Australia, west coast of United Kingdom and east and west coast of Africa are some of these potentials. Any of these sites possess the desirable requirement, however for the reasons listed earlier northern parts of Africa and in particular Morocco is suggested as the best candidate for testing and closer examination of the scheme where along with technical capabilities of the scheme socio-economic impact of the plant could also be tested.

III. System Design Concept

In the proposed scheme potable water will be produced offshore at sufficient depth and then pumped to an onshore storage tank using submersible pumps where, if necessary, post treatment could take place prior to distribution (Fig. 2).

The integrated system is suitable for the locations where deep water is available within few kilometers offshore. Moreover, selection of wave power generator devices depends entirely on the location and characteristics of wave regime in the area. It needs to be stressed, even though the power supplied by wave power devices is intended to minimize the CO_2 emission of the system, reduction in power consumption can still be claimed even if the scheme is powered entirely from the grid. In addition to lower energy consumption and therefore lower CO_2 emission, benefits such as longer membrane lifetime and elimination or significant reduction of pre-treatment can be achieved. According to (Pinet P. R., 2008) "Ocean's temperature decreases steadily with depth as the result, although the ocean's surface temperatures vary greatly from 40°C to -2 ℃, average temperature in ocean's depth is almost constant and around 3-4°C". Therefore, lower operating temperature will generally result in less corrosion and therefore lower associated maintenance costs. Moreover, since high pressure water is abundant at sufficient depth, the plant can be operated at lower conversion ratio (ratio of product water to feed water) which is been proven to improve membrane's functionality and lifetime. It is known that pulsating pressure waves due to operation of high pressure pumps are known to decrease the overall performance and lifetime of membrane modules in reverse osmosis plants, utilizing natural hydrostatic pressure for reverse osmosis process eliminates the need for high pressure pumps and with it pulsating pressure waves which can lead to longer membrane lifetime. Bio-fouling due to organic contamination in feed water is also one of the challenges in reverse osmosis plants and typically chemical pre-treatment is used to avoid such fouling. Since deep-sea water is relatively free from critical organic and inorganic contaminations (Pacenti P. et al, 1999), just a coarse filtration is sufficient and chemical pre-treatment can be reduced or completely eliminated which result in economic benefit as well as minimization of harmful environmental impact.

IV. The Concept and Proposed Design Solution

Despite the attractiveness of the proposed scheme, there are some important challenges that need to be addressed. Among these, corrosion and accessibility are of prime importance. Corrosive nature of seawater is one of the most important concerns for any system deployed at sea; therefore the deep-sea desalination device is designed in such way that minimizes this effect. While corrosion can be reduced by several methods such as applied coatings and anodic protection, in most cases decreasing exposed area is the most effective and economical approach. To achieve this, reverse osmosis units as well as other important components of the system are installed in an enclosed container filled with less corrosive solution such as fresh water and then submerge in the ocean.

Moreover, if the units are to be submerged, providing access for necessary maintenance process is equally important, in the following, the descriptions and recommended methods to tackle these issues are outlined. Offshore maintenance processes are typically more expensive and complex compared to onshore procedures. In addition if these procedures are to be carried out in great depth complexity and cost of such processes are several times greater. Therefore the offshore reverse osmosis units are designed with a mechanism that allows the unit to be submerged and surfaced at any time and as the result complexity and cost of the maintenance operations can be reduced significantly.

A. Proposed Design

Figs 6 and 7 show the proposed design for the offshore reverse osmosis unit which satisfies accessibility requirements and at the same time reduces corrosion by eliminating contact of sensitive equipment with seawater.

