Renewable energy powered membrane technology: Brackish water desalination system operated using real wind fluctuations and energy buffering

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A B S T R A C T

The performance of a wind powered membrane filtration system using a brackish water reverse osmosis (BW30) module and synthetic brackish (5500 mg/L NaCl) feed water was determined. When tested with real wind speed data (average wind speed 6.1 m/s; interval of 1 s) over one day of realistic fluctuation levels, the wind membrane system produced 0.78 m^3 of water with a final concentration of 191 mg/L NaCl at an average specific energy consumption (SEC) of 7.2 kWh/m^3. When a single bank of supercapacitor (SC) energy buffers were added to the system, performance increased to 0.93 m^3 of permeate produced and a final concentration of 173 mg/L NaCl at average SEC of 4.2 kWh/m^3. Tripling the size of the SC bank further increased productivity to 1.15 m^3 (47% increase) at a final concentration 172 mg/L NaCl and average SEC of 3.1 kWh/m^3 (57% reduction). The time spent within the safe operating window (SOW) per day, increased from 8 h12 m under the poorest operating conditions up to 19 h56 m with the triple SC bank. Importantly, the results indicate that steady state system performance at an average wind speed can be used as a very good indicator of the expected performance under fluctuating wind conditions. The results described can assist with the design of autonomous, decentralised, off grid renewable energy powered water treatment systems and help decide whether to include energy buffering components.

Keywords:
Brackish water
Desalination
Reverse osmosis
Wind energy
Energy storage

1. Introduction

Membrane based desalination is currently the most energy efficient desalination process, however the energy required takes the form of high value electricity [1]. With our population's ever increasing requirements for electricity and water, membranes have a significant role to play in meeting these demands [2]. Life cycle assessment studies have indicated that the environmental impact of such an energy intensive process is improved greatly if brackish groundwater, instead of seawater, is used due to the significantly lower osmotic pressures encountered [3,4]. Furthermore, in remote locations where there is no grid electricity available, it has been demonstrated that renewable energy powered membrane (RE membrane) systems powered by solar or wind energy can be a cost effective solution for the provision of clean drinking water from brackish water sources [5]. Subramani et al. [6] emphasise that photovoltaic (PV) powered reverse osmosis (RO) systems for remote areas are indeed a proven combination, given the maturity and minimal maintenance required with the technologies. Richards et al. [7] demonstrated that a PV powered RO system was able to reliably remove salts and inorganic contaminants over a wide range of pH and real operating conditions. While the embodied energy of water treatment solutions is known to be high [8] and the use of renewable energy (RE) does not reduce the direct energy consumption *per se*, it does enable the electricity provision to be achieved in an environmentally sustainable manner. One of the main challenges for the further penetration of such autonomous and decentralised RE membrane systems is the intermittent and fluctuating nature of the RE resource, which can potentially result in poorer permeate quality and lower productivity.

Directly coupled RE membrane systems which possess no energy storage components such as batteries can operate well when sufficient solar or wind power is being generated. Cloudy or calm periods, however, can result in unacceptable permeate quality being produced in certain systems [9]. While there are several reports of successful operation of directly coupled RE powered membrane

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systems under varying pressure and flow conditions [10 16], the transient operation of these systems under fluctuations is not well understood. Peter Varbanets et al. [17] have reported that intermittent operation of a membrane filtration system can result in increased average flux. However, this was for a low pressure ultrafiltration system operating and the fluctuations were on the order of days. The greater crossflow velocities encountered in turbulent flow regimes in the range of 2.5 10 bar have been shown to result in minimal concentration polarisation with nanofiltration [18].

Several experimental studies have examined the initial feasibility of a directly connected RE membrane system for desalination, but have resulted in limited analysis of performance data. A directly coupled wind powered membrane (wind membrane) system for brackish water (2750 and 5500 mg/L NaCl) desalination [19,20] was developed based on an earlier photovoltaic powered version [21,22]. The wind membrane system performance was investigated systematically during short term wind speed fluctuations and intermittency on system operation [19,20], using sinusoidal waves and square waves, respectively. An interesting result was that the system performed well over widely varying wind speed fluctuations, while periods of intermittency were found to be particularly detrimental to water quality and quantity. Periods of less than 1 min without power had a greater impact on the permeate quality, since the change in the measured salt concentration was greatest when the power to the system was removed [20]. Although fluctuations in the wind energy resource can range in time scale from seconds to months, it is important to note that the most frequent occurrence of turbulence is known to last for periods of around 1 min [23]. From a membrane science background, unsteady flows were have been known as a method to decrease concentration polarisation and fouling in pressure driven membranes, thus enhancing the system performance [24,25]. Thus, investigating and understanding wind membrane system performance at a high temporal resolution at times periods of one second or less is crucial for the future of the technology.

The result above also highlighted the potential for energy storage to improve system performance by buffering these very frequent short term periods of intermittency. Subsequently, supercapacitors were identified to be much better suited to wind membrane systems where energy buffering results in many repeated charge/discharge cycles of a few minutes in length throughout the day [26]. Unlike the more traditional electrical storage technology of lead acid batteries, supercapacitors (SC) may endure hundreds of thousands of cycles and are able to supply more instantaneous power [27]. Further advantages are the very high round trip efficiencies (84 98%) and typically long operating lifetimes of 8 12 years [27 30]. However, the self discharge loss of a SC is much higher than lead acid batteries, ranging from 0.5% to 40% over a 24 h period [27] compared to more like 2% per month for a lead acid battery [31]. As the fraction of energy lost increases greatly with time, this limits the overall period for which energy can be stored with a SC to a few minutes. The membrane system incorporating SC energy buffering was tested using power fluctuations and brackish feed water (5500 mg/L NaCl) [26]. Under intermittent operation (repeated off times of 30 s to 5 min within a 1 h period) the use of SC buffering resulted in a 40% increase in the average flux and a 15% lower permeate conductivity. Under fluctuating (sine wave) energy conditions, the results were even more impressive with the average flux and permeate quality increased by 85% and 40%, respectively, due to the increased power stability. Overall, it was observed that the supercapacitors were very effective at absorbing oscillations over a wide range (15 s to 20 min) and therefore further investigation was warranted to determine how a wind membrane system performs under real wind conditions, incorporating both periods of intermittency as well as rapid short term fluctuations. Soric et al. tested the performance of a photovoltaic powered RO system that included a 250 F supercapacitor for the desalination of feed water with a salinity ranging from 8 to 22 g/L [32], however the performance was not examined under high temporal resolution.

