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Renewable energy powered membrane technology: Supercapacitors for buffering resource fluctuations in a wind-powered membrane system for brackish water desalination

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Abstract

The potential for supercapacitors to expand the safe operating window of a wind-powered reverse osmosis membrane (wind-membrane) system by buffering short term wind fluctuations and intermittency was investigated. Experiments were carried out using synthetic brackish water (5500 mg/L NaCl) with three sizes of supercapacitor bank to determine the effect of increasing the short term energy storage capacity. The wind speed ranged from 4 – 14 m/s for both intermittency and fluctuation experiments, with periods of no-power of 0.5 – 5 min and 15 s – 20 min cycles, respectively. When the wind-membrane system was powered by the supercapacitors, wind speeds of >7 m/s were required for the supercapacitor bank state of charge (SOC) to increase, otherwise they discharged gradually to a threshold value dictated by the control electronics. While the SOC of the supercapacitors was above this threshold value, the operation of the wind-membrane system was as under steady-state conditions, thereby achieving independence of the wind speed fluctuations or intermittency. This resulted in an 85 % increase in the average flux and 40 % increase in permeate quality under fluctuations when compared to the system performance without supercapacitors. It is concluded that supercapacitors are an effective method of buffering short term wind speed fluctuations to provide steady-state performance and improve the productivity of renewable energy membrane systems.

Keywords: Supercapacitor; Intermittent operation; Wind energy; Reverse osmosis; Renewable energy

1. Introduction

There is a growing awareness of the inextricable link between water and energy, and the capacity for water provision technologies such as membranes to contribute to a more sustainable future [1]. In particular, renewable energy-powered membrane (RE-membrane) systems show great potential for removing salts [2] as well as microbial and chemical pollutants from groundwater in remote or off-grid locations [3, 4]. The main challenge with the implementation of these systems is the intermittency and fluctuations of the renewable energy (RE) resource. Directly-coupled systems without energy storage can have higher efficiency, but the variable and unpredictable nature of the RE resource can cause lower permeate quality and productivity resulting in the water demand not being met. While potable water can be stored for several days to overcome longer term periods of intermittency, past research has hinted at the potential of short term energy storage to buffer fluctuations and improve the average quality and quantity of the permeate [2, 5].

The distribution of energy content of wind turbulence is described by the Van der Hoven wind speed spectrum [6]. This shows a clear distinction between long term wind speed fluctuations caused by the passage of weather systems (synoptic variations) or time of day (diurnal) and shorter fluctuations caused by turbulence [6, 7]. There is a ‘spectral gap’ observed in the region between two hours and ten minutes where there is little energy between the synoptic-diurnal region and the turbulent region. This gap is attributed to the lack of any physical process that could cause wind speed fluctuations in that range of frequency [6]. The turbulent region occurs over time periods ranging from 5 s up to 10 min with a peak at 1 min. Turbulence causes fluctuations in power that have a negative effect on the quality of power delivered by a wind turbine, therefore these short term fluctuations are considered to be the most significant for the implementation of energy storage in wind energy systems [8].

The most common energy storage technology implemented in off-grid RE-membrane systems is lead-acid batteries [9-13], which are both relatively cheap and readily available [14]. Lead-acid batteries are ideal for long-term energy storage due to their high energy density, efficiency (85 – 90 %) and low self discharge rate of 2 % of rated capacity per month [15]. The main disadvantage associated with lead-acid batteries is their lifespan, characterised by low cycle lifetime (500 – 1800 cycles) and reduced life caused by deep discharging or operation at high temperatures [14, 15]. When connected to RE systems that supply a daily load, typical lifetimes are between 3 – 5 years [16] and in extreme circumstances only 2 years [17]. To reduce the cost and maintenance requirements associated with batteries, several RE-membrane systems have overcome the challenge of longer term fluctuations and intermittency by storing the permeate water in a tank [18-23]. However, this does not address the effects of reduced power quality and frequent system shut-down [2, 5], or potential damage to the pump motor and RO membrane [10, 22] caused by the short term variability of the RE resource.

