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Wave Powered Deep-Sea Desalination Scheme

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Abstract. According to the United Nation Environmental program, water scarcity and global warming are the most important concerns of the 21st century. Fresh water resources are limited and in fact availability for human use is equivalent to only less than 0.08% of all the Earth's water. While desalination can potentially provide unlimited supply of fresh water produced from infinite oceans surrounding us, high energy consumption and associated environmental impacts are major drawbacks. This paper presents a practical solution 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 presented approach, since only the product water needs to be pumped to the surface the specific energy consumption can be reduced to 2.46 kWh.

Keywords: Desalination, Hydrostatic, Reverse Osmosis, Submerged

1. Introduction

The idea of using renewable energies to operate desalination plants with the aim of both meeting the future water demand and satisfying the CO2 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, as early as 1960s, using 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 times water scarcity and global warming have led to intensification in research in this area by many 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 produced water 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. Figure 1 shows breakdown of costs in a typical reverse osmosis plant. With reference to figure1, major factor contributing to the total cost in a typical reverse osmosis desalination plant are the fixed cost and energy cost. Fixed cost depends on many parameters such as location of the plant and implemented technology and generally all the possible measures will be taken to reduce this cost. 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

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percentages, a 25% increase in energy cost would increase the cost of produced water by 11%. Unless another alternative solution is found that can greatly reduce the amount of used energy in desalination processes, the share of desalination costs attributable to energy will rise as energy prices rise (Cooley H. et al, 2006).

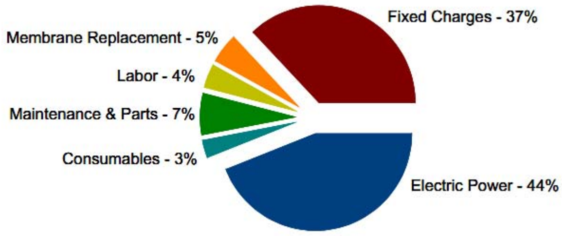

Fig. 1: Typical cost for a reverse Osmosis desalination plant (USBR and SNL, 2003)

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 unites at higher recovery ratio, this will result in shorter membranes lifetime and increases the overall operational cost. In contrast, in proposed submerged reverse osmosis system, units are relocated to a sufficient depth and potable water is produced using the natural hydrostatic pressure of the water. As the 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. Figure 2 shows a graphical demonstration of this approach.

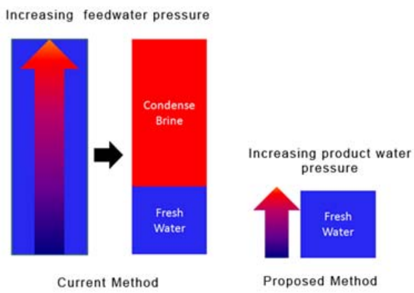

Fig. 2: Graphical comparisons between the submerged reverse osmosis system and the current method.

2. The Concept of the Scheme

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. Figure 3 illustrates the proposed arrangement for wave powered deep-sea desalination scheme. As it can be observed, grid connection is also shown in the figure which is intended to provide necessary power to run the submersible pumps in occasions when climate does not allow sufficient electricity to be generated from the waver power devices.

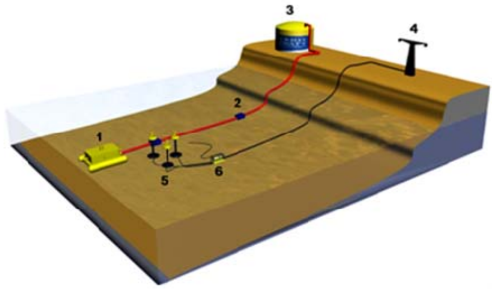

Fig. 3: Wave powered deep-sea desalination scheme

1-Submerged RO unit, 2-Submerged pumps, 3- Storage tank
4- Main grid connection, 5-Wave energy generators, 6-Power converter

The scheme 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 CO2 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 CO2 emission, benefits such as longer membrane lifetime and elimination or significant reduction of pre-treatment can be achieved. "Ocean's temperature decreases steadily with depth as the result, although the ocean's surface temperatures vary greatly from 40°C to -2°C, average temperature in ocean's depth is almost constant and around 3-4°C (Pinet P. R., 2008)". 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.

3. Major Concept and the Proposed Design Solution

Despite 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 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. Followings are descriptions and recommended methods to tackle these issues. 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.

3.1. The Proposed Design

Figures 4 and 5 show the proposed design for an offshore reverse osmosis unit which satisfies accessibility requirements and at the same time reduces corrosion by eliminating contact of sensitive equipment with seawater.

