View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Edinburgh Research Explorer

THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Renewable Energy Powered Membrane Technology: The effect of intermittent operation on a wind-powered membrane system for brackish water desalination

Citation for published version:
Park, GL, Schaefer, A & Richards, BS 2012, 'Renewable Energy Powered Membrane Technology: The effect of intermittent operation on a wind-powered membrane system for brackish water desalination' Water Science and Technology, vol 65, no. 5, pp. 867-874. DOI: 10.2166/wst.2012.912

Digital Object Identifier (DOI):
10.2166/wst.2012.912

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Water Science and Technology

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.

OPEN ACCESS

Download date: 28. Apr. 2017

The effect of intermittent operation on a wind-powered membrane system for brackish water desalination

G. L. Park*, A. I. Schäfer**, B. S. Richards*

* School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK

(E-mail: *glp2@hw.ac.uk*; *B.S.Richards@hw.ac.uk)*

** School of Engineering, University of Edinburgh, Edinburgh EH9 3JL, UK

(E-mail: *Andrea.Schaefer@ed.ac.uk*)

Abstract

Renewable energy powered membrane systems that are directly-connected must take account of both the inherent fluctuations and the intermittency of the energy resource. In order to determine the effect of intermittent operation, a membrane system was tested with variables of i) amplitude from 60 – 300 W and ii) length of time with no power from 0.5 – 3 minutes. This was performed over one hour periods with six on/off cycles to simulate the system operating under intermittent operation for short periods of time when directly-connected to a small wind turbine. The setup used a Filmtec BW30-4040 brackish water reverse osmosis membrane with feed waters of 2750 mg/L and 5500 mg/L NaCl. The results showed that the membrane system produced potable water under the majority of intermittency experiments performed. There was a relatively large increase in the average salt concentration of the permeate, especially when the system was off for shorter periods of time (0.5 – 1 min). Longer periods of no power (>1 min) did not have as significant an effect on the average water quality. This is important when the need for energy buffering or short term storage is considered for these systems as it shows the potential for improving the overall flux and water quality using temporary energy storage.

Keywords

Desalination; power fluctuation; renewable energy; reverse osmosis; wind energy

INTRODUCTION

While considerable attention and resources have been directed at the worldwide water crisis, the latest Millennium Development Goals report showed that there are still 884 million people without access to improved water sources, of which 84 % live in rural areas (United Nations, 2009). This problem is compounded by the fact that 85 % of the 1.5 billion without access to electricity also live in rural areas (International Energy Agency, 2009). Serving these rural areas with a centrally supplied water system is impractical and expensive which emphasises the need for decentralised water treatment systems that are off-grid and able to satisfactorily remove pollutants. The use of renewable energy technologies coupled with membrane systems (RE-membrane) provide a promising solution for brackish water desalination in these remote regions as they are relatively cost effective, energy efficient and can be designed according to the pollutants in the water supply, number of inhabitants and the energy resource (Park *et al*., 2011).

In particular, the use of wind turbines is one of the most promising technologies for desalination as it is economically feasible and the technology is well advanced (Forstmeier *et al*., 2007). The main challenges associated with the use of the wind resource are intermittency and fluctuations over short periods of time (Manwell, 2002). This is a considerable challenge for the direct connection of wind turbines to membrane systems (wind-membrane), as membranes are designed to operate under constant pressure and cross-flow velocity to avoid structural damage (Dow Water Solutions, 2010). An additional consideration is that the variability and unpredictability of the wind resource may result in the water demand not being met (Miranda, Infield, 2003; Tzen, 2006). In order to overcome these problems, most of the small-scale wind-powered systems that have been developed utilised electrical energy storage in batteries (Petersen *et al*., 1981; Infield, 1997; Weiner *et al*., 2001; Mohamed, Papadakis, 2004; Tzen *et al*., 2004) or mechanical storage in a pressure vessel (Robinson *et al*., 1992; Liu *et al*., 2002). An alternative method for overcoming the intermittency of wind is to store the potable water which greatly reduces the capital and maintenance costs of these systems and avoids the many issues associated with the use of lead acid batteries (Thomson, Infield, 2005; Richards *et al*., 2008). Operation of wind-membrane systems under fluctuations in pressure and flow rate has been documented (Lising, Alward, 1972; Gocht *et al*., 1998; Miranda, Infield, 2003; de la Nuez Pestana, *et al*., 2004; Moreno, Pinilla, 2005; Heijman *et al*., 2009) and pilot studies have shown that membranes can be operated in a variable manner without deteriorating over short periods of time (Gocht *et al*., 1998; de la Nuez Pestana *et al*., 2004), however there is little known about the long term consequences and safe operating window. The main issue that has been raised is that frequent switching on and off of membrane systems should be avoided as it causes reduced permeate quality and increased wear on the pump and motor (Lising, Alward, 1972; McBride *et al*., 1987; Thomson, Infield, 2005). However, until now, there has been no study that quantifies the overall impact of intermittency on RE-membrane system performance. Therefore, in order to fully understand and optimise the operation of any RE-membrane system, the effect of intermittent operation must be investigated.