Supercapacitors are energy storage devices that operate by building up positive and negative charge within an electrolytic solution, as opposed to the chemical reaction used in batteries [24]. They are also referred to as ultracapacitors or electrochemical double layer capacitors and are one of the most promising devices for buffering short term fluctuations from RE sources [25, 26]. While high power batteries such as lithium-ion are more appropriate for longer periods of time (10 – 15 min), supercapacitors are much better suited to situations where they are charged/discharged over periods of 1 – 2 min [27]. The charge/discharge process of supercapacitors is highly reversible, allowing them to undergo hundreds of thousands of cycles at a much higher rate than batteries [14]. Supercapacitors have a high round-trip efficiency between 84 – 98 %, and typical operating lifetimes of 8 – 12 years [14, 28-30]. However, one of the main disadvantages of supercapacitors is the high self-discharge rate compared to batteries, which has been quoted as anywhere between 0.5 – 40 % after 24 hours depending on the state of charge (SOC) [14].

Supercapacitors have been used in parallel with batteries to extend battery lifetime by reducing the number of charge/discharge cycles and buffering the peak currents in the battery [15, 16, 31-34]. A synergy exists between both technologies where high power or current pulses can be met by the supercapacitors while longer-term energy requirements are provided by the battery [16, 32]. There are also numerous examples of the application of supercapacitors to large-scale grid-connected RE systems in order to smooth fluctuations, provide power during intermittency and re-start turbines when the grid fails [25, 32, 35, 36]. Experimental research using a 3kW wind turbine simulator with power output fluctuations (0 – 700 W) demonstrated the ability of supercapacitors to buffer wind fluctuations over short periods of time (300 s) [37]. Although the power reduced to zero on several occasions, the ability of the supercapacitor bank to buffer intermittency was not examined in that study [37]. By installing supercapacitor storage in a 500 W wind turbine system, the availability of the system was increased by over 30 % at wind speeds higher than 5 m/s during a three hour period [38]. The results showed that the system performance deteriorated at wind speeds less than 5 m/s due to insufficient power from the wind turbine [38]. These applications highlight the feasibility of coupling supercapacitors with RE-membrane systems to improve their performance with the inherent short term variability of the resource.

Previous work by the authors has examined the effect of short term wind speed fluctuations on the operation of a wind-powered membrane (wind-membrane) system for brackish water desalination (2750 mg/L and 5500 mg/L NaCl) without any form of energy storage [2, 5]. A systematic investigation using controlled sinusoidal waves for wind fluctuations and square waves for intermittency was used to map out the safe operating window and further understand the dynamics of the system [2]. The results showed that the system was able to perform well over a wide range of wind speed fluctuations but periods of intermittency were particularly detrimental to the water quality and quantity. A further examination of intermittency showed that short periods without power (<1 min) had a higher relative impact on the permeate quality due to the concentration gradient being highest when the power initially stopped [5]. This highlighted the potential for energy storage to improve system performance by buffering these very frequent short term periods of intermittency. In this paper, the objective was to examine the potential for supercapacitors to expand the safe operating window of the wind-membrane system under short term intermittency and fluctuations. By improving the quality of power delivered to the pump motor and reducing the number of intermittent periods, there could be large improvements to the average flux and permeate quality by increasing average pressure and reducing the impact of diffusion.

2. Materials and methods

2.1. Wind-membrane system

The operation and experimental setup of the wind-membrane system was described previously without the use of short term energy storage [2]. A Filmtec BW30-4040 brackish water reverse osmosis (RO) membrane module [39] was used with a set-point of 10 bar and feed flow rate of 300 L/h at 240 W input power from a wind turbine simulator. All of the experiments were performed with a feed water concentration of 5500 mg/L NaCl (8800 μS/cm using a conversion factor, k = 0.625), pH of 6.8 ± 0.2 and temperature of 13 ± 0.5 °C as used previously [2]. The permeate and concentrate streams were recycled back into the feed tank to maintain a constant feed concentration throughout the experiments.

A wind turbine simulator based on the wind turbine generator described previously [2] was used for all experiments as shown in Figure 1. The wind turbine simulator was designed using a geared induction motor (Nord, SK51E-160M/4) with a 10:1 speed reduction (range 300 – 1000 rpm) that was controlled with a vector frequency inverter (Nord, SK700E-112-340-A). By varying the speed output of the frequency inverter and taking into account the inertias of the various components, the torque that would have been applied by the wind rotor was given to the 1 kW wind turbine generator. A LabVIEW interface was used to control the operation of the simulator and supply wind speed data to the frequency inverter.