Fig. 6. Offshore reverse osmosis unit

1-The main container, 2-Pressure exchanger, 3-Filling pipe, 4-Intake with coarse filter, 5-Discharge, 6-Watertight access door, 7-Balast tanks, 8-freshwater storage tank, 9-Freshwater pipe

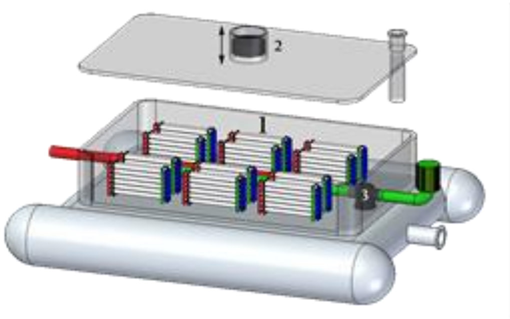


Fig. 7. Offshore reverse osmosis unit

1-Reverse osmosis membrane units, 2-Pressure exchanger, 3-Low head circulation pump

The offshore reverse osmosis unit is shipped to the desired location and connected to pre-laid subsea piping system via a flexible pipe. With reference to the above figures of the offshore reverse osmosis design unit (designed with the aim of eliminating corrosive seawater contact with sensitive equipment). The main container is filled with fresh water through the filling pipe. The blast tanks and the flexible pipe connection allow the unit to be submerged for operation and surfaced for maintenance procedure.

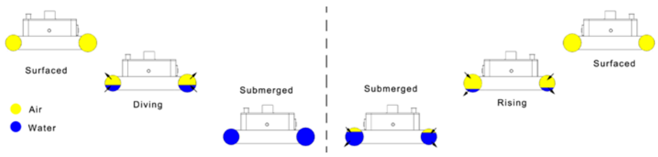


Fig. 8. Submerging and surfacing procedure

Fig. 8 above illustrates the principles of the submerging and surfacing operations. The whole unit is submerged by allowing seawater to enter the blast tanks and surfaced by removing water from them using flow of high pressure air into the tanks. Pressure exchanger shown in Fig. 7 allows inside pressure to remain exactly the same as surroundings while the unit is submerged and surfaced, consequently eliminating stresses on the main container walls which otherwise exist due to pressure difference between inside and outside of the main container which in turn eliminates the necessity for pressure vessel and therefore reduces the associated cost. When the unit is lowered to the required depth, low head circulation pump is switched on and freshwater production begins. The produced potable water is allowed to drop to the freshwater storage tank component of the unit and then pumped to an onshore storage tank, using submerged pumps as, where if necessary, post treatment can take place prior to water distribution. Concentrated brine is discharged through the illustrated discharge pipe. For maintenance procedure, once the unit is surfaced freshwater in the main container is drained and reverse osmosis units are accessed using the designed waterproof access door.

B. System Energy Consumption

Reverse osmosis is a pressure-driven process and the main energy consumers in any membrane desalination plant are the high pressure pumps. As the result, it would be justified to evaluate the proposed scheme by calculating pumps energy consumption. In order to evaluate the submerged system, required pumping power is calculated and compared to specific energy consumption in a typical reverse osmosis desalination plant. With reference to the Fig. 9 demonstrating a schematic diagram of submerged reverse osmosis unit, power consumption for seawater circulating pump and freshwater pump is calculated and the total power consumption is then the summation of these powers.
Assuming that the flow is turbulent, the pipes are is stainless steel and ignoring minor losses and the following fixed parameters:

Recovery ratio = 25 %
Capacity 20,000 m3 a day
Seawater pipe diameter = 0.5 m
Brine pipe diameter = 0.5 m
Freshwater pipe diameter = 0.25 m
Friction factor for all pipes = 0.012
Assuming turbulent flow and stainless steel pipes
Total depth = 550m
Horizontal distance to the shore = 2.5 km
Length of seawater feed pipe = 10 m
Length of disposal brain pipe = 50 m
Density for freshwater = 1000 kg m-3
Density for seawater = 1025 kg m-3
Density for Brain = 1035 kg m-3
Ignoring minor losses
Pumps efficiency = 80 %