The system described here was previously tested with four different nanofiltration/reverse osmosis (NF/RO) membranes under steady-state conditions (Schäfer *et al*., 2007), and directly-connected to photovoltaic (PV) panels over several solar days (Richards *et al*., 2008). Initial results showed that the PV-powered system could operate under fluctuations with minimal effect on the permeate quality but that further testing of the system at low levels of power would be required (Richards *et al*., 2008). A systematic investigation of the membrane system under wind speed fluctuations showed that the system produced good-quality drinking water with a feed water of 2750 mg/L NaCl but the performance was marginal with 5500 mg/L NaCl (Park *et al*., 2011). The main cause of reduced system performance was shown to be from large amplitude fluctuations at longer period of oscillation that caused the power to shut off. This work adds to what was done previously with fluctuations by investigating the effect of intermittent operation in more detail with respect to the permeate quality and quantity by varying the length of off-time and the amount of power available.

MATERIALS AND METHODS

Wind-membrane system set-up

The wind-membrane system (*Figure 1*) consisted of a polypropylene micro filter (SupaGard, pore size 1μm, cartridge volume 1.2 L) for pre-treatment and a Filmtec BW30-4040 brackish water RO membrane (Dow Water Solutions, 2010). The main power requirement was a 300 W progressive cavity pump (Mono Pumps, Australia) that drew water through the pre-treatment stage and provided the pressure required for desalination of the brackish feed water (up to 12 bar). The feed waters were prepared using deionised water and general purpose grade NaCl (Fisher Scientific, UK) in a stainless steel feed tank (volume 130 L). Permeate and concentrate flows were recycled into the feed tank to maintain a constant feed concentration while homogenous mixing of the feed solution was achieved using an air bubbling system with the temperature of the feed water maintained at 13 °C using a water chiller. At the start of each experiment, a set point was determined by the input power, pump motor speed and the regulating valve on the concentrate stream. This point was set at

Renewable Energy Powered Membrane Technology: The effect of intermittent operation on a wind-powered membrane system for brackish water desalination
Park, G. L. , Schaefer, A. & Richards, B. S. 2012 In : Water Science and Technology. 65, 5, p. 867-874.

system pressure of 10 bar and feed flow rate of 300 L/h under constant power operation at 240 W. The set point was also used to determine the pure water flux of the membrane (J_0 = 25 L/m².h at 10 bar) to ensure that the membrane performance had not altered during testing.