In system operation, three challenges relate to power variability: (i) frequent system shut down and start up due to power intermittency may result in damage to system components; (ii) fluctuations can result in the system spending a greater fraction of time in regions of poor performance; and; (iii) due to both of the previous factors, water production is highly variable and hence storage is required. With regard to storage options, there is a choice in such systems between storing water or storing energy. Perhaps the simplest option is to consider storing the permeate in a tank for a period of several days [11 16]. In terms of intermittency, this might assist with water provision in the longer term, however it does not address problems associated with frequent system shut down [19,20] or poorer permeate quality. With regard to fluctuations, possible potential damage to the RO membrane and pump motor [10,22] can result from the short term variability of the wind resource. The final option for energy storage is the hydraulic accumulator type that has been implemented in mechanical windmill powered membrane systems to reduce the variability of pressure and flowrate as well as provide a buffer for periods of low wind resource [33,34]. This suggests that mechanically based systems could exhibit good robustness [33], however the periods analysed have only been over periods of hours so far [35].

The safe operating window (SOW) of a RE membrane system was originally proposed by Feron [36] and more recently modelled by Pohl et al. [37]. Richards et al. have developed an experimental methodology to determine the SOW [38]. The two most promising operating strategies for a wind membrane system constant recovery and constant set point (the position that the back pressure valve on the concentrate stream is set to in order to restrict the flow and create the desired pressure) were evaluated under steady state (constant pressure and flow) conditions. As a balance between excellent performance and system robustness, constant set point was recommended [38], and further tests are now required to evaluate this operating strategy over a full day under high temporal resolution.

In this paper, the three main objectives were to,

(1) determine the effectiveness of the constant set point operating strategy using a 24 h segment of wind data (data interval of 1 s) that contains a variety of short term intermittency events and fluctuations;
(2) examine the potential for supercapacitors to enhance the performance of the wind membrane system when operated over the same full day period; and
(3) investigate the fraction of time that the system operates within the SOW as a function of (a) operating strategy and (b) the addition of SC energy buffering.

By smoothing out fluctuations and reducing the number of system shut downs due to intermittency, large improvements to the average flux and permeate quality may be possible due to the increasing average pressure and crossflow velocity, and hence reducing periods of high diffusion. Conducting such research using high resolution RE resource data is vital in the realisation of robust, directly coupled (batteryless) RE membrane systems for the provision of clean drinking water in remote areas.

2. Materials and methods

2.1. Wind speed data and simulated wind turbine output

Experiments using real wind speed data were conducted in order to evaluate the most effective system operating strategy for maximum wind membrane system performance over a 24 h period both with and without supercapacitor buffering. High resolution (4 Hz) wind speed data from a wind farm in Emden (Germany) [39] was used as the input to a wind turbine simulator. The data was corrected for the original hub height of 20 m to 8 m, which is more realistic for a small wind turbine, using the log law as given in Manwell [40]. After correcting for the lower hub height, the average wind speed was calculated over the entire 24 h period to be 6.1 m/s. This period was chosen due its challenging nature: periods of high wind speed (0:00 05:00), followed by periods of intermittent calms (05:00 17:00) and then a typical average wind speed value (17:00 24:00).

The wind turbine simulator comprised of the hub of a small wind turbine (FuturEnergy, rated power 1 kW at 12.5 m/s, 48 V_{DC}) connected to a geared induction motor (Nord, SK51E 160M/4, 10:1 speed reduction, range 300 1000 rpm) that was controlled by a vector frequency inverter (Nord, SK700E 112 340 A) as described previously [19]. A LabVIEW interface con trolled the operation of the simulator and supplied wind speed data to the frequency inverter, which in turn applied the correct torque to the wind turbine which delivered the power to the wind membrane system. This setup permitted the system to be subjected to exactly the same 24 h of wind such that different operating strategies and system configurations could be com pared. The wind turbine simulator is shown in the top of the schematic in Fig. 1.

2.2. Supercapacitor energy buffering

Storage of electrical energy in supercapacitors (SC) was inves tigated to determine effectiveness in improving system perfor mance with real wind speed fluctuations. The size and connections between the modular SC banks (15 V_{DC} Maxwell Boostcap 58 F) were chosen as described in Park et al. [26] in order to achieve a maximum output voltage of 60 V_{DC} and a storage capacity of either 1:30 min or 4:00 min storage time for a single (SC $\times$ 1) or triple (SC $\times$ 3) bank, respectively.

2.3. Wind membrane system

The wind powered brackish water RO membrane system used has been extensively described in previous publications [19,38]. The system is based on a progressive cavity pump (Mono Sunsub SM022) driven by a three phase 300 W DC motor, which sucks water through a polypropylene micro filter (SupaGard 1 μm) at 0.3 bar before passing at up to 600 L/h through the RO membrane at up to 12 bar. Many sensors were implemented to monitor all operating parameters under tran sient operation:

- pressure: Bürkert 8323 for P1 P3 (feed, permeate, concentrate) with 4 20 mA output
- flow rate: Omega FTB9510 for F2 (permeate); Omega FTB9512 for F1 (feed) and F3 (concentrate); all equipped with Omega FLSC 62A signal conditioners for 4 20 mA output
- electrical conductivity: Georg Fischer Signet 3 2821 for C2 (permeate); Georg Fischer Signet 3 2822 for C1 (feed) and C3 (concentrate); all equipped with Georg Fischer 2850 transmit ters with 4 20 mA output
- temperature in feed tank: Omega KTSS thermocouple
- pH in feed tank: Georg Fischer Signet 2717 with 2720 pre amplifier and 8750 transmitter with 4 20 mA output
- current: Omega DRF IDC for I1 I3, located before and after SC bank, as well as after the motor controller
- voltage: Omega DRF VDC for V1 V2, located before and after the motor controller.