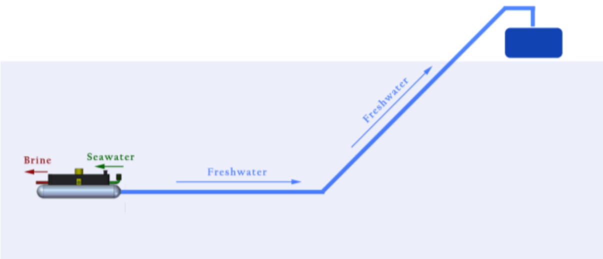


Fig. 9. Deep sea reverse osmosis scheme

Denoting:

S = Seawater
F = Fresh water
B = Brine

The well-known formula for calculating the head loss due to friction and the formula for calculating the power consumption (denoting s = seawater, f = fresh water and b = brine) are given in the following:

$$H_f = \frac{8fLQ^2}{g\pi^2 D^5} \qquad P = \frac{\rho g h Q}{\eta}$$

where f is friction factor, L is the length of pipe, Q is flow rate, g is gravitational acceleration, and D is diameter and is efficiency. The total capacity is 20,000 m3 per day, therefore flow rates:

$$Q_f = \frac{20000}{24 \times 3600} = 0.23\ m^3/s$$

$$Q_s = Q_f \times 4 = 0.92\ m^3/s \qquad Q_b = Q_f \times 3 = 0.69\ m^3/s$$

Fresh water:

$$H_{f_f} = \frac{8 \times 0.012 \times (550 + 2500) \times 0.23^2}{g\pi^2 0.25^5} = 164\,m$$

Seawater:

$$H_{f_b} = \frac{8 \times 0.012 \times 50 \times 0.69^2}{g\pi^2 0.5^5} = 0.76\,m$$

Fresh water:

$$P_f = \frac{1000 \times 9.81 \times (164 + 550) \times 0.23}{0.8} = 2.014\ MW$$

Seawater:

$$P_s = \frac{1025 \times 9.81 \times 0.3 \times 0.92}{0.8} = 0.003\ MW$$

Brine:

$$P_b = \frac{1035 \times 9.81 \times 0.76 \times 0.69}{0.8} = 0.007\ MW$$

Therefore the total power consumption is:

$$P_t = P_f + P_s + P_b = 2.024\ MW$$

Therefore specific energy consumption per 1 m^3 of fresh water would be:

$$E = \frac{P_t}{Q_f \times 3600} = \frac{2.024}{0.23 \times 3600} = 2.44\ kWh/m^3$$

This result is roughly one third of the energy requirement in a typical reverse osmosis plant. For comparison, the Ghar Lapsi desalination plant in Malta produces 20,000 m3 freshwater per day with specific electricity energy consumption of 6.12 kWh/ m3 (Reali M. et al, 1997). Specific energy consumption based on the above calculations is plotted against distance from the shore and presented in the Fig. 10. It can be observed while the lowest specific energy consumption can be obtained for schemes within range of 1km from the shore, the energy consumption remains considerably less than those of typical sea water reverse osmosis plants even for distances as far as 10 km from the shore.