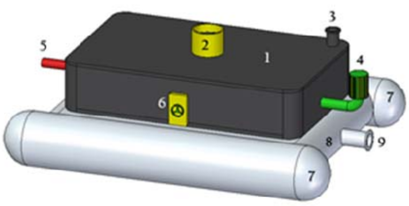

Fig. 4: Offshore reverse osmosis unit

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

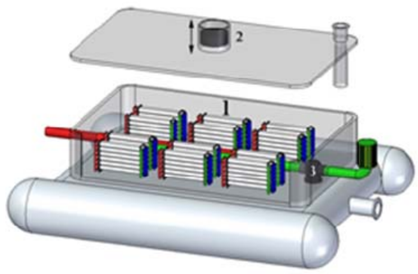

Fig. 5: Offshore reverse osmosis unit
1-Reverse osmosis membrane units, 2-Pressure exchanger, 3-Low head circulation pump

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 Figures 4 and 5 showing the offshore reverse osmosis design, 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.

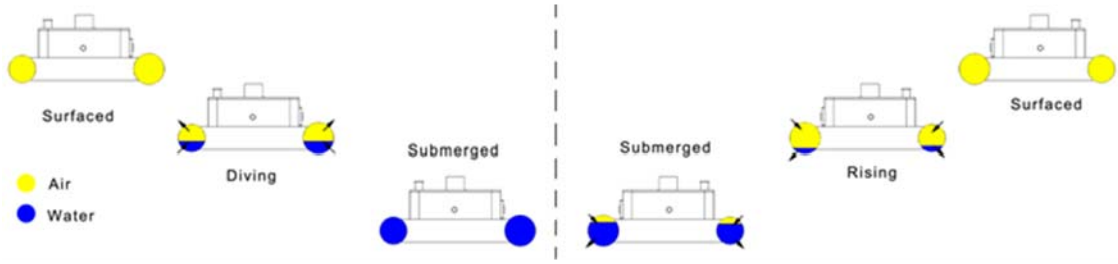

Fig. 6: Submerging and surfacing procedure

Figure 6 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 the Figures 5 and 6 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 illustrated in Figure 3, 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.

4. Primarily Evaluations

Practicality of the system is evaluated by contrasting energy consumption of the proposed deep sea scheme against current reverse osmosis technology.

4.1. 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 Figure 7 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.

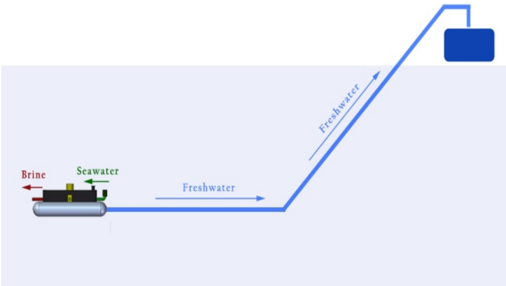

Fig. 7: Deep sea reverse osmosis scheme

Assumptions:

a) Recovery ratio = 25 %
b) Capacity 20,000 m3 a day
c) Seawater pipe diameter = 0.5 m
d) Brine pipe diameter = 0.5 m
e) Freshwater pipe diameter = 0.25 m
f) Friction factor for all pipes = 0.012
g) Assuming turbulent flow and stainless steel pipes
h) Total depth = 550m
i) Horizontal distance to the shore = 2.5 km
j) Length of seawater feed pipe = 10 m
k) Length of disposal brain pipe = 50 m
l) Density for freshwater = 1000 kg m^{-3}
m) Density for seawater = 1025 kg m^{-3}
n) Density for Brain = 1035 kg m^{-3}
o) Ignoring minor losses
p) Pumps efficiency = 80 %

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 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:

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

Seawater:

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

Fresh water: $P_f = \dfrac{1000 \times 9.81 \times (164 + 550) \times 0.23}{0.8} = 2.014\ MW$

Seawater: $P_s = \dfrac{1025 \times 9.81 \times 0.3 \times 0.92}{0.8} = 0.003\ MW$

Brine: $P_b = \dfrac{1035 \times 9.81 \times 0.76 \times 0.69}{0.8} = 0.007\ MW$

Therefore the total power consumption is: $P_t = P_f + P_s + P_b = 2.024\ MW$

Therefore specific energy consumption per 1m3 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 Figure 8. With reference to figure 8, 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 10km from the shore.