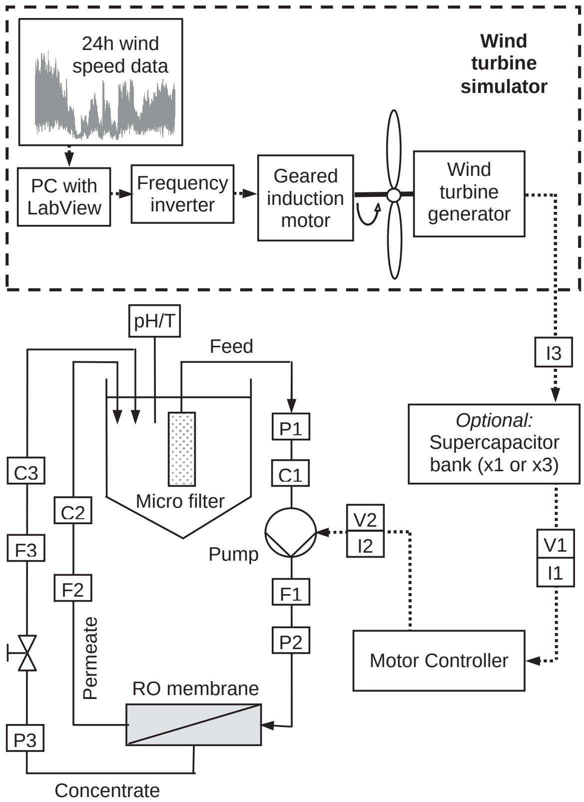

Fig. 1. Schematic diagram of the wind-membrane system. The high-resolution 24 h wind speed data is fed into the wind-turbine simulator and the output is connected to the supercapacitor bank (optional) and a motor controller to drive the pump motor. The feed water is sucked through a micro-filter and pumped through the RO membrane. The sensors connected to the system are: current (I1–13), voltage (V1–V2), pressure (P1–P3), flow (F1–F3), conductivity (C1–C3), pH and temperature (pH/T).

Note that all sensors have a response time of 1 s or less, except the pH electrode (5 s). The location of all sensors are shown in Fig. 1, and the outputs recorded using a datalogger (dataTaker DT800, rate 1 Hz) and displayed instantaneously on a computer running LabVIEW. Throughout all experiments, the feed water temperature was maintained at 13.5 ± 1.0 °C as discussed in [19] and the pH observed to remain within 7.1 ± 0.1. A constant feed concentration throughout the experiments was achieved by recy cling both permeate and concentrate flows back into the feed tank, as shown in Fig. 1.

2.4. Water quality

The feed water was prepared using deionised water and NaCl (Fisher Scientific, general purpose grade) to a salinity (NaCl concentration) of 5500 mg/L. The NaCl concentration (mg/L) was calculated from electrical conductivity (*EC*, S/cm) using a conver sion factor $k = 0.625$, determined by calibration with NaCl dis solved in chilled deionized water at 13 °C. The osmotic pressure of the 5500 mg/L NaCl solution was calculated to be 4.36 bar.

2.5. Membrane choice

The brackish water RO membrane chosen for this study was a Dow Filmtec BW30 4040 [41]. This 4 in. element exhibited 28% recovery and 97.0% retention of the 5500 mg/L NaCl feed water when the wind membrane system was operated with 240 W power, transmembrane pressure (TMP) 10 bar, and feed flowrate 300 L/h [38]. Membrane specific parameters TMP, flux (J), recovery (Y), retention (R) and SEC were all determined as previously defined [19,21,22]. Note, that where average values of parameters (namely flux, recovery, retention, and SEC) are reported, these averages were taken only during for periods where flux > 0.0 L/m^2 h in order not to distort the values during the off periods.

2.6. Operating strategies and system configuration

In order to have a baseline for performance comparison under fluctuating energy conditions, an identical membrane system "set point" was determined at the start of each experiment. This was achieved by setting the power available to the pump motor (240 W) and adjusting the regulating valve on the concentrate stream to realise a TMP of 10 bar at a feed flowrate of 300 L/h under constant power operation [19,38]. The experiments to evaluate the system operation strategy and effectiveness of super capacitor energy buffering were undertaken using 24 h of real wind data and performed with the BW30 membrane module and a feed water concentration of 5500 mg/L NaCl with the following configurations:

(i) 7 bar set point to illustrate a non ideal system operating strategy that is just within the lower bounds of the SOW as demonstrated in [38];
(ii) 10 bar set point the known optimised set point performance under steady state conditions from [38];
(iii) 10 bar set point with a single bank of supercapacitors; and
(iv) 10 bar set point with a triple bank of supercapacitors.

3. Results and discussion

The system performance was examined using a 24 h segment of real wind speed data in order to determine the:

(i) impact of a full day containing real wind fluctuations and intermittency;
(ii) actual productivity of the system and allow comparison with the steady state results;
(iii) effectiveness of two different size supercapacitor banks for improving the overall system performance; and
(iv) fraction of time spent within the SOW.

Thus, the system performance was evaluated both instantaneously as well as determining the cumulative quantity and quality of water produced over the day (typically with 86,400 points in each data set). The wind membrane system performance has been evaluated over a wide range of wind speeds, with several different membranes and with a wide range of NaCl concentrations. Therefore, it is anticipated that these results can then be scaled to predict the productivity of a wind membrane system under longer term operation in different locations, taking into account the quality of both water and wind resources.

3.1. Instantaneous system performance without energy storage

Fig. 2 shows the operating performance of the wind membrane system in terms of pump motor power, flux and permeate NaCl concentration for each of the system setups over the full 24 h period. The average wind speed over the 24 h period was 6.1 m/s with a very wide range from 0 to 20 m/s (Fig. 2A). Based on the average wind speed and hub height of 8 m, this would be categorised as a class 4 5 wind resource, which would generally be considered suitable for wind energy production [40]. The wind resource exhibited both fluctuations and intermittency as are typical of any windy day, where the latter was defined to be any period of time where a system shut down occurs due to insufficient power. This occurred at wind speeds ≤ 3 m/s where the pump motor power decreased below 40 W, consistent with previous experiments using simulated wind speed fluctuations [19]. The intermittent periods can be seen in Fig. 2B, where the pump motor power drops to 0 W several times between the times of 7:00 and 14:10.

