Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1021101

57 (2016) 51–57
January

Taylor & Francis
Taylor & Francis Group

Prospect of stand-alone wave-powered water desalination system

Nahidul Hoque Samrat, Norhafizan Ahmad*, Imtiaz Ahmed Choudhury

Faculty of Engineering, Department of Mechanical Engineering, Centre for Product Design and Manufacturing (CPDM), University of Malaya 50603 Kuala Lumpur, Malaysia, Tel. +60 3 79677625; Fax: +60 3 79675317; emails: sam_3e60@yahoo.com (N.H. Samrat), norhafizan@um.edu.my (N. Ahmad), imtiaz@um.edu.my (I.A. Choudhury)

Received 5 October 2014; Accepted 4 February 2015

ABSTRACT

Our earth is a water planet; nearly two thirds of the earth's surface is covered by ocean water. But the shortage of fresh water is a major problem in many areas, especially in rural villages near to the sea or islands. Now, renewable energy-based desalination system is rising around the world due to the adverse environmental effect and high-energy requirements of the conventional fuel-based desalination system. This paper describes the prospect of an off-grid stand-alone wave-powered reverse osmosis desalination system for those areas. A simulation model for the prediction of the wave power delivered for a given value of the wave height and period is adopted. Based on the availability of the wave data, the amount of the water produced at different sites of Malaysia can be calculated in this paper. In addition, this paper deals with an economical analysis of wave energy production for reverse osmosis desalination system.

Keywords: Wave power; Stand-alone; Desalination; Islands; Reverse osmosis

1. Introduction

Water is essential for the origin and continuation of humankind. There are thousands of people in all over the world who does not have access to a secure fresh water source [1]. Nevertheless, since many dry areas are coastal regions or islands, seawater desalination is a reasonable choice in this case. But the desalination processes require high amount of electrical energy. The energy supply in these remote islands and coastal areas may be a problem, especially if the electric power grid is not available. Some of this area used conventional energy sources for electricity generation; but in this case, with the remoteness, the fuel cost increases significantly. In addition, it raises the greenhouse gas emissions, which may be the key source of global warming. Since most islands or coastal regions have high green energy resources, the use of green energies in seawater desalination shows an interesting chance, or even the only way to present a secure fresh water source.

As an island and coastal areas associated with the sea, wave-powered reverse osmosis (RO) desalination system can be considered as one of the environmentally friendly secure fresh water sources for these arid regions. Among the various renewable energy sources, wave energy is the most promising

*Corresponding author.

Presented at the International Conference on Business, Economics, Energy and Environmental Sciences (ICBEEES) 19–21 September 2014, Kuala Lumpur, Malaysia

environmental friendly clean and renewable energy source. It has a greater potential than any other power source to solve global energy problems. Extensive research on the idea of wave energy has been conducted, since the oil crisis in the year 1970s. But the first patent of wave energy extraction was recorded in the late eighteenth century [2,3]. Many WECSs have been patented and new patents are granted each month [4], which are based on nine basic techniques. These nine basic techniques are cavity resonators or oscillating water column (OWC), heaving and pitching bodies, pressure devices, particle motion converters, surging wave energy converters, Russell's rectifier, Cockerell's rafts, Salter's duck, and wave focusing techniques [2–5]. Among the various wave energy converters, OWC is generally considered as one of the most promising ocean wave energy conversion devices [6].

The main objective of this article is to show the wave-powered RO desalination system potentiality as a viable alternate fresh water source among the islands and coastal areas. Hence, a RO desalination system driven by wave powered is proposed. A simulation model is used to predict the amount of the water production based on the wave conditions and feed water salinity (3,000, 5,000, 7,000, and 10,000 mg/L).