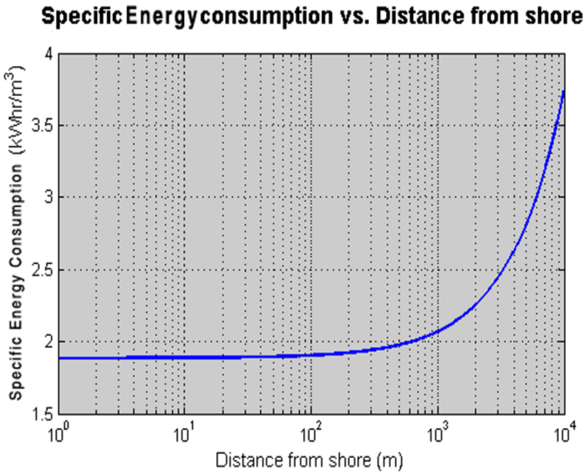


Fig. 10. Specific energy consumption vs. distance from shore

C. *Scheme Comparison*

Seawater reverse osmosis desalination was first commercialized in late 1970's (Wang L. K., et al, 2011). Due to lack of energy recovery systems and inefficient membranes, energy consumptions in early systems were as high as 10kWhr/m3. In early 1980's Pelton wheel and recovery pumps where used to improve the reverse osmosis process efficiency by recovering energy from the concentrated stream. As the result of utilising early recovery devices, specific energy consumption was reduced to around 6kWhr/m3. By late 1990's, thank to isobaric energy recovery technology, the energy consumptions were further reduced to about 3kWhr/m3. Despite these improvements, nearly all of them are only feasible if used in large plants and the specific energy consumption in small scale plants without recovery devices is still very high (Wang L. K., et al, 2011). Table 1 below, illustrates specific energy consumption as well as corresponding energy saving and reduction of CO2 emission per day, with respect to the purposed scheme, in several seawater reverse osmosis plants around the world.

TABLE I: ENERGY CONSUMPTION COMPARISON

Plant Name	Country	Product Flow Rate m^3/day	Energy Consumption kW.hr/m^3	Energy Saving MWhr/day	CO2 Emission Reduction Tons/day 0.544kgCO2/kWh
Ashkelon	Israel	330,000	4	514.8	280
Taweelah	UAE	227,000	4		193
Carlsbad	USA	189,000	3.6	17%	119
Fujairah	UAE	170,000	3.8		126
Palmachin	Israel	150,000	2.91	71	38
Kwinana - Perth	Australia	140,000	3.7	176	96
Ionics Trinidad	Trinidad and Tobago	136,000	3.8	185	101
Tuas	Singapore	136,000	4.1	226	123
Tugun Queensland	Australia	133,000	3.6	154	84
Medina-Yanbu II	KSA	128,000	5.56	399	217
Jeddah Phase I & II	KSA	113,600	8.2	654	356
Tampa Bay	USA	95,000	2.96		27
Al-Jubail	KSA	91,000	7.45	70%	248
Las Palmas III-IV	Spain	80,300	4.4		86
Marbella	Spain	55,000	4	86	47
Larnaca	Cyprus	54,000	4.5	111	61
Grand Cayman	Cayman Island	37,000	4.2	65	35
Sureste	Spain	33,000	4.4	65	35
Calculated Data	-	20,000	2.44	0	0
Cirkewwa	Malta	18,600	4.5	38	21
Porto Santo	Portugal	6,000	4.28	11	6

Source for Resources conversion factors, Carbon Trust UK, Available from: http://www.carbontrust.co.uk/cut-carbon-reduce-costs/calculate/carbon-footprinting/Pages/conversion-factors.aspx, [Accessed 15 January 2011]

With reference to Table I, it is clear the improvement potential is directly linked to both current energy consumption status and capacity of a particular plant. For instance huge saving of over 650 MWhr per day, representing 70% saving in energy consumption, in Jeddah SWRO plant could be achieved whereas this figure could be as little as 71 MWhr/day or in other word around 17% reduction of energy consumption in Palmachin. Even though these figures are very attractive, the result should be treated with care.

Fig. 11 shows composite plot. The scatter plot of specific energy consumption (SEC) was presented in Table 1 along with the calculated data for the proposed submerged scheme and the theoretical minimum according to SEC (UNESCO Centre for Membrane Science and Technology University of New South Wales, 2008). With reference to table 1 and while plants such as Tampa Bay in the USA have achieved SEC as little as 2.96 kWhr/m3 which is close to the calculated energy consumption rate for the proposed scheme, majority of desalination plants still operate at SEC of around 4kwhr/m3 w. This is generally because of outdated technology used in these plants which itself is the result of high capital costs involved in implementation of new technologies.

The Figure also exemplifies the reduction of specific energy consumption in seawater reverse osmosis process over time. Even though considerable difference between the current status of SEC and the theoretical minimum at 0.96 kWhr/m3 still exist, dramatic reduction of specific energy consumption over past three decades is clear.