The TMP of the two different system configurations not containing energy storage are plotted in Fig. 2C. The TMP for the 7 bar set point sits significantly lower than the 10 bar set point. Relatively poor performance with the 7 bar set point was observed compared to 10 bar due to the low TMP, which was often not enough to overcome the osmotic pressure of the feed water (4.4 bar). This resulted in a maximum flux (Fig. 2E) that was reduced by a factor of two (~ 8 L/m^2 h compared to ~ 16 L/m^2 h). This reduced pressure caused significantly increased permeate NaCl concentration (Fig. 2G), which exceeded the target value of 1000 mg/L for the 7 bar set point when the wind speed dropped below 4 m/s. In contrast, for the 10 bar set point, the target value was only exceeded for very short periods of time when the system was restarted after a period of intermittency. This confirms previous observations [20]. It should be noted that also seem to be periods where the TMP has dropped below the required osmotic pressure but there is still flux (from Figs. 2D and F). These are due to isolated large fluctuations in TMP, which, however, are momentary events that do not last long enough for the system to fully respond to and thus observe a decline in flux.

An important point that has not been addressed previously is the potential for short term pressure fluctuations to damage the membrane module. The membrane manufacturer states that a 'soft start' at rate of feed pressure increase of less than 0.7 bar/s should be used to prevent possible damage caused by excessive pressure or flowrates and hydraulic shock [41]. Analysis of the rate of change of trans membrane pressure (ΔTMP) from the 24 h experiments showed that with a 10 bar set point, the maximum ΔTMP increased to 0.7 bar/s (or 11.1 bar/min over any 60 s window). Therefore, even with extreme wind speed fluctuations, it can be concluded that the maximum rate of pressure change was within the allowable region for a 'soft start' and hence is not a cause for concern during long term operation.

3.2. Instantaneous system performance with SC energy buffering

At this point is poignant to remember that, by definition, adding an energy storage component to a system cannot make it more efficient; however, the benefit of the SCs is exhibited by reducing the magnitude and frequency of fluctuations experienced by the wind membrane system. The addition of the triple and single SC banks buffered the fluctuating power output from the wind turbine and provided relatively constant power for the first five hours while the average wind speed was > 9 m/s (Fig. 2B). Once the wind speed dropped below this value the state of charge of the SC bank reduced to the threshold for usable energy and the wind speed fluctuations started to impact on the performance. This is consistent with the previously published experimental results on the SC performance that were conducted using systematic sine wave fluctuations [26]. The impact of this is then clear on the TMP (Fig. 2D), where the first five hour period of operation is very constant due to the buffering of power fluctuations and the provision of increased power quality to the pump motor. For the remainder of the day (5:00 to 24:00) it can be seen that there are less peaks in the TMP values compared to the 10 bar set point values (Fig. 2C). The flux values are notably higher (Fig. 2F) than for those with no energy storage, while the improvement resulting from tripling the size of the SC bank also

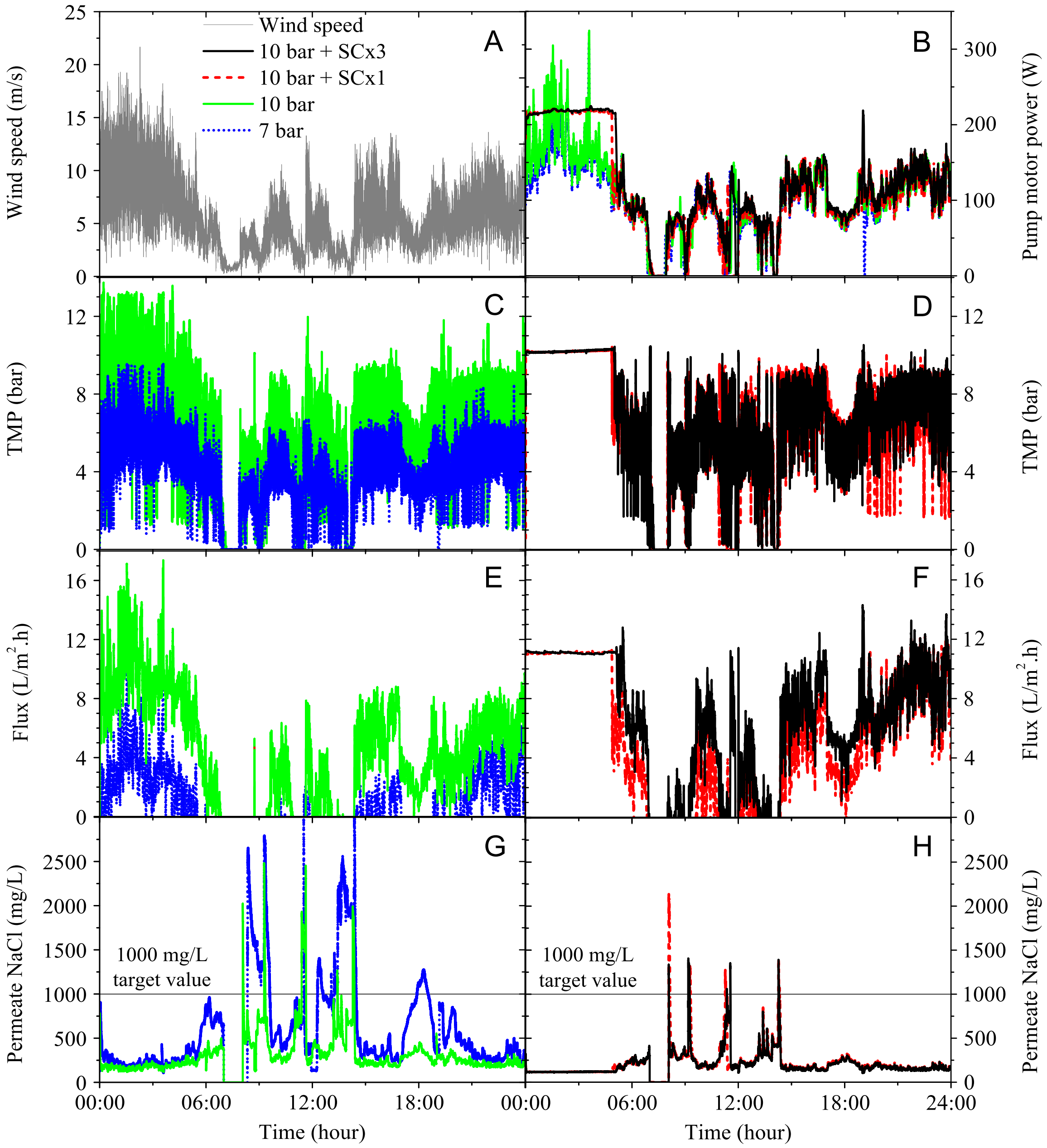

Fig. 2. Performance of wind membrane system over 24 h showing the: (A) high-resolution wind speed data obtained from the Emden wind farm; (B) power consumption of the pump motor; as well as TMP, flux, permeate NaCl concentration both with (D, F, H) and without (C, E, G) supercapacitor storage (BW30, 5500 mg/L NaCl).

becomes apparent. With either of the SC buffers present, the system is only producing water that does not meet the target value of 1000 mg/L for 12 min of the day, compared to 52 min and 186 min for the 10 bar and 7 bar set points. The addition of SC energy buffering resulted in a further reduction of the maximum ΔTMP values to 0.5 bar/s (or 10 bar/min within any 60 s window).