2. Wave data analysis

Malaysia is surrounded by sea and its latitude and longitude is 20–30´ N and 112˚–30´ E. It has a total coastline of 4,675 km and about 878 islands [3,7–9]. Therefore, Malaysia has a huge potential of wave power generation that may be a vital source of electrical energy generation for the wastewater treatment plant and water desalination system. The wave data used in this article was recorded and measured at five locations; these locations are Sarawak, Kota Kinabalu, Mabul Island, Pulau Mentagor Island, and Perhentian Island. This wave data is obtained from Malaysian Meteorological Department Labuan (MMDL) from 2005 to 2012. MMDL collected this data using voluntary observation ship scheme and acoustic Doppler current profiler equipment. Wave data of Mabul Island and Kota Kinabalu for the month of February and that of Pulau Mentagor for the month of December are not included in the analysis, as the data were unavailable from MMDL. Then, the collected MMDL data have been analyzed by the "hindcast" technique [10] for calculating the appropriate wave power level. The wave data of these five selected locations are shown in Fig. 1–5, respectively.

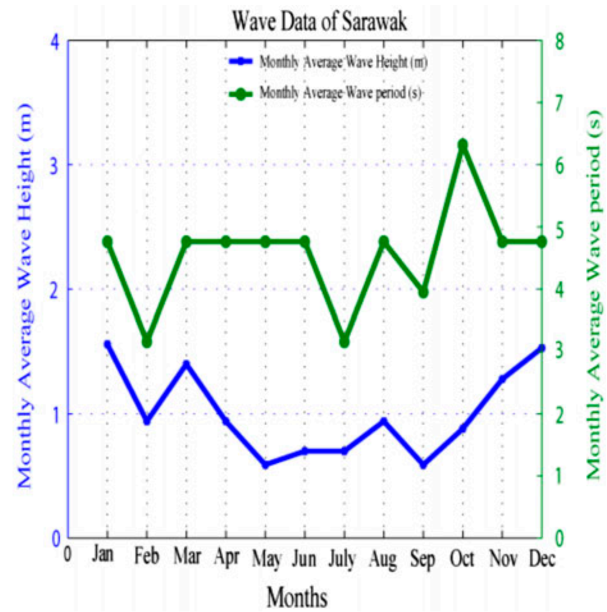

Fig. 1. Wave height/wave period data of a year for Sarawak.

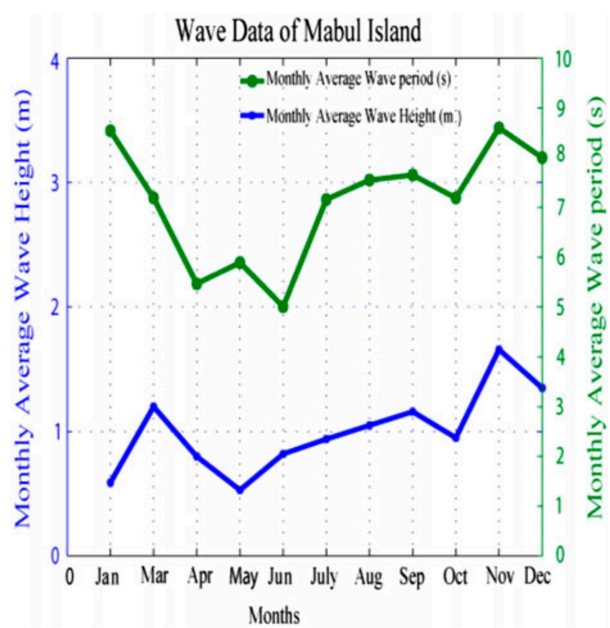

Fig. 2. Wave height/wave period data of a year for Mabul Island.