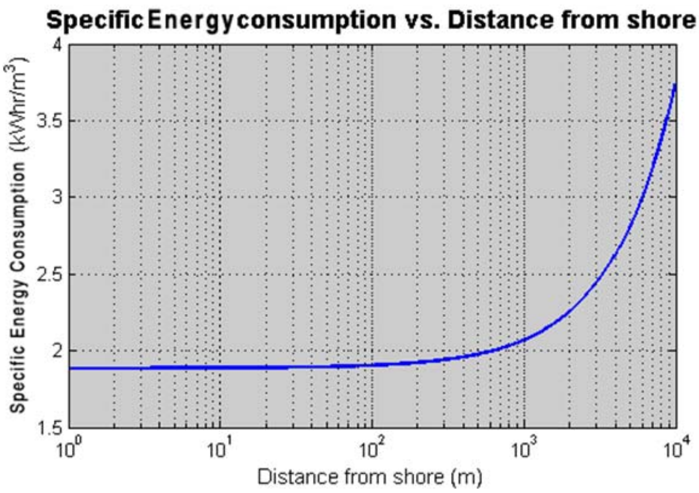

Fig. 8: Specific energy consumption vs. distance from shore

4.2. 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.

With reference to table 1, 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 650MWhr per day, representing 70% saving in energy consumption, in Jeddah SWRO plant could be achieved whereas this figure could be as little as 71MWhr/day or in other word 16% reduction of energy consumption in Palmachin. Even though these figures are very attractive, the result should be treated with care.

Table 1: 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	354	193
Carlsbad	USA	189,000	3.6	219	119
Fujairah	UAE	170,000	3.8	231	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	49	27
Al-Jubail	KSA	91,000	7.45	456	248
Las Palmas III-IV	Spain	80,300	4.4	157	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]

Figure 9 shows scatter plot of specific energy consumption, SEC, of the plants presented in Table 1 along with the calculated data for the proposed submerged scheme and the theoretical minimum SEC (UNESCO Centre for Membrane Science and Technology University of New South Wales, 2008).

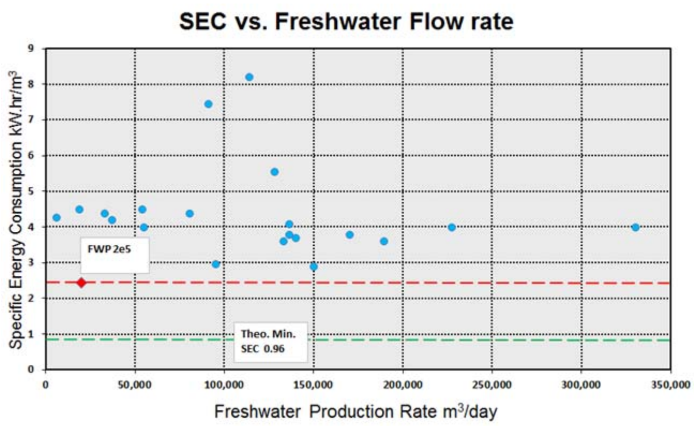

Fig. 9: Specific energy consumption vs. freshwater production rate.

With reference to the above figure and while plants such as Tampa Bay in the USA have achieved SEC as little as 2.96kWhr/m3 which is close to the calculated energy consumption for the proposed scheme, majority of desalination plants still operate at SEC of around 4kwhr/m3 w. This is generally because of out-dated technology used in these plants which itself is the result of high capital costs involved in implementation of new technologies.

Figure 10 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 0.96kWhr/m3 still exist, dramatic reduction of specific energy consumption over past three decades is clear.

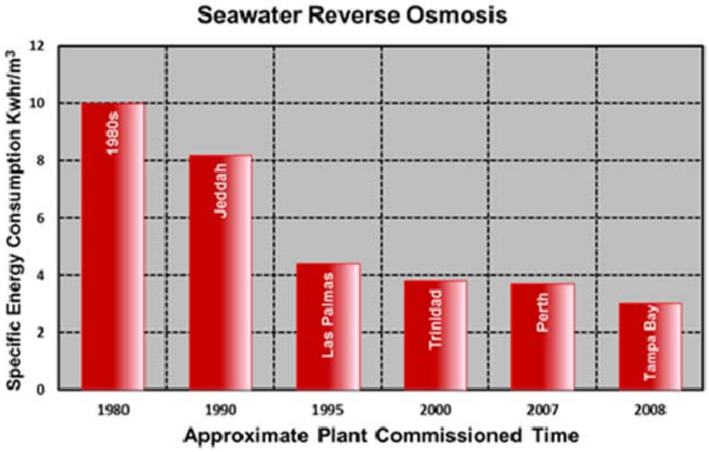

Fig. 10: Reduction of specific energy consumption over Time

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 compete with other 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.

5. Conclusions

Wave powered deep sea reverse osmosis desalination scheme can provide a practical solution to meet both future water demand and CO_2 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 proposed scheme 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 such as lower environmental impact and reduction or complete elimination of pre-treatments can also be claimed. Moreover, the necessity of CO_2 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.

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