3.3. Cumulative and average system performance

Fig. 3 illustrates the cumulative potable water production and permeate NaCl concentration of the wind membrane system over the 24 h period for the four different experimental setups. These are the values if the permeate is all going into a potable water storage tank and no water is being withdrawn from the tank during the entire period. From 00:00 to 05:00, the average wind speed was > 7 m/s (Fig. 2A) and there was a high rate of water production (Fig. 3A). The permeate NaCl concentration (Fig. 3B) reduced from the initially high value produced when the membrane system was turned on. Once the wind speed dropped below 7 m/s, the rate of water production was lower and the concentration increased gradually over the rest of the day. All four of the system setups produced low permeate concentrations of < 300 mg/L NaCl at the end of the day and at no point did the average concentration go above the target value of 1000 mg/L, even during the periods of intermittency. This highlights the importance of having an adequate average wind speed to produce sufficient permeate to increase productivity and maintain adequate permeate quality. Which wind speeds meet this criteria for this feed water quality will be discussed later.

The average performance values and cumulative potable water production over the 24 h period are summarised in Table 1 for further comparison. The impact of changing the set point from

7 to 10 bar is shown particularly in the permeate production which increased from 0.23 to 0.79 m^3 and the average SEC reduced from a very high 18.5 kWh/m^3 at 7 bar to 7.2 kWh/m^3 at 10 bar set point operation. Once the SC banks are added, the advantages become even more apparent. Specifically, the SC $\times$ 1 bank resulted in an 18% increase in permeate production (0.93 m^3) and a reduction in the average SEC from 7.2 to 4.2 kWh/m^3, as shown in Table 1. Upon tripling the size of the SC bank (SC $\times$ 3), only a slight decrease in SEC and average NaCl conductivity was achieved, however permeate production still increased by a further 24% to 1.15 m^3. The average values of recovery and retention yield trends in the expected direction, increasing from 7.6% and 90.3%, respectively, in the 7 bar configuration up to 26.7% and 96.3%, respectively, in the SC $\times$ 3 configuration.

All of these results highlight the inherent characteristics of supercapacitors; that they provide an excellent source of power but a poor source of energy, even at increased capacity. Previous work estimated that the expected lifetime of the supercapacitor bank operating under sine wave fluctuations is about 8.8 years for the 4 $\times$ 1 bank and 12.2 years for the 4 $\times$ 3 bank, given the reduced number of load cycles endured by the larger supercapacitor bank [26]. This compares to lifetimes of about five years for batteries for a well designed off grid RE power system undergoing regular maintenance.

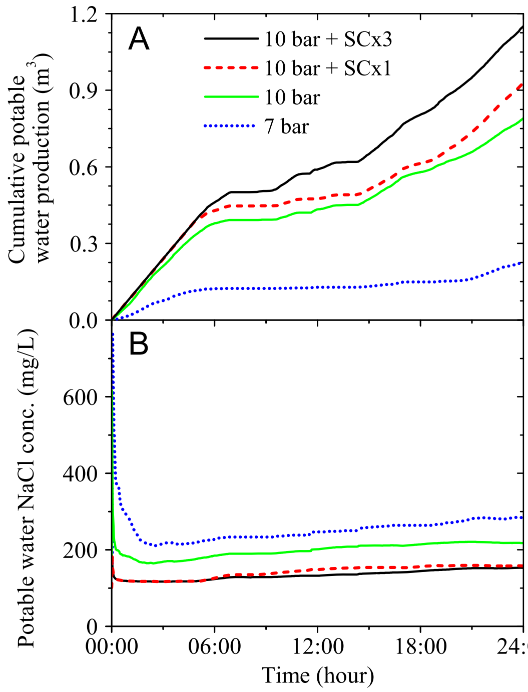

Fig. 3. Cumulative performance of wind-membrane system over 24 h period in terms of (A) potable water produced and (B) potable water NaCl concentration (BW30, 5500 mg/L NaCl).

3.4. *Time spent within the SOW*

Richards et al. [38] have demonstrated that the SOW for a RE membrane system, theoretically developed by Feron [36] and Pohl [37], can be experimentally realised for a range of membranes and feed water concentrations. The results below, take this work one step further by overlaying the operating point of the