3. The wave-powered RO system

The wave-powered-driven RO system consists of the membrane separation segment, which is connected with a reciprocating high-pressure pump. A hydroturbine is connected to this high-pressure pump for

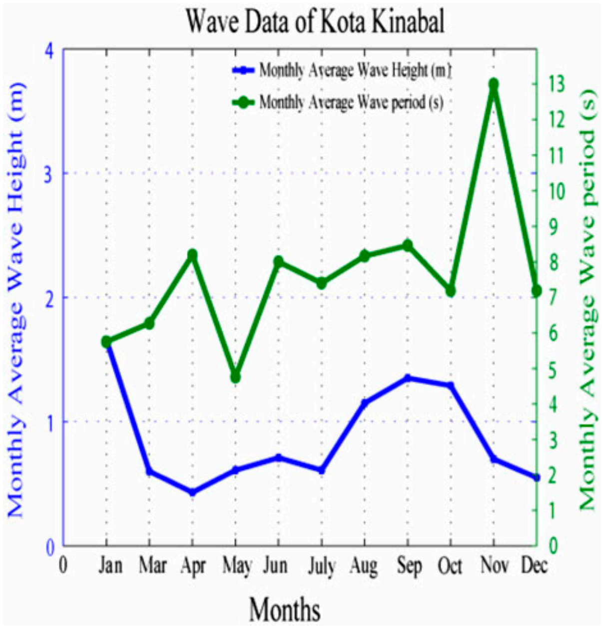

Fig. 3. Wave height/wave period data of a year for Kota Kinabalu.

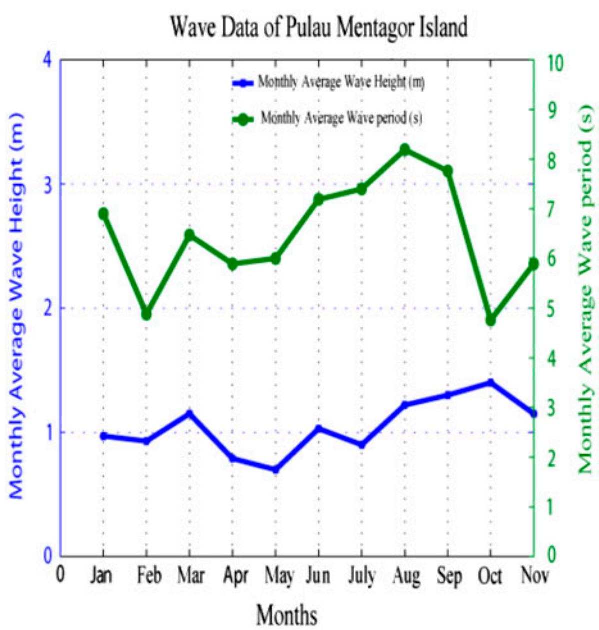

Fig. 4. Wave height/wave period data of a year for Pulau Mentagor Island.

the energy recovery by the process of the brine stream leaving. Then, this reciprocating pump is operated by a three-phase motor which is driven by electrical energy. In this case, the OWC wave power device

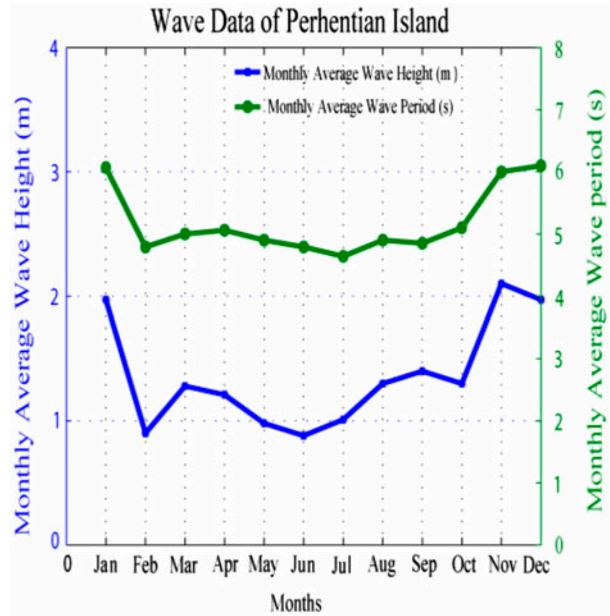

Fig. 5. Wave height/wave period data of a year for Perhentian Island.

produces electrical energy. Fig. 6 shows the schematic diagram of the proposed RO system, and Table 1 indicates the technical parameters of utilized OWC. The whole system requires an advanced control algorithm for the regulation of the system power and voltage.