The output from the wind turbine generator along with all of the system electronics, supercapacitor bank and the pump motor for the membrane system (Figure 1) were direct current (DC). This particular wind turbine was designed to charge a 48 V_{DC} battery bank with maximum voltage ~60 V_{DC}, therefore the supercapacitor bank was sized to operate with a maximum voltage of 60 V_{DC}. Further details on the sizing of the supercapacitor bank and the control electronics used are given in the next section. The supercapacitor charging current from the wind turbine simulator (I3) was measured at a rate of 1 Hz along with the various membrane parameters and current/voltage either side of the motor controller [2]. It should be noted that the voltage output from the wind turbine generator was governed by the SOC of the supercapacitor bank and therefore equal to V1. The membrane system load of 210 W corresponds to the set-point of 240 W described above including the average efficiency of the motor electronics (~86 %).

2.2. Sizing of supercapacitor banks

For these experiments, modular (15 V_{DC}) supercapacitors (Maxwell BOOSTCAP BPAK0058 E015 B01, parameters shown in Table 1) were chosen to allow for expansion and experimentation with the optimum supercapacitor bank size. These modules had the cells enclosed in durable packaging for safety, with integrated balancing electronics to ensure the cell-to-cell voltage was balanced when connected in series and the leakage current was minimised [24]. Within each supercapacitor, the cells are stacked in series to increase their limited voltage range (1 – 3 V_{DC}) caused by low voltage stability of the electrolyte, and extend the useable voltage output which varies linearly according to the SOC [28].

The following design steps were used to size the supercapacitor bank (values from Table 1) [24]:

1. The maximum voltage output from the wind turbine (V_{max} ~60 V_{DC}) determined the maximum charging voltage and therefore the size of the supercapacitor bank based on the rated voltage of the supercapacitor modules (V_R). The number of supercapacitor modules in series (N_{series}) was calculated using

$$N_{series} = \frac{V_{max}}{V_R}, \qquad (1)$$

where N_{series} was determined as four for this system.

2. The total amount of charge stored was determined by the capacitance of the supercapacitor bank, C_{bank}, Farads (F) as

$$C_{bank} = C_{module} \times \frac{N_{parallel}}{N_{series}}, \tag{2}$$

where C_{module} is given in Table 1, N_{series} was four and the number of parallel rows ($N_{parallel}$) was varied from 1 – 3 (therefore C_{bank} = 14.5, 29, 43.5 F) to increase the amount of system run-time and therefore determine the most appropriate size of energy storage for the system.

3. Two efficiency losses associated with supercapacitors are the equivalent parallel resistance (EPR) and the equivalent series resistance (ESR). The EPR represents a current leakage path within the supercapacitor that limits the long term capabilities of the device. This value was given as 1 mA by the manufacturer (Table 1) and was dependent upon the charge voltage and ambient temperature. Experiments showed the typical energy loss due to current leakage as 1 – 2 % per day. The ESR is important for charge/discharge efficiency as it represents the material resistances of the electrode and electrolyte that result in internal heating [24]. The ESR depends on the number of cells in series or parallel. Increasing cells in parallel reduces the resistance whereas more cells in series increases the resistance. The resistance of the supercapacitor bank (R_{bank}) was calculated using

$$R_{bank} = ESR \times \frac{N_{series}}{N_{parallel}}, \tag{3}$$

with the resistance of the 4x1 – 4x3 supercapacitor banks (4 in series x 1, 2 or 3 rows in parallel) being 76, 38 and 25 μΩ, respectively.

4. In order to get an indication of the amount of storage time (Δt) available from the supercapacitor bank, the following equation was used

$$\Delta t = \frac{C_{bank}}{I_{avg}} \cdot \left(\Delta V - I_{avg} R_{bank}\right), \tag{4}$$

where I_{avg} is the average discharge current and ΔV is the voltage difference between V_{max} (60 V_{DC}) and the minimum operating voltage (31.2 V_{DC}). This equation could be used for charging or discharging. For an average discharge current of 5.3 A, this would give a discharge time of 78 s for a 4x1 supercapacitor bank. As discussed earlier, this length of time would be ideal for improving the power quality from the wind turbine by buffering turbulent wind speed fluctuations that frequently occur at periods of about 1 min [6].