Considering the improvements in membrane technologies in conjunction with advances in state of art energy recovery devices such as modern pressure exchangers which inevitably result in further reduction of SEC in the near future in one hand, and the associated cost of new technology and predictable high fuel prices in the near future in other, it would be very difficult to suggest whether or not the proposed deep sea reverse osmosis system can exceeds the performance of emerging technologies. Therefore, even though theoretically the proposed scheme seems to be very efficient and economical, there are other important factors which have to be taken into account prior to commercial development of the system. As the result, implementation of an experimental system is necessary step to provide reliable guidelines for further development.

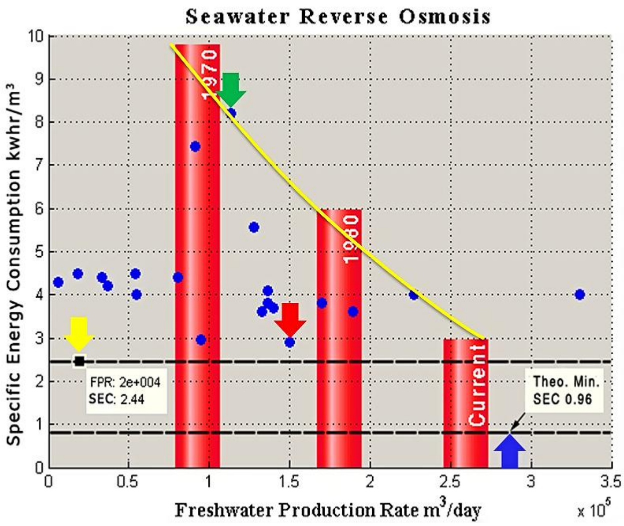


Fig. 11. Specific energy consumption vs. freshwater production rate.

V. Conclusions

Wave powered deep sea reverse osmosis desalination system and operational scheme can provide practical solution to meet both future water demand and CO2 reduction requirements. While energy consumed by high pressure pumps represent the major factor in the overall cost of produced freshwater in the current reverse osmosis desalination process, presented data illustrate potentials of the wave powered deep sea desalination scheme in reducing energy requirement. The energy requirement is considerably lower than the current systems and the system can be operated at lower recovery ratio which leads to longer membrane lifetime and therefore reduces the overall cost of produced water. Other important advantages include lower environmental impact and reduction or complete elimination of pre-treatments. Moreover, the necessity of CO2 emission reduction, soaring fossil fuel prices and rapid technological advances in wave energy conversion sector promises a bright future for this sector and therefore purposed combination of the scheme with energy generated form ocean waves is an ideal choice. In contrast the major drawback is identified as the complicated maintenance procedure associated with deep sea structures which can overshadow the benefits of the system. Nevertheless to provide a more complete picture and realize the true technical and operational challenges in one hand and economical and ecological benefits in the other, a specific experimental scheme needs to be implemented.

References

[1] Ahmad GE and Schmid J., Feasibility study of brackish water desalination in the Egyptian deserts and rural regions using PV systems. Energy Conversion and Management, 2002, 43:2641– 9.

[2] Al Kharabsheh S., *An innovative reverse osmosis desalination system using hydrostatic pressure. Desalination*, 2006, 196:210–4.

[3] Charcosset C., *A review of membrane processes and renewable energies for desalination, Elsevier*, 2009.

[4] Colombo D, de Gerloni M, Reali M., *An energy-efficient submarine desalination plant, Desalination*, 1999, 122:171–6.

[5] Cooley H., Gleick P. H., Wolff G., *Desalination, With A Grain of Salt (A California Perspective), Pacific Institute for Studies in Development, Environment and Security*, 2006.

[6] Drude BC., *Submarine units for reverse osmosis, Desalination*, 1967, 2:325–8.