According to the McCormick [3,11], there are two types of energy components available within the sea waves, one is the potential energy and another one is the kinetic energy. Potential energy of the waves is related with the wave height, while the kinetic energy of the wave is related with the water rate of the particles within the waves. Mathematically, oceanic waves can be approximated by a sine wave. Therefore, it can exhibit a smooth, regular oscillation. The total energy of regular (sinusoidal) waves is:

$$E = E_p + E_K = \frac{\rho g H^2 \lambda}{8} \quad (1)$$

where ρ is the mass density of water (1,000 kg/m^3 for fresh water or 1,030 kg/m^{3}for salt water), g is the acceleration due to gravity (9.8 m/s^2), H is the wave height (m), and λ is the wave length. According to the linear theory described in [9,11], the total energy in deep water of a wave is equally composed of potential energy E_p and kinetic energy E_K where:

$$E_p = E_K = \frac{\rho g H^2 \lambda}{16} \quad (2)$$

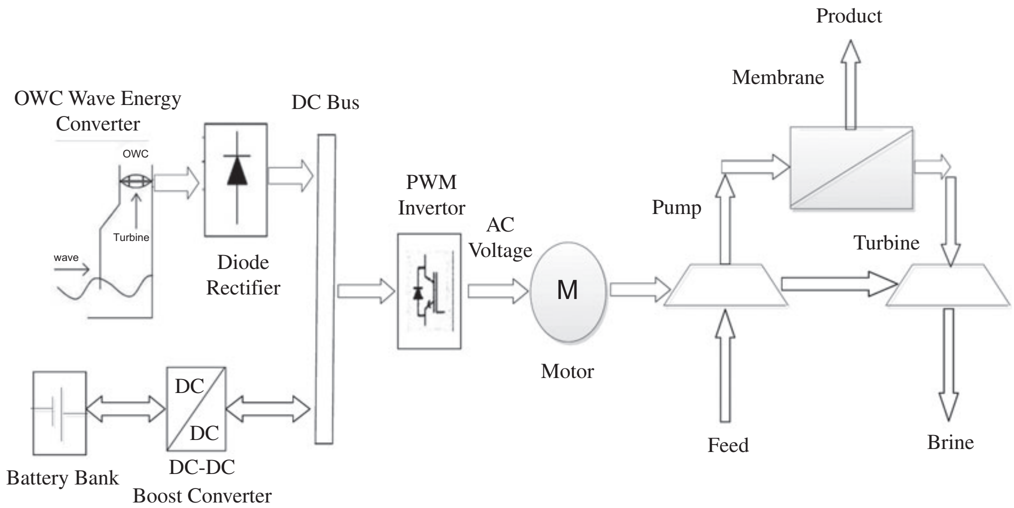

Fig. 6. Wave-powered RO desalination system schematic diagram.

Table 1
Technical parameters of utilized OWC

Chamber width (m)	2
Turbine power conversion rate (%)	30
Water density (kg/m^3)	1,030

The potential energy is a progressive wave of height H, whereas the kinetic energy is dependent on the particles motion. For a variable sea state, the wave energy transfer from point to point in the direction of the wave travel is characterized by the energy flux or more commonly, wave power given by:

$$P = \frac{\rho g H^2 C_g}{8} \quad (3)$$

where C_g is the group velocity and is characterized by:

$$C_g = \frac{C}{2}\left\{1 + \frac{2kh}{\sinh(2kh)}\right\} = nC \quad (4)$$

where C is the phase velocity. In deep water, $C_g = \frac{C}{2}$ and in shallow water $C_g = C$.