5. The energy (Wh) stored in the supercapacitor bank (Figure 2) was proportional to the charge voltage (V) squared where

$$E = \tfrac{1}{2} C_{bank} V^2 \tag{5}$$

Therefore, it was possible to use 75 % of the electrical energy stored in the supercapacitor bank by discharging to half of its maximum voltage (60 V_{DC}) [28]. Although supercapacitors have no lower operating threshold and can be discharged to zero volts, most DC/DC converters have a minimum voltage which limits the use of energy [24]. In this particular application the DC/DC converter limited the minimum voltage at 31.2 V_{DC} which was equivalent to 27 % minimum SOC (Equation 6).

6. The SOC of the supercapacitor bank is a useful measure of the available energy as a percentage of the banks maximum energy capacity (E_{max}) [24], and was calculated as

$$SOC = \frac{E_{bank}}{E_{max}} \cdot 100\%, \tag{6}$$

where the energy was calculated using Equation 5 with 60 V_{DC} for E_{max} and the supercapacitor bank charge voltage for E_{bank}.

2.3. Connection of supercapacitor bank to wind-membrane system

The voltage output from a supercapacitor varies linearly during the discharge process. Therefore a DC/DC converter was required to provide the appropriate voltage to the pump motor. The DC/DC converter was integrated into the control electronics for the pump motor as part of a maximum power point tracker [2]. By drawing more current as the voltage of the bank decreased from 60 to 31.2 V_{DC}, the DC/DC converter was able to provide constant voltage input to the pump motor controller (~70 V_{DC}).

The supercapacitor bank was charged directly by the wind turbine without the use of control electronics. A primary consideration was that once completely discharged a supercapacitor is equivalent to a short circuit for the charging source [24]. This was only a concern when the supercapacitors were completely uncharged, when new or unused for a very long time (on the order of months). During normal operation the minimum SOC of the supercapacitors was 27 % as dictated by the lower operational limit of the DC/DC converter. However for the initial charge, a pulse charge power supply or suitable charger should be used to manage the high initial charge current.

2.4. Experimental design

Experiments were performed on the supercapacitor bank and the membrane system in a systematic manner to understand the dynamics of the system without the uncontrollable variability of real wind. By simulating the behaviour of wind through intermittent and fluctuating behaviour, the effect of these characteristics on the membrane system performance can be more easily understood. To allow more detailed analysis the effects of fluctuations and intermittency were treated separately; where intermittent operation was taken to be any period of time where the system shut down due to insufficient power. All of the experiments were performed over the full operational range of the wind-membrane system with wind speeds from 4 – 14 m/s in increments of 2 m/s for each of the three sizes of supercapacitor bank:

1. Steady-state conditions: the wind speed was held constant to determine its effect on the charging/discharging characteristics of the supercapacitor bank. Experiments were performed using the wind turbine simulator with and without the membrane system to determine the effect on the SOC and verify the amount of membrane system run-time available from each size of supercapacitor bank.
2. Intermittent wind: square wave wind speed inputs were used to establish how effectively the supercapacitor banks could prevent system shut-down during

intermittent operation and the effect on water quality and quantity. The square waves were used to turn the power off over a range of time periods (0.5 – 5 min).

3. Simulated fluctuations: sinusoidal wind speed oscillations can be used to simulate real wind fluctuations [2]. These experiments were used to determine the effectiveness of supercapacitors in buffering a wide range of short term wind fluctuations. Oscillating wind speeds with varying period of oscillation from 15 s – 20 min were tested over a wide range of turbulence intensities from 0.1 to 0.6 (extreme fluctuations). The wide range of periods was important as previous work showed detrimental effects of longer periods of oscillation (>75 s) on the permeate quality and quantity with no energy storage [2].

3. Results and discussion

3.1. Charging of supercapacitor banks without load

The main aim of this study was to determine the effectiveness of supercapacitors in buffering short term wind speed fluctuations to provide a more stable supply of power to the wind-membrane system. This type of operation should result in both improved water quality and quantity, as well as an expansion of the safe operating window by increasing the quality of power delivered by the wind turbine and reducing the number of intermittent periods [21, 40].

An essential part of mapping out the performance of the supercapacitors was to understand the relationship between the wind speed input to the system and the SOC of the supercapacitor bank in the absence of an electrical load. Figure 3 illustrates the effect of the wind speed on the charging time of the supercapacitor bank with no load attached for the three different bank sizes. Each of the charging profiles followed the same trend with increasing wind speed, which was inverse to the wind turbine power curve [2]. The rapid increase in the charging rate from 4 – 8 m/s represented the additional energy available in the wind, which is proportional to the cube of the wind speed. Furling of the wind turbine in order to protect the generator from overheating at high rotational speeds resulted in the charging time leveling off at higher wind speeds [2]. The charging time of the supercapacitor banks was proportional to the capacitance and the ESR as shown by Equation 4. Hence, a longer time was required to charge a larger bank size.