[7] Global wave power resources, *Pelamis Wave Power Ltd*, [Online], Available: http://www.pelamiswave.com/global-resource, [Accessed 12 March 2012]

[8] Gocht W, Sommerfeld A, Rautenbach R, Melin T, Eilers L, Neskakis A, et al., *Decentralized desalination of brackish water by a directly coupled reverseosmosis- photovoltaic-system – a pilot plant study in Jordan. Renewable Energy*, 1998, 14(1–4):287–92.

[9] Grassi G, Chiaramonti D, Helm P, Pacenti P, Reali M, Toci F., *Hydrostatic pressure plant for separation/concentration/desalination of liquids, in particular sea or brackish water, via reverse osmosis.*, Eur. Pat. Appl. EP 968755, 2000.

[10] How many people can the land support, *Food and Agriculture Organization of the UN (FAO)*, [Online], Available: http://www.fao.org/docrep/u8480e/U8480E0E.HTM, [Accessed 12 March 2012].

[11] Pacenti P., de Gerloni M., Reali M., Chiaramonti D., O. Gärtner S., Helm P., Stöhr M., *Submarine seawater reverse osmosis desalination system, Elsevier.*, 1999.

[12] Paulsen K and Hensel F., *Introduction of a new energy recovery system – optimized for the combination with renewable energy. Desalination.*, 2005, 184:211–5.

[13] Paulsen K and Hensel F., *Design of an autarkic water and energy supply driven by renewable energy using commercially available components. Desalination*, 2007, 203:455–62.

[14] Piccari FM and Hardy A., *Method and plant for desalting seawater using hydrostatic pressure*, WO9906323., 1999.

[15] Pinet P. R., *Invitation to Oceanography (Fifth Edition), Jones & Bartlett Publishers*, 2008.

[16] Raether RJ., *Apparatus for desalinating salt water*, US 5916441., 1999.

[17] Reali M, de Gerloni M, Sampaolo A., *Submarine and underground reverse osmosis schemes for energy-efficient seawater desalination. Desalination*, 1997, 109:269–75.

[18] Richards BS, Schäfer AI., *Design considerations for a solar-powered desalination system for remote communities in Australia. Desalination*, 2002, 144:193–9.

[19] Robinson R, Ho G, Mathew K., *Development of a reliable low-cost reverse osmosis desalination unit for remote communities, Desalination*, 1992, 86:9–26.

[20] U.S. Bureau of Reclamation and Sandia National Laboratories (USBR and SNL), *Desalination and Water Purification Technology Roadmap: A Report of the Executive Committee. Desalination & Water*

Purification Research & Development Report #95., 2003, United State Department of the Interior, Bureau of Reclamation, Water Treatment and Engineering Group.

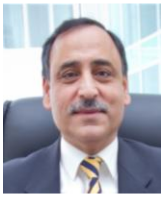
[21] UNESCO Centre for Membrane Science and Technology University of New South Wales, *Emerging trends in desalination: A review, Waterlines Report Series No 9*, 2008.

[22] Vujcˇic´ R, Krneta M., *Wind-driven seawater desalination plant for agricultural development on the islands of the county of Split and Dalmatia. Renewable Energy,* 2000, 19:173–83.

[23] *Water Scarcity, United Nation*, [Online]. Available: http://www.un.org/waterforlifedecade/scarcity.shtml, [Accessed 12 March 2012].

[24] Wang L. K., Wang Lawrence K., Chen J. P., Shammas N. K., *Membrane and Desalination Technologies*, 2011, vol. 13, Humana press.

Reza Dashtpour is a graduate petroleum engineering student at the Norwegian University of Science and Technology. He received his BEng (Hons) degree from Heriot Watt University. He is an Associate Member of Institute of Mechanical Engineers and his research interests include developing sustainable systems and also deep sea drilling..



Professor Sarim AL-Zubaidy is Vice-Dean (Teaching and Learning) at the School of Engineering, Nazarbayev University, Kazakhstan. He has over thirty year experience in both senior academic and administrative positions in a variety of higher education institutions around the world. His expertise ranges from traditional to newly formed universities to those in transition from colleges and polytechnics.