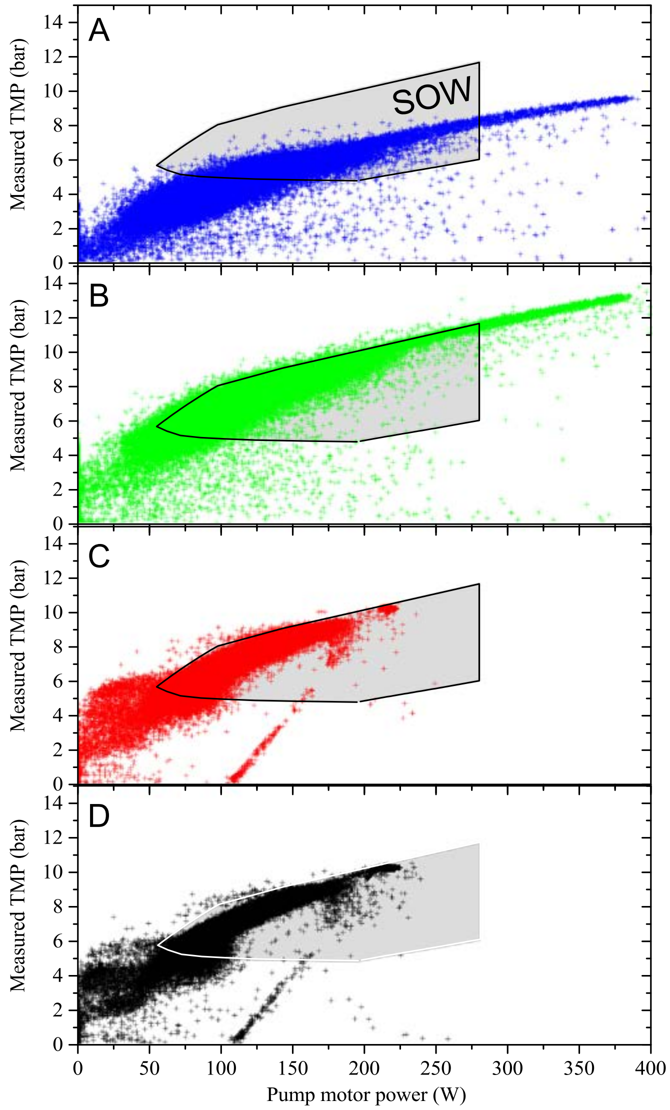

Fig. 4. Performance at each second of the 24 h period plotted on top of the SOW for four different system configurations: (A) 7 bar set point; (B) 10 bar set point; and then the 10 bar set point with the addition of either a (C) single or (D) triple bank of supercapacitors. The SOW was determined from steady-state values for the wind-membrane BW30 membrane and 5500 mg/L feed water [38].

Table 1
Average and cumulative performance parameters of wind-membrane system over 24 h period at set-points of 7 bar and 10 bar, and then at 10 bar with the addition of single (SC $\times$ 1) and triple (SC $\times$ 3) supercapacitor energy buffers.

System configuration	Avg. pump motor power (W)	Avg TMP (bar)	Max. ΔTMP (bar/min)	Avg. flux† (L/m^2 h)	Avg. recovery† (%)	Avg. retention† (%)	Avg. permeate NaCl † (mg/L)	Avg. SEC† (kWh/m^3)	Cumulative potable water production (m^3)	Time within SOW (hh:mm)
7 bar	103	4.1	7.3	3.9	7.6	90.3	279	18.5	0.23	08:12
10 bar	106	6.3	11.1	6.2	18.4	95.0	191	7.2	0.78	16:47
10 bar + SC $\times$ 1	117	6.6	9.9	6.1	21.6	96.2	173	4.2	0.93	19:34
10 bar + SC $\times$ 3	121	6.9	10.2	9.2	26.7	96.3	172	3.1	1.15	19:56

† The values for these parameters were only taken for periods where flux > 0.0 L/m^2 h.

wind membrane system at every second throughout the day (86,400 data points) on the SOW, plotted in terms of pump motor power and TMP (Fig. 4).

It can be seen that when operating the wind membrane system at the 7 bar set point (Fig. 4A), during many times of the day the TMP is too low to overcome the osmotic pressure of the feed water. Also, for a total of nearly 11 min out of the total 24 h period the system is providing the pump motor with greater than the 300 W it is rated for. Although this is for a relatively small fraction of time, it is still potentially damaging if long term operation was conducted in this mode. Overall, the wind membrane system spent 8:12 h within the SOW. This figure more than doubled to 16:47 h when changing to the 10 bar operating set point as shown in Fig. 4B. The time spent at powers greater than 300 W increased to 22 min, due to the higher set point allowing greater fluctuation in parameters (such as TMP). It should also be noted that the 24 h results closely follow the upper limit of the TMP versus motor power relationship, giving further confidence that the earlier results establishing the experimental SOW framework [38] indeed are still relevant for the wind membrane system when tested under extremely variable conditions.

When adding SC buffers to the system (Figs. 4C and D) two immediate changes are noticed in the SOW performance. The buffering action of both the single (SC × 1) and triple (SC × 3) banks, firstly, smooth out the maximum power seen by the pump motor. Now the wind membrane system does not spend *any* time operating at greater than 300 W. Secondly, the reduced scatter in the data clearly indicates that the system is operating within a tighter regime, again due to the buffering action of the SCs lifting up the performance during these troughs or valleys in the wind speed spectrum. The pump motor power is also somewhat reduced as the SC's are not 100% efficient and that for every new component included in the system there is a balance between losses and benefits. Overall, the wind membrane system spends 19:34 h and 19:56 h within the SOW when implementing the SC × 1 and SC × 3 buffers. This small increase is in line with some of the average values reported in Table 1, with the TMP only increasing from 6.6 to 6.9 bar. It should be note that there is no additional power available for the system, what is available is just using it more effectively. Evidence of this can be seen in Table 1 with the significantly improved average SEC when tripling the size of the SC buffers: decreasing from 4.2 to 3.1 kWh/m^3 and the potable water production still increasing from 0.93 to 1.15 m^3. Only the addition of long term energy storage (high capacity batteries or a hydraulic accumulator) could achieve significantly better performance in the low range (0 5 bar and 0 75 W), noting that these technologies will intro duce their own short comings and inefficiencies as previously discussed.

3.5. *Prediction of long term system performance*

The final important result can be seen when the real wind speed results from this work are compared to the steady state system performance values determined previously [38]. This is demonstrated in Fig. 5, where the average values from Table 1 for the 10 bar set point (plotted with ● symbol) lie very closely to the relationship for the BW30 module and 5500 mg/L feed water (also determined using 10 bar set point). The permeate production for the 24 h average (Fig. 5A) is extremely close to the steady state values, while the NaCl conductivity lies slightly lower (Fig. 5B). The greatest difference is evidenced in the SEC (Fig. 5C) where the 24 h average value of 7.2 kWh/m^3 is significantly greater than steady state value of 4.0 kWh/m^3 at 6.1 m/s. This difference is attributed to the power losses that occur during the quite extreme fluctuations in the wind resource. The difference is evident in SEC since the pump motor is no longer operating near its maximum efficiency at 240 W (the power at which the steady state experiments were performed at). Instead, operation at significantly higher and lower powers are encoun tered for the 24 h data (as indicated by the spread of data in Fig. 4B) both leading to a reduced pump motor efficiency [19]. As shown in Fig. 5C, the average SEC values closely match the steady state operation SEC value once the SC buffers are added to the system. Overall, the above results highlight that the steady state performance can be used to predict the productivity according to the average wind speed. For example, simply measuring the wind membrane system performance with a con stant wind speed of 6.1 m/s for 20 min (allowing time for steady state to be reached) is enough to get a relatively good prediction for a site with a known average RE resource. The cost of adding SC storage to a RE membrane system has been discussed by Park et al. [26], indicating that, overall, a 13 26% reduction in the cost of clean drinking water produced can be achieved. Therefore, based on the preliminary studies undertaken here, it is anticipated that the cost of water produced can be cheaper than the provision surface water via water tankers or vendors in remote sub Saharan African regions (typically in the range of US $5 10/m^3) [42].