The SOC was the most useful measure of the amount of energy available in the supercapacitor bank and was calculated by measuring the voltage across the supercapacitors (Equation 6). The effect of wind speed on the SOC during the charging process over time with no load (membrane system) attached to the supercapacitor bank is shown in Figure 4. Higher wind speeds resulted in increased power output from the wind turbine and more charging current being provided to the supercapacitor bank causing increased rate of charge. With an average wind speed of 6 m/s (120 W), full supercapacitor charge was achieved in 3 min for 4x1 (Figure 4A) and 9 min for 4x3 (Figure 4B) supercapacitor banks.

3.2. Discharging of supercapacitor banks with membrane system load

The amount of membrane system run-time provided solely by the supercapacitor bank was important for verifying the effectiveness of the supercapaitors in buffering intermittent wind. The load of the membrane system was provided solely by the pump, with the

maximum power consumption controlled by the set-point (240 W). The SOC of the supercapacitor banks discharging over time with the membrane system as the load and no power supplied by the wind turbine is shown in Figure 5. The discharge time was directly related to the storage capacity of the supercapacitor bank as the power consumption of the pump was constant. The voltage and current output from the supercapacitor bank followed an exponential decay curve therefore the DC/DC converter was essential for delivering constant power to the membrane system. Full supercapacitor discharge took 1:20, 2:30 and 4:00 min for supercapacitor banks of 4x1, 4x2 and 4x3, respectively. These figures represent the maximum length of no-power from the wind turbine during which power could be supplied by the supercapacitor banks without any detrimental effect on the operating characteristics of the membrane system.

3.3. Impact of wind speed on supercapacitor bank SOC with membrane system load

Establishing the relationship between average wind speed and performance of the wind-membrane system operating with supercapacitor storage was necessary for determining the safe operating window for the system. Coupling the wind turbine and membrane system to the supercapacitor bank allowed simultaneous charging/discharging of the supercapacitor bank and operation of the membrane system under constant power. As demonstrated previously in Figure 4, the time required for charging the supercapacitor banks was dependent on the wind speed. However, with the membrane system connected (Figure 6), wind speeds of 4 – 6 m/s resulted in more power being consumed by the membrane system (240 W) than produced by the wind turbine, causing the supercapacitor bank to discharge. The rate of discharge was related to the amount of power produced by the wind turbine therefore higher wind speeds resulted in longer discharge time. Wind speeds of >7 m/s resulted in surplus power being produced and charging of the supercapacitor bank.

3.4. Effect of wind intermittency on system performance

Previous research demonstrated that intermittent operation was particularly detrimental with respect to permeate quality and quantity, especially at shorter off times (<60 s) where the rate of change to the permeate concentration was highest due to the increased initial rate of diffusion within the membrane [5]. By varying the period of intermittency or off-time over a range from 0.5 to 5 min, the effectiveness of the supercapacitor banks in buffering these short power-cuts was investigated. Figure 7 illustrates the effect of increasing the off-time on the largest supercapacitor bank (4x3) with a wind speed of 10 m/s. This set of experiments was chosen to demonstrate the effect of intermittent operation as the longest off-time of 5 min was sufficient to cause system shut-down and demonstrate the operating range of the wind-membrane system (Figure 7A).

As shown in Figure 7B, the current output from the wind turbine fluctuated between 0 – 10 A according to the power output from the wind turbine and the SOC (Figure 7D), while the current drawn by the pump motor remained constant at 3 A up to 4 min off-time. The supercapacitor bank was charged and discharged according to the power available from the wind turbine while the membrane system was drawing constant power (240 W) all of the time. This is shown by the increase and decrease of the voltage of the supercapacitor bank (Figure 7C) and therefore the SOC (Figure 7D). The expected discharge time as shown in Figure 5 for the 4x3 supercapacitor bank was 4 min. This intermittency experiment reinforces that result by showing that the supercapacitor bank could provide power to the membrane system for a maximum off-time of 4 min of no wind while 5 min caused the SOC to reduce to the unusable threshold. By comparison, the 4x1 supercapacitor bank could provide power for periods of intermittency up to 1:20 min long and the 4x2 up to 2:30 min.