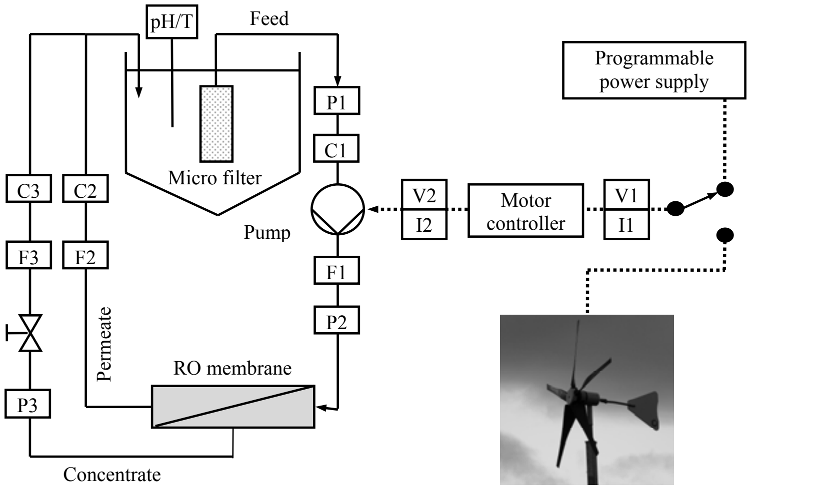

Figure 1 Schematic of wind-membrane system with electrical connections (dotted lines) and water flow (solid lines) to connect components of the wind-membrane system where: P1 – P3: pressure transducers; F1 – F3: flow sensors; C1 – C3: conductivity sensors; V1 – V2: voltage sensors; I1 – I2: current sensors; pH/T: pH and temperature sensor.

The transient operation of pressure, flow rate, conductivity, temperature, pH, current and voltage were taken at a reading rate of 1 Hz using a datalogger (dataTaker, DT800). These values were used to calculate the following membrane specific parameters: transmembrane pressure (TMP), flux (J), recovery (Y), retention (R), specific energy consumption (SEC) and total dissolved solids (TDS) using the relationships defined previously (Schäfer *et al*., 2007; Richards *et al*., 2008; Park *et al*., 2011). The measured electrical conductivity (EC, µS/cm) was converted into TDS (mg/L) using a conversion factor k = 0.625, as measured using deionised water at 13°C.

Experimental design

To assess the effect of real wind speed fluctuations, experiments were performed with the membrane system directly-connected to a wind turbine (FuturEnergy, 1 kW rated power, 48 V_{DC} output) mounted in a wind tunnel. This testing was used to examine the effect of fluctuations and also to determine the important issues for a directly-connected system. While previous work dealt with the effect of wind speed fluctuations on system performance (Park *et al*., 2011), this work examines the other issue associated with renewable energy, which is intermittency. Intermittent operation was taken to be any period of time when the system shut off due to insufficient power. In order to test the wind-membrane system under controlled conditions, the wind turbine was replaced by a programmable power supply (Agilent Technologies, model E4350B-J02, 0 – 80 V_{DC}, 6 A). The effect of intermittent operation on the average system performance over one hour with six on/off cycles was determined with variables of i) amplitude from 60 – 300 W and ii) length of time with no power (t_{off}) from 0.5 – 3 minutes as shown in *Figure 2*. Six periods of zero-power were chosen

as this was the maximum number that allowed the permeate quality to return to its original value once the power had been switched on (t_{on}) within a one hour period over the range of t_{off}, up to 3 minutes. Experiments were performed using two feed waters of 2750 mg/L and 5500 mg/L NaCl.

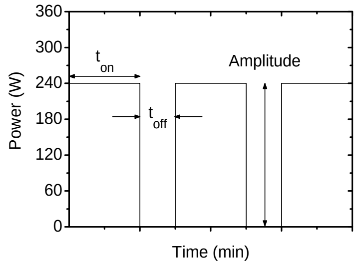

Figure 2 Power input to membrane system using programmable power supply for experiments on intermittent operation.

RESULTS AND DISCUSSION

The effect of real wind speed fluctuations on system performance

The wind turbine was mounted in a wind tunnel so that the wind speed could be controlled in order to investigate the effect of wind fluctuations on system performance. The results (*Figure 3*) showed that the wind turbine power (*Figure* ***3****B*), TMP (*Figure 3C*) and the flux (*Figure 3D*) followed the same pattern as the wind speed (*Figure 3A*). There was minimal hydraulic lag observed due to the small volume of water (~5 L) that was contained at any one time within the pressure vessel. The power to the membrane system (*Figure 3B*) did not always follow the wind speed fluctuations due to system shutdown at low power. This is an in-built feature of the system in order to reduce loading on circuits and wear on the pump motor by constant restarting. The system turned off if the input power dropped below 40 W for greater than 3 s as a result of large wind speed fluctuations. While wind speed fluctuations had a large impact on the TMP and therefore the flux, there was little immediate impact on the permeate concentration (*Figure 3E*). Results showed that periods of intermittency (system shutdown) had more of an effect on the permeate concentration as evidenced by the increase in concentration following a lag time (*Figure 3E*). This lag was a result of the time taken for diffusion of salts through the membrane and for the permeate flux to flush out the poor quality water.