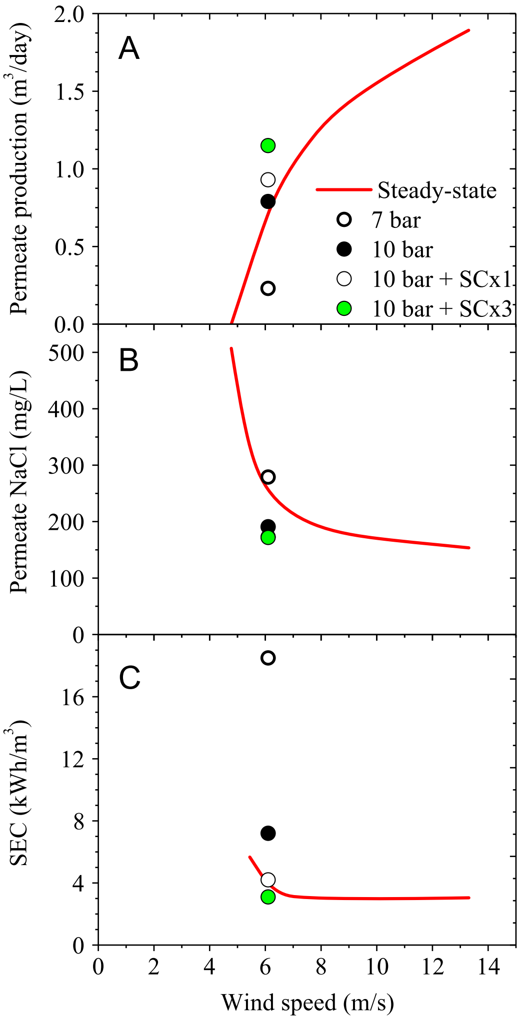

Fig. 5. Performance of wind-membrane system under steady-state conditions (solid curve – data taken from [38]) compared to the different system configurations explored in this paper at the average wind speed of 6.1 m/s and results shown for (A) permeate production, (B) permeate NaCl concentration, and (C) SEC. The most relevant comparison is the 10 bar set-point data (●).

4. Conclusions

A wind membrane system was tested over a 24 h period using real wind speed data (average wind speed 6.1 m/s) from a wind farm in Germany. When operated with a 10 bar set point and 4 in. BW30 membrane, the wind membrane system produced nearly 800 L of clean drinking of water with a final concentration of 191 mg/L NaCl at an average SEC of 7.2 kWh/m^3 from 5500 mg/L feed concentration. When a single bank of supercapacitors (SC $\times$ 1) was added to the system, the permeate production increased by 19%, while the final NaCl concentration and average SEC were 10% and 42% lower, respectively. Tripling the size of the supercapacitor bank (SC $\times$ 3) further increased productivity to 1.15 m^3 (a 47% increase compared to no energy buffering) at a final permeate concentration of 172 mg/L NaCl and average SEC of 3.1 kWh/m^3 (47% reduction). The average recovery and retention in the latter system configuration were 26.7% and 96.3%, respectively. The time the system spent within the SOW increased greatly from only 8:12 h with a 7 bar set point to 19:56 h with the SC $\times$ 3 configura tion. A comparison between the steady state and 24 h fluctuations results shows that the system performance can be reliably pre dicted assuming constant operation at the average wind speed. Thus, the approach described here can assist with the design and evaluation of the performance of a wide range of autonomous, decentralised, off grid renewable energy powered water treat ment systems.