The performance of the wind-membrane system was determined by the SOC of the supercapacitor bank, which was dependent on the availability of power from the wind turbine. When sufficient energy was available from the supercapacitor bank (SOC above unusable threshold, Figure 7D) the membrane system operated with constant energy and the desalination performance was as during steady-state conditions (Figure 7E-H). During steady-state conditions, the TMP (Figure 7F) was 10 bar according to the set-point, resulting in flux of 11 $L/m^2.h$ and recovery (Figure 7G) of 26 %. The TMP determined the driving force for the desalination process by providing the hydraulic pressure required to overcome the osmotic pressure of the feed water and boundary layer and the relatively small resistance of the membrane. At low TMP (<5.5 bar) and recovery (<10 %), the retention of NaCl was limited by the relatively high rate of NaCl diffusion in comparison to the water flux (<2.5 $L/m^2.h$). In contrast, there was increased concentration polarization at high TMP (>10 bar) and recovery (>40 %) due to high concentration of rejected ions in the boundary layer that resulted in increased diffusion of NaCl across the membrane and a deterioration of permeate quality.

The retention of the membrane (Figure 7G) was lower than the expected value according to the manufacturer [39] as a result of the chosen set-point (lower pressure, feed flowrate and temperature) and the age of the membrane. The membrane was used for field trials in Australia in 2005 [41, 42] and extensive laboratory testing since 2008. While the flux was consistent with the expected values and previous experimentation, the retention under these operating conditions has reduced from 96 % to 92 % over the lifetime of the membrane [2, 43]. Note that retention >89 % is sufficient to produce good quality permeate (<600 mg/L) from a feed water of 5500 mg/L NaCl according to the WHO guidelines [44], which is why the membrane continues to be used. Experimental analysis of a new BW30 membrane showed retention of 97 % at the set-point. In comparison to the new membrane, the flux of the old membrane was ~12 % higher, resulting in increased recovery (~6 %) and reduced SEC (~18 %). Note however that this variation in flux was within the ± 20 % range for individual modules as given by the manufacturer [39].

The SEC is a measure of the energy required to produce a unit of clean water and is useful for determining efficiency in terms of energy requirements and water productivity. The energy required varied according to the operating conditions (pressure, flow rate, salt concentration) and exhibited a close relationship to the recovery of the system. For example, at low power the SEC was high because most of the energy was used to overcome the osmotic pressure due to the salinity difference across the membrane (~4 bar), resulting in low recovery. The SEC obtained for this system under the chosen operating conditions was 2.7 kWh/m^3 (Figure 7H).

The usability index (UI) was proposed [2] to show the combined impact of fluctuations on the flux (Figure 7F) and the permeate quality or retention (Figure 7G). The UI (Figure 7H) exhibited steady-state conditions throughout periods of intermittency up until the point when the supercapacitors were discharged. Once the supercapacitor SOC reached the unusable threshold (5 min), there was no more usable energy and the membrane system shut down (Figure 7E). Apart from buffering the intermittent periods up to 4 min, this highlights another advantage of using supercapacitors as they can be charged while the membrane system is turned off and therefore supply a sufficiently large amount of power to re-start the pump motor. This is useful both for overcoming the static friction of the pump and reducing the impact of intermittency on the average permeate quality. By using the supercapacitors to provide high power and therefore flux, the membrane can be rapidly purged of the of poor quality permeate produced by diffusion (measured as 2 L ± 10 % depending on operating conditions) [2]. The effectiveness of the supercapacitors in buffering short term wind intermittency is highlighted by comparing the system performance without any energy storage. By using the 4x3 supercapacitor bank to provide constant power over one hour with six intermittent periods of 3 min, there was a 40 % increase in the average flux and 15 % improvement in overall permeate quality when compared to the same experiment without energy storage [5]. This was a result of the supercapacitor bank providing constant power over this period, while the system without energy storage had zero flux during the off-time and poor quality permeate produced upon re-starting the system due to diffusion of NaCl. The increased performance was dependent on the amount of energy stored in the supercapacitors, which was a function of the size of supercapacitor bank and the SOC. Therefore, the performance increase was lower with wind speeds <7 m/s, longer off-time and smaller supercapacitor banks as a result of the reduced amount of energy stored. Overall, the supercapacitors were able to improve the performance (average flux and permeate quality) of the wind-membrane system by providing power during short-term intermittent periods and reducing the impact of longer-term intermittency on the recovery time and average permeate quality.