Now the output power for deep water is given from Eq. (3), such that: $P = \frac{\rho g H^2 C\ b}{16}$ [for deep water $C = \frac{gT}{2\pi}$]

$$P = \frac{\rho g^2 H^2 T b}{32\pi} \quad (5)$$

T is the period of wave (s). From above wave power equation, it is concluded that the multiplication of the wave period and the square of the wave height is directly proportional to the wave power, if other parameters of the equation are constant.

Using the above-mentioned model, the power delivered for a given value of wave height and period is predicted. The relationship between the electrical energy consumption and water salinity for the RO system is shown in Fig. 7. With brackish water of 5,000 and 2000 mg/L TDS, the amount of energy required is 1.6 and 1.1 kWh/m^3, respectively [12,13].

4. Technical analysis and discussion

Using the proposed OWC wave mathematical model, the power delivered for a given value of wave height and period is predicted. In this analysis, the total daily operation of OWC is considered 10 h. Then, the relationship between electrical energy consumption and water salinity for the RO desalination system

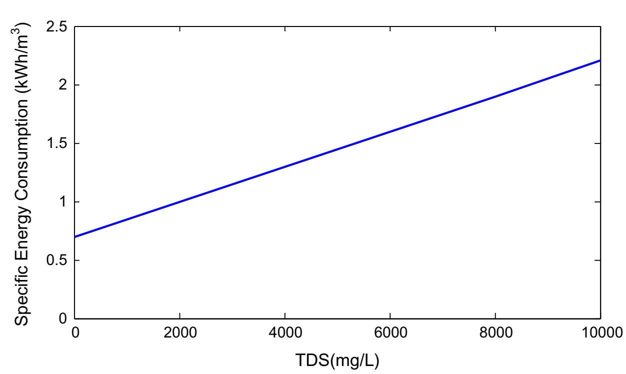

Fig. 7. Energy consumption of the RO desalination system as a function of TDS [12,13].

(shown Fig. 7) is used to calculate the amount of water produced by the system. Figs. 8–12 represent the daily amount of water production during a one-year cycle at the selected locations for different TDS values (3,000, 5,000, 7,000, and 10,000 mg/L). Fig. 13 shows the annual amount of water production at all the five selected sites for different values of TDS.

Based on the above-obtained results, all the selected sites are considered to be "adequate" for wave-powered RO desalination system. Because annual water production rate of wave-powered RO desalination system is much higher than the wind-powered [14] and solar-powered RO system [12,13]. Finally, it ascertained that wave-powered RO desalination is a good option for islands or those areas which is near to the sea.

5. Economical analysis and discussion

The average estimated peak power equipment of five selected sites for RO desalination system is 5 kW. So, in our study, a 5 kW wave power plant is considered for the RO desalination system. The electrical energy cost for driving RO system is discussed in this section and this cost analysis is done without considering turbine, wave chamber, and RO system cost.

5.1. Energy from wave device

The peak energy requirement of wave device can be calculated by multiplying maximum power generated by wave power plant and total operation times of plant.

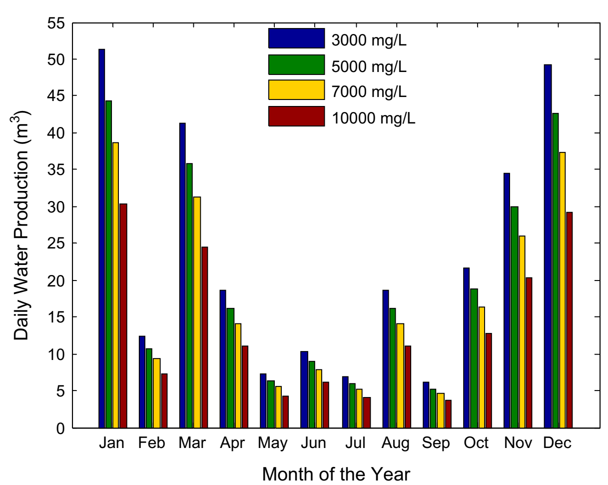

Fig. 8. The daily water production at Sarawak during a one-year cycle.