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References

[1] M.A. Shannon, P.W. Bohn, M. Elimelech, J.G. Georgiadis, B.J. Marinas, A. M. Mayes, Science and technology for water purification in the coming decades, Nature 452 (2008) 301–310.
[2] J.M. Wellington, A.Y. Ku, Opportunities for membranes in sustainable energy, J. Membr. Sci. 373 (2011) 1–4.
[3] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: water sources, technology, and today's challenges, Water Res. 43 (2009) 2317–2348.
[4] I. Munõz, A.R. Fernández-Alba, Reducing the environmental impacts of reverse osmosis desalination by using brackish groundwater resources, Water Res. 42 (2011) 801–811.
[5] J. Bundschuh, M. Litter, V.S.T. Ciminelli, M.E. Morgada, L. Cornejo, S.G. Hoyos, J. Hoinkis, M.T. Alarcón-Herrera, M.A. Armienta, P. Bhattacharya, Emerging mitigation needs and sustainable options for solving the arsenic problems of rural and isolated urban areas in Latin America – a critical analysis, Water Res. 44 (2010) 5828–5845.
[6] A. Subramani, M. Badruzzaman, J. Oppenheimer, J.G. Jacangelo, Energy minimization strategies and renewable energy utilization for desalination: a review, Water Res. 45 (2011) 1907–1920.
[7] L.A. Richards, B.S. Richards, A.I. Schäfer, Renewable energy powered membrane technology: salt and inorganic contaminant removal by nanofiltration/ reverse osmosis, J. Membr. Sci. 369 (2011) 188–195.
[8] W. Mo, Q. Zhang, J.R. Mihelcic, D.R. Hokanson, Embodied energy comparison of surface water and groundwater supply options, Water Res. 45 (2011) 5577–5586.
[9] M. Thomson, D. Infield, Laboratory demonstration of a photovoltaic-powered seawater reverse-osmosis system without batteries, Desalination 183 (2005) 105–111.
[10] J.A. Carta, J. Gonzalez, V. Subiela, Operational analysis of an innovative wind powered reverse osmosis system installed in the Canary Islands, Solar Energy 75 (2003) 153–168.
[11] I. de la Nuez Pestana, F. Javier Garcia Latorre, C. Argudo Espinoza, A. Gomez Gotor, Optimization of RO desalination systems powered by renewable energies. Part I: Wind energy, Desalination 160 (2004) 293–299.
[12] W. Gocht, A. Sommerfeld, R. Rautenbach, T. Melin, L. Eilers, A. Neskakis, D. Herold, V. Horstmann, M. Kabariti, A. Muhaidat, Decentralized desalination of brackish water by a directly coupled reverse-osmosis-photovoltaic-system – a pilot plant study in Jordan, Renew. Energy 14 (1998) 287–292.
[13] S.G.J. Heijman, E. Rabinovitch, F. Bos, N. Olthof, J.C. van Dijk, Sustainable seawater desalination: stand-alone small scale windmill and reverse osmosis system, Desalination 248 (2009) 114–117.
[14] E.R. Lising, R. Alward, Unsteady state operation of a reverse-osmosis desalination unit, Desalination 11 (1972) 261–268.
[15] M.S. Miranda, D. Infield, A wind-powered seawater reverse-osmosis system without batteries, Desalination 153 (2003) 9–16.
[16] F. Moreno, A. Pinilla, Preliminary experimental study of a small reverse osmosis wind-powered desalination plant, Desalination 171 (2004) 257–265.
[17] M. Peter-Varbanets, W. Gujer, W. Pronk, Decentralized systems for potable water and the potential of membrane technology, Water Res. 46 (2012) 3272–3282.
[18] S. Lee, C.-H. Lee, Effect of operating conditions on $CaSO_4$ scale formation mechanism in nanofiltration for water softening, Water Res. 34 (2000) 3854–3866.
[19] G.L. Park, A.I. Schäfer, B.S. Richards, Renewable energy powered membrane technology: the effect of wind speed fluctuations on the performance of a wind-powered membrane system for brackish water desalination, J. Membr. Sci. 370 (2011) 34–44.
[20] G.L. Park, A.I. Schäfer, B.S. Richards, The effect of intermittent operation on a wind-powered membrane system for brackish water desalination, Water Sci. Technol. 65 (2012) 867–874.
[21] A.I. Schäfer, A. Broeckmann, B.S. Richards, Renewable energy powered membrane technology. 1. Development and characterization of a photovoltaic hybrid membrane system, Environ. Sci. Technol. 41 (2007) 998–1003.
[22] B.S. Richards, D.P.S. Capão, A.I. Schäfer, Renewable energy powered membrane technology. 2. The effect of energy fluctuations on performance of a photovoltaic hybrid membrane system, Environ. Sci. Technol. 42 (2008) 4563–4569.
[23] I. Van der Hoven, Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour, J. Meteorol. 14 (1957) 160–164.
[24] V.G.J. Rodgers, R.E. Sparks, Effect of transmembrane pressure pulsing on concentration polarization, J. Membr. Sci. 68 (1992) 149–168.
[25] H.B. Winzeler, G. Belfort, Enhanced performance for pressure-driven membrane processes: the argument for fluid instabilities, J. Membr. Sci. 80 (1993) 35–47.
[26] G.L. Park, A.I. Schäfer, B.S. Richards, Renewable energy powered membrane technology: supercapacitors for buffering resource fluctuations in a wind-powered membrane system, Renew. Energy (2013) 126–135.
[27] M. Beaudin, H. Zareipour, A. Schellenberglabe, W. Rosehart, Energy storage for mitigating the variability of renewable electricity sources: an updated review, Energy Sustain. Dev. 14 (2010) 302–314.
[28] B. Willer, Investigation on Storage Technologies for Intermittent Renewable Energies: Evaluation and recommended R&D strategy. Supercaps Report, INVESTIRE NETWORK, Deliverable No. 5 (ENK5-CT-2000-20336), 2003.
[29] Z. Yun, Z. Jiancheng, L. Gengyin, L. Aiguo, Research on energy efficiency of supercapacitor energy storage system, in: Proceedings of International Conference on Power System Technology, IEEE, 2006, pp. 1–4.
[30] J.P. Barton, D.G. Infield, Energy storage and its use with intermittent renewable energy, IEEE Trans. Energy Convers. 19 (2004) 441–448.
[31] I. Hadjipaschalis, A. Poullikkas, V. Efthimiou, Overview of current and future energy storage technologies for electric power applications, Renew. Sustain. Energy Rev. 13 (2009) 1513–1522.
[32] A. Soric, R. Cesaro, P. Perez, E. Guiol, P. Moulin, Eausmose project desalination by reverse osmosis and batteryless solar energy: design for a 1 m^3 per day delivery, Desalination 301 (2012) 67–74.
[33] R. Robinson, G. Ho, K. Mathew, Development of a reliable low-cost reverse osmosis desalination unit for remote communities, Desalination 86 (1992) 9–26.
[34] C.C.K. Liu, P. Jae-Woo, R. Migita, Q. Gang, Experiments of a prototype wind-driven reverse osmosis desalination system with feedback control, Desalination 150 (2002) 277–287.
[35] C.C.K. Liu, Wind-Powered Reverse Osmosis Water Desalination for Pacific Islands and Remote Coastal Communities, Desalination and Water Purification Research and Development Program Report No.b 128, US Department of the Interior (Bureau of Reclamation), 2009.
[36] P. Feron, The use of windpower in autonomous reverse osmosis seawater desalination, Wind Eng. 9 (1985) 180–199.

[37] R. Pohl, M. Kaltschmitt, R. Holländer, Investigation of different operational strategies for the variable operation of a simple reverse osmosis unit, Desalination 249 (2009) 1280–1287.
[38] B.S. Richards, G.L. Park, T. Pietzsch, A.I. Schäfer, Renewable energy powered membrane technology: safe operating window of a wind-powered brackish water desalination system, J. Membr. Sci. (2014), http://dx.doi.org/10.1016/j.memsci.2014.05.053, accepted for publication..
[39] J. Peinke, S. Barth, F. Böttcher, D. Heinemann, B. Lange, Turbulence, a challenging problem for wind energy, Phys. A: Stat. Mech. Appl. 338 (2004) 187–193.
[40] J.F. Manwell, J.G. McGowan and A.L. Rogers and the published location is Chichester, U.K.
[41] Dow, Water & Process Solutions – Resources, 2013.
[42] A.I. Schäfer, H.A. Cope, B.S. Richards, G. Hughes, Renewable energy powered membrane technology: a leapfrog approach to rural water supply technologies in developing countries? Renew. Sustain. Energy Rev. (2014) (submitted for publication).