Renewable Energy Powered Membrane Technology: The effect of intermittent operation on a wind-powered membrane system for brackish water desalination
Park, G. L. , Schaefer, A. & Richards, B. S. 2012 In : Water Science and Technology. 65, 5, p. 867-874.

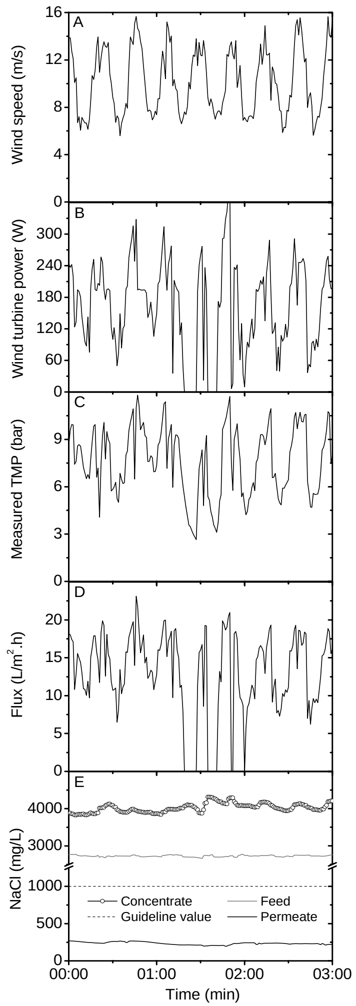

Figure 3 Performance of the wind-membrane system as a function of time using real wind speed fluctuations (wind tunnel) with a feed water of 2750 mg/L and average wind speed 10 m/s.

Analysis of intermittent operation

In order to gain a better understanding of the system response under intermittent operation, a square wave input in power is shown (*Figure 4*) with a feed water of 5500 mg/L where the power was switched off for 3 minutes from 240 W. As shown by line ①, when the power was switched off, the feed and permeate flow rates (*Figure 4A*) responded immediately while the concentrate stream continued to flow for several minutes due to back-pressure from the pump. The concentration of the permeate stream (*Figure 4B*) had a delayed response (~30 s) once the power was switched off (①). This was due to permeate water being drawn back into the membrane in order to achieve equilibrium, known as osmotic suck-back (Thomson, 2003). During this period the flow rate was zero as the sensor could not measure reverse flow and the conductivity measured was that of water that had already passed through the sensor. Once all of the available water had been drawn back into the membrane, the sensor read zero. When the power was switched back on (③) it took ~1 min for the pressure to increase sufficiently and the permeate flow to resume (④).

While the power was turned off (①-③), diffusion of salts across the membrane occurred, this is represented by a large spike in permeate concentration (④) once the system was re-started. The concentrate stream exhibited a sharp decrease in concentration when the power was switched off (①) as the system was no longer desalinating and the concentrate concentration was the same as the feed. This was followed by an increase (②) which showed salts from the boundary layer being washed through the system. A mass balance performed on several experiments (3% error) showed that the further drop in the concentrate concentration (between ③ and ④) was a result of diffusion of salts into the permeate stream. The net flux of NaCl across the membrane from the feed to the permeate during off-time was calculated based on experimental data as 0.46 mg/m².s for a feed water of 2750 mg/L and 0.87 mg/m².s for a feed water of 5500 mg/L NaCl (Park *et al*., 2011). The volume of water that remained in the membrane vessel which had to be purged to return to normal conditions was 2 L ±10 %.