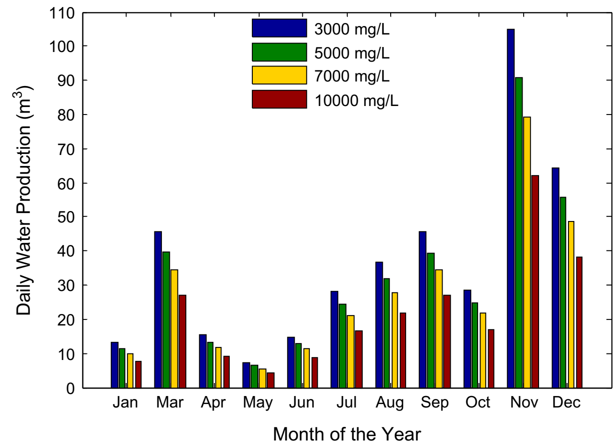

Fig. 9. The daily water production at Mabul Island during a one-year cycle.

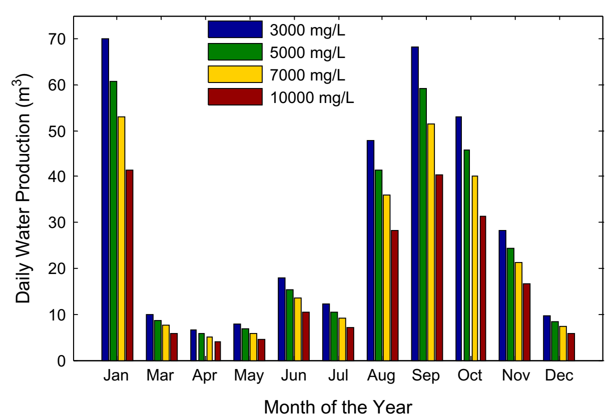

Fig. 10. The daily water production at Kota Kinabalu during a one-year cycle.

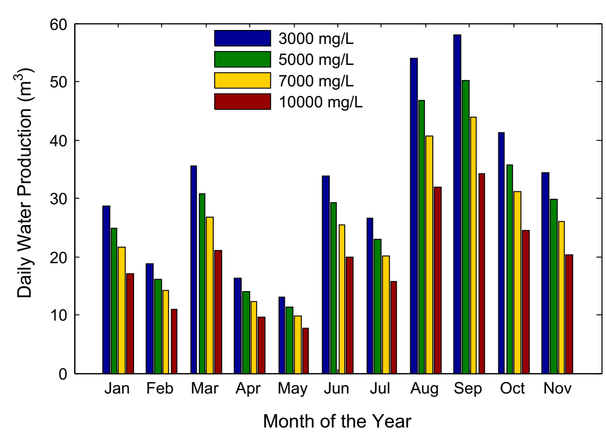

Fig. 11. The daily water production at Mentagor Island during a one-year cycle.

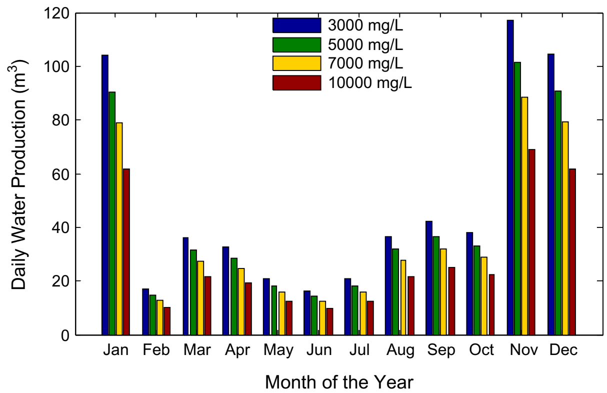

Fig. 12. The daily water production at Perhentian Island during a one-year cycle.

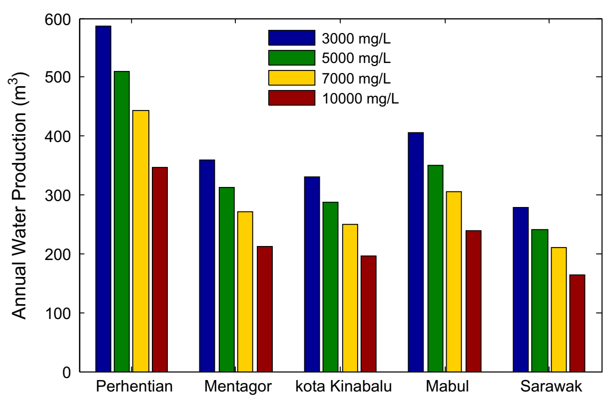

Fig. 13. The annual water production for all the five selected locations.

The maximum generated power = 5 kW.
Peak energy requirement = 5 kW × 10 h = 50 kWh/d.

5.2. Equipment cost

Cost of the 5 kW generator = 179.88 USD [15].
Cost of the 5 kW inverter = 450 USD [16].
For 50 kWh/d operation,
The battery capacity (Ah)

$$= \frac{\text{Total Watt-hours per day used by RO system} \times \text{Days of autonomy}}{0.85 \times 6.6 \times \text{nominal battery voltage}}.$$

$$= \frac{50 \times 10^3 \times 1}{0.85 \times 0.6 \times 96} = 1022\ Ah$$

In this case, total 12 pieces of 12 V, 96 Ah battery is required.

The total battery cost = 12 × 753 USD = 9,036 USD [17].

Cost of the 5 kW ac to dc converter = 1,250 USD [18].

5.3. Engineering design and management cost

Project management, design, and engineering labor cost = 3.4 USD/man-h (based on Malaysia) [18].

Project management, design, and engineering hours per kWp = 2 h.

Total project management, design, and engineering cost for 5 kW wave plant = 33,748 USD.

5.4. Installation labor cost

Installation labor cost = 1.53 USD (based on Malaysia) [19].

Installation man hour required for per kWp = 12 h.

Total installation labor cost of 5 kW wave power plant = 92,039 USD.

5.5. Operation and maintenance cost

According to the literature, in reference [9], the operation and maintenance cost = 60 USD/kWh.

The total annual operation and maintenance cost = 219,000 USD.

Total cost of the plant = equipment cost + engineering design and management cost + installation labor cost + operation and maintenance cost = 355,703 USD.

Annual cost of the plant if project lifetime is 20 years $= \frac{\text{Total cost of the plant}}{20} = 17785.15$ USD.

The cost of the per kWh $= \frac{\text{Annual cost}}{\text{Annual energy output}} = 4.87$ USD. Payback period of the plant $= \frac{\text{System cost}}{\text{total energy income per year}} = 7.68$ years ≈ years

It can be concluded from the above economical analysis that stand-alone wave power is viable for the RO system compared to the stand-alone solar-powered RO system in reference [20]. For the RO desalination system, the cost of the wave energy per kWh is higher than the cost of the conventional energy per kWh, but the wave energy have quick payback period and good environmental advantages. The author believes that the issue of the increasing greenhouse gas day by day due to the burning of conventional fuels should not be underestimated.

6. Conclusion

The main aim of this paper is to present the possibility of the wave-powered RO desalination system for islands or those areas which is near to the sea, where electric power grid and fresh water source are not available. It has been believed that from the both technical and economical analysis, the proposed wave-powered RO desalination system has considered promising desalination system for fresh water production. Future planning of the proposed wave-powered RO system must focus on exploring different wave power and desalination methods to find a better way to resolve fresh water issues.

Acknowledgment

The authors would like to thank the KeTTHA, Ministry of Energy, Green Technology, and Water (53-02-03-1102) and the Postgraduate Research Fund, University of Malaya (PG085-2013B) for providing financial support.