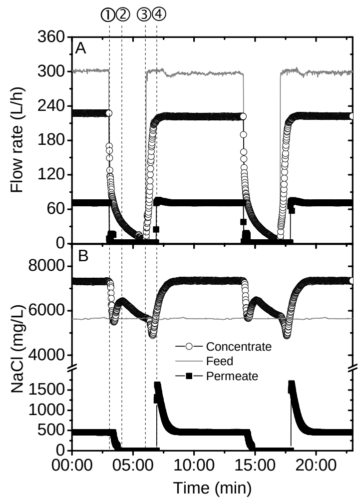

Figure 4 The effect of intermittent operation using a feed water of 5500 mg/L NaCl with the power switched off for 3 minutes from 240 W on A: Flow rate and B: NaCl concentration.

To determine the effect of intermittent operation on the permeate quality and quantity, experiments were performed over one hour with six on/off cycles and the performance parameters averaged over this time period (*Figure 5*). The first point to note is that the membrane system produced water within the guideline value (1000 mg/L) at all off-times with a feed water of 2750 mg/L (*Figure 5A*), and with 5500 mg/L at power ≥120 W (*Figure 5B*). This shows the resilience of the system to periods of intermittency in terms of the water quality. The permeate concentration (*Figure 5A, 5B*) increased with longer off-time as a result of greater time available for diffusion of salt through the membrane. Increasing the power resulted in improved permeate concentration due to higher TMP and therefore flux (*Figure 5C, 5D*), which reduced the amount of time required to purge the system of the poor quality permeate water and obtain equilibrium. The permeate concentration with a feed water of 5500 mg/L was higher because of the increased osmotic pressure of the feed that offset the TMP (4.4 bar with 5500 mg/L compared to 2.2 bar with 2750 mg/L).

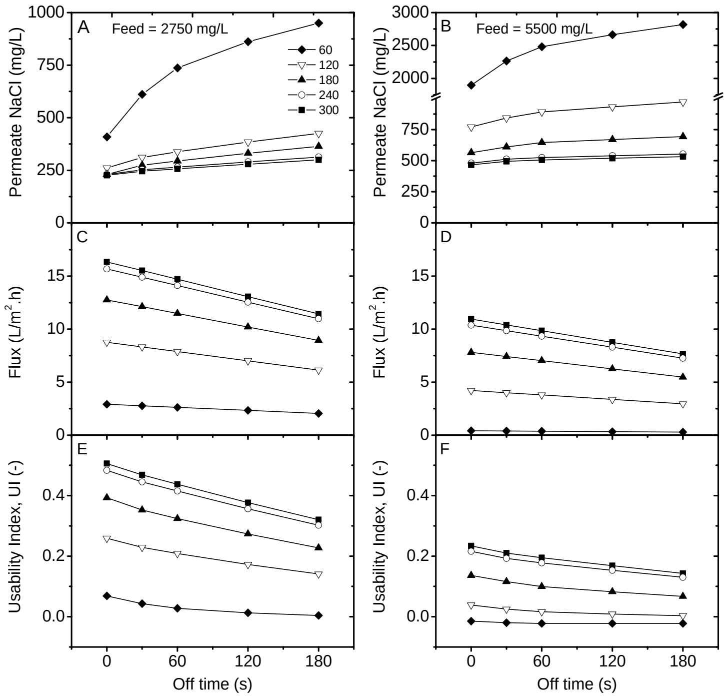

Figure 5 Intermittent operation over one hour with six on/off cycles and feed waters 2750 and 5500 mg/L. The effect of increasing the off-time and power on average A: permeate NaCl; B: flux and C: usability index (UI).

The change of permeate concentration with off-time showed a similar relationship for all of the experiments as shown (*Figure 5A, 5B*). The curve for wind turbine power of 60 W showed the most obvious trend due to the reasons mentioned above and may be used to illustrate the effect of increasing the off-time. The permeate concentration exhibited a steep slope up to an off-time of 60 s, followed by a more gradual increase for off-times of 120 s and 180 s. This was a result of the higher initial rate of diffusion due to the increased concentration gradient when the power was firstly turned off. As the salt diffused across the membrane, the concentration gradient reduced over time and the change in permeate concentration at longer off-time was not as significant. This is an interesting point as it may be more beneficial to reduce the number of intermittent periods of 60 s or less than attempt to buffer these longer periods of no power in order to reduce the impact of intermittency on the average permeate quality.