References

[1] M. Ashraf, M. Maah, A. Qureshi, M. Gharibreza, I. Yusoff, Synthetic polymer composite membrane for the desalination of saline water, Desalin. Water Treat. 51 (2013) 3650–3661.

[2] A. Muetze, J. Vining, Ocean wave energy conversion—A survey, in: Industry Applications Conference, 2006. 41st IAS Annual Meeting. Conference Record of the 2006 IEEE, vol.3, IEEE, Tampa, USA, October 8–12, 2006, pp. 1410–1417.

[3] N.H. Samrat, N.B. Ahmad, I.A. Choudhury, Z.B. Taha, Modeling, control, and simulation of battery storage photovoltaic-wave energy hybrid renewable power generation systems for island electrification in Malaysia, Sci. World J. 2014 (2014) 1–21.

[4] M.E. McCormick, Ocean Wave Energy Conversion, Courier Dover Publications, New York, NY, 2013.

[5] J. Halliday, D. Dorrell, Review of wave energy resource and wave generator developments in the UK and the rest of the world, in: IASTED EuroPES Conference, Rhodes, Greece, June 28–30, 2004.

[6] R.-S. Tseng, R.-H. Wu, C.-C. Huang, Model study of a shoreline wave-power system, Ocean Eng. 27 (2000) 801–821.

[7] M.A. Ashraf, I. Yusoff, M. Yusof, Y. Alias, Study of contaminant transport at an open-tipping waste disposal site, Environ. Sci. Pollut. Res. 20 (2013) 4689–4710.

[8] S. Batool, S. Akib, M. Ahmad, K.S. Balkhair, M.A. Ashraf, Study of modern nano enhanced techniques for removal of dyes and metals, J. Nanomater. 2014 (2014) 1–20.

[9] N.H. Samrat, N.B. Ahmad, I. Choudhury, Z. Taha, Prospect of wave energy in Malaysia, in: Power Engineering and Optimization Conference (PEOCO), 2014 IEEE 8th International, IEEE, Langkawi, Malaysia, March 24–25, 2014, pp. 127–132.

[10] R.G. Quayle, M. Changery, Estimates of coastal deepwater wave energy potential for the world, in: OCEANS 81, IEEE, Boston, MA, September 16–18, 1981, pp. 903–907.

[11] D. Dorrell, W. Fillet, Investigation of a small-scale segmented oscillating water column utilizing a Savonius rotor turbine, Proceedings of International Conference on Energy and Environment (ICEE 2006), Selangor, Malaysia, 2006, pp. 23–32.

[12] D.P. Clarke, Y.M. Al-Abdeli, G. Kothapalli, The effects of including intricacies in the modelling of a small-scale solar-PV reverse osmosis desalination system, Desalination 311 (2013) 127–136.

[13] M.S. Mohsen, J.O. Jaber, A photovoltaic-powered system for water desalination, Desalination 138 (2001) 129–136.

[14] E.S. Hrayshat, A wind-powered system for water desalination, Int. J. Green Energy 4 (2007) 471–481.

[15] STC-5kw three phase FOBFUZHOU, [Online 2014]. Available from: <http://www.alibaba.com/>.

[16] Prostar 5kw power inverter, [Online 2014]. Available from: <http://www.alibaba.com/>.

[17] 12v 90ah dry cell battery 12v Sonnenschein A412/90 F10 12v deep cycle batteries price NGA4120090H-SOFA, [Online 2014]. Available from: <http://www.alibaba.com/>.

[18] AC to DC converter, [Online 2014]. Available from: <http://www.alibaba.com/>.

[19] List of minimum wages by country, [Online 2014]. Available from: <http://en.wikipedia.org/wiki/List_of_minimum_wages_by_country>.

[20] E.S. Mohamed, G. Papadakis, E. Mathioulakis, V. Belessiotis, A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems—A technical and economical experimental comparative study, Desalination 221 (2008) 17–22.