The flux exhibited a linear decrease with increasing off-time (*Figure 5C, 5D*) due to the periods of zero flux, and the fact that the flux returned immediately to its original value once the power was switched back on as shown previously (*Figure 4A*). There would be zero flux with an off-time of 10 minutes as this would be 100 % of the cycle. The usability index (UI) (*Figure 5E, 5F*) is useful for understanding the combined impact on the permeate concentration and the flux. This parameter is dimensionless and was developed to determine the safe operating window for a membrane system under fluctuations in power by taking into account the permeate quality and quantity averaged over a period of time (Park *et al*., 2011). The graphs (*Figure 5E, 5F*) show that there was a more rapid

decline in the UI up to 60 s (representative of the rate of change of permeate quality) followed by a more gradual reduction, which again highlights the potential for short term energy buffering. The UI was negative with a feed water of 5500 mg/L and power of 60 W (*Figure 5F*) as a result of the permeate concentration being higher than the guideline value of 1000 mg/L (World Health Organisation, 2008), which showed the system functioning outside the safe operating window. The difference in the UI obtained with feed waters of 2750 mg/L and 5500 mg/L illustrates the difference in the permeate quality and quantity that can be obtained depending on the characteristics of the feed water.

An important consideration which is not covered here due to the time scales involved is the effect of long term intermittent operation on the pump and motor. However, short term energy buffering of 60 s would help to reduce the number of system restarts as well as improving the average permeate concentration and flux. This type of energy storage could not be achieved in deep-cycle lead acid batteries as they have poor charge/discharge time and efficiency, whilst only able to undergo a relatively small number of cycles (~1500) (Richards *et al*., 2008). Therefore other forms of energy buffering like electrical storage in supercapacitors or mechanical storage in pressure vessels would be worth investigating.

CONCLUSIONS

The operation of a directly-connected wind-membrane system is described under intermittent operation. The effect of on/off cycling was seen immediately in the power, TMP and flux, whereas there was a lag time associated with the permeate concentration due to the time taken for diffusion and flushing of the system. The fact that the fluctuations were seen immediately in terms of the system hydraulics is important as it means that there is no form of buffering of the fluctuations. The membrane system showed good resilience to intermittency in terms of permeate quality by producing potable water for all of the conditions except with a high feed concentration at low power (5500 mg/L NaCl at 60 W). As would be expected, increased power and less off-time resulted in a higher average permeate quality and flux over a one hour period. The amount of power available to re-start the system after a period of intermittency was important for the average permeate concentration as it determined the TMP, flow rate and flux which purged the system of high salinity permeate. Due to the concentration gradient being highest when the power was initially turned off, the increase in permeate concentration was highest at off-times up to 60 s, which highlights the potential for short term energy buffering.

ACKNOWLEDGEMENTS

The PhD studentship for Gavin L. Park was provided by the Joint Research Institute in Energy, part of the Edinburgh Research Partnership in Engineering and Mathematics. We thank Scottish Enterprise for funding the use of their wind tunnel facility at the Energy Technology Centre (East Kilbride, Scotland) and TUV NEL for their technical support and consultation. We also thank Ronald Millar and Curtis Abbott for their technical support.

REFERENCES

de la Nuez Pestana I., Javier García Latorre F., Argudo Espinoza C. and Gómez Gotor A. (2004). Optimization of RO desalination systems powered by renewable energies. Part I: Wind energy. *Desalination*, **160**(3): 293-299.

Dow Water Solutions (2010). Membrane datasheet Filmtec BW30-4040. http://www.dow.com/PublishedLiterature/dh_0109/0901b80380109c07.pdf (accessed 9 December 2010).

Forstmeier M., Mannerheim F., D'Amato F., Shah M., Liu Y., Baldea M. and Stella A. (2007). Feasibility study on wind-powered desalination. *Desalination*, **203**(1-3): 463-470.

Gocht W., Sommerfeld A., Rautenbach R., Melin T., Eilers L., Neskakis A., Herold D., Horstmann, V., Kabariti M. and Muhaidat A. (1998). Decentralized desalination of brackish water by a directly coupled reverse-osmosis-photovoltaic-system - a pilot plant study in Jordan. *Renewable Energy*, **14**(1-4): 287-292.

Heijman S. G. J., Rabinovitch E., Bos F., Olthof N. and van Dijk J.C. (2009). Sustainable seawater desalination: Stand-alone small scale windmill and reverse osmosis system. *Desalination*, **248**(1-3): 114-117.

Infield D. (1997). Performance analysis of a small wind powered reverse osmosis plant. *Solar Energy*, **61**(6): 415-421.

International Energy Agency (2009). World Energy Outlook: Access to Electricity. http://www.worldenergyoutlook.com/electricity.asp (accessed 9 December 2010).

Lising E. R. and Alward R. (1972). Unsteady State Operation of a Reverse-Osmosis Desalination Unit. *Desalination*, **11**(3): 261-268.

Liu C. C. K., Jae-Woo R., Migita R. and Gang Q. (2002). Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control. *Desalination*, **150**(3): 277-287.

Manwell J. F. (2002). *Wind Energy Explained: Theory, Design and Application*. John Wiley & Sons Ltd.

McBride R., Morris R. and Hanbury W. (1987). Wind power a reliable source for desalination. *Desalination*, **67**: 559-564.

Miranda M. S. and Infield D. (2003). A wind-powered seawater reverse-osmosis system without batteries. *Desalination*, **153**(1-3): 9-16.

Mohamed E. S. and Papadakis G. (2004). Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics. *Desalination*, **164**(1): 87-97.

Moreno F. and Pinilla A. (2005). Preliminary experimental study of a small reverse osmosis wind-powered desalination plant. *Desalination*, **171**(3): 257-265.

Park G. L., Schäfer A.I. and Richards B.S. (2011). Renewable Energy Powered Membrane Technology: The effect of wind speed fluctuations on the performance of a wind-powered membrane system for brackish water desalination. *Journal of Membrane Science*, **370**(1-2): 34-44.

Petersen G., Fries S., Mohn J. and Muller A. (1981). Wind and solar powered reverse osmosis desalination units - design, start up, operating experience. *Desalination*, **39**: 125-135.

Richards B. S., Capão D. P. S. and Schäfer A.I. (2008). Renewable Energy Powered Membrane Technology. 2. The Effect of Energy Fluctuations on Performance of a Photovoltaic Hybrid Membrane System. *Environmental Science & Technology*, **42**(12): 4563-4569.

Robinson R., Ho G. and Mathew K. (1992). Development of a reliable low-cost reverse osmosis desalination unit for remote communities. *Desalination*, **86**(1): 9-26.

Schäfer A. I., Broeckmann A. and Richards B.S. (2007). Renewable Energy Powered Membrane Technology. 1. Development and Characterization of a Photovoltaic Hybrid Membrane System. *Environmental Science & Technology*, **41**(3): 998-1003.

Thomson A. M. (2003). *Reverse-Osmosis Desalination of Seawater Powered by Photovoltaics Without Batteries*. PhD thesis, Loughborough University. UK.

Thomson M. and Infield D. (2005). Laboratory demonstration of a photovoltaic-powered seawater reverse-osmosis system without batteries. *Desalination*, **183**(1-3): 105-111.

Tzen E. (2006). Overview of the Desalination Technologies Powered by Renewable Energies. Proceedings of International Seminar: Desalination Systems Powered by Renewable Energy, Amman, Jordan, ADU-RES.

Tzen E., Theofilloyianakos D., Sigalas M. and Karamanis K. (2004). Design and development of a hybrid autonomous system for seawater desalination. *Desalination*, **166**: 267-274.

United Nations Department of Economic and Social Affairs (2009). The Millennium Development Goals Report. New York, United Nations.

Weiner D., Fisher D., Moses E.J., Katz B. and Meron G. (2001). Operation experience of a solar- and wind-powered desalination demonstration plant. *Desalination*, **137**(1-3): 7-13.

World Health Organisation (2008). *Guidelines for Drinking-water Quality*. Third Edition, WHO Press, Geneva.