A method of improving the performance of the supercapacitor bank by increasing the discharge time and decreasing the wind speed required for charging would be to reduce the amount of power required by changing the set-point of the membrane system. This set-point (10 bar at 300 L/h feed flow rate and 240 W power) was established in previous work to provide high flux and retention with low specific energy consumption (SEC) and water recovery within the operating limits of the wind-membrane system [2]. High water recovery coupled with low cross flow velocity causes concentration polarization, resulting in lower flux and increased salt diffusion. In feed waters with sparingly soluble salts (i.e. calcium carbonate, calcium sulfate and silica) high water recovery can also cause increased risk of scaling [39]. Operation of small membrane systems at low recovery (~25 %) with regular forward flushing is a recognised method of preventative cleaning to avoid scaling thereby enhancing membrane performance and lifetime [39]. Reducing the maximum motor speed and therefore power drawn by the membrane system would result in lower SEC with the consequence of reduced performance in terms of flux and retention due to lower transmembrane pressure (TMP). At low pressure, the permeate flux and recovery are controlled by mass transfer and therefore directly proportional to the TMP which is the driving force [45]. Hence, changing the set-point of the membrane system may result in more buffer time from the supercapacitor bank, but this would be at the expense of membrane system performance.

There are unique design criteria required for developing membrane systems to operate in remote regions with renewable energy. Designing systems with a focus on low energy consumption and robust long term membrane operation can be achieved by sacrificing efficiency in terms of high TMP, flux, recovery and salt rejection [46]. For example, to operate the membrane system at the test conditions given by the manufacturer (TMP of 15.5 bar, feed flowrate 1750 L/h with 5500 mg/L) [39], the power consumption would be 1840 W [2]. This would require a pump approximately six times the size of the existing one (300 W). While a larger pump may have increased hydraulic efficiency (pump used here had efficiency 25 – 50 % depending on operating conditions), smaller pumps have lower energy requirements which determine the capital cost of the system by reducing the size of renewable energy generator required. The membrane is the weak link in the wind-membrane system with an expected working lifetime of 3 – 5 years in comparison to 10 – 20 years expected for the other components [39, 47]. In order to prolong the lifetime of the membrane, the recovery should be set to ~25 % (Figure 7G) and adequate pretreatment (such as ultrafiltration) used to minimise the effects of fouling over the longer term, particularly under intermittent operation [48, 49]. The reduction of mechanical stress to the membrane modules by buffering intermittency and fluctuations using supercapacitors will help to further enhance the lifetime of the system.

3.5. Effect of simulated wind fluctuations (sine wave oscillations)

Controlled sinusoidal wind speed fluctuations were used to determine whether supercapacitors could improve the quality of power delivered to the membrane system and improve the overall system performance. Simulated fluctuations were examined over a range of periods of oscillation from 15 s – 20 min to cover the maximum range of short term wind speed fluctuations [6]. Previous experimentation without energy storage showed that the system performance deteriorated significantly with longer periods of oscillation (>60 s) at high turbulence intensity due to a combination of high loading from the pump motor and insufficient power to achieve system pressure, resulting in the power switching off [2]. Figure 8 shows the wind-membrane system operating with the smallest supercapacitor bank (4x1) under a wide oscillating wind speed range 3 – 11 m/s with periods of oscillation 15 and 20 min. This data was used to demonstrate the system performance as it showed the operating limits of the 4x1 supercapacitor bank.

By buffering the periods of low wind speed (Figure 8A-D) and providing power to the pump motor, the supercapacitor bank was able to provide constant power during long periods of oscillation at high turbulence intensity (0.4) with no detrimental effect on the performance of the membrane system (Figure 8E-H). The performance of the membrane system was as under steady-state conditions as described above. Shorter periods of oscillation (15 s – 10 min) had less effect on the SOC, as did increasing the size of supercapacitor bank. The SOC (Figure 8D) showed the supercapacitor bank absorbing the fluctuations in power whilst operating at the limit of the available voltage range (Figure 8C). Note that while the membrane system did not shut down with the maximum oscillation period of 20 min, if the maximum supercapacitor voltage was limited to 60 V_{DC} then these fluctuations would have caused the SOC to reach the threshold value for the 4x1 supercapacitor bank, and it would have shut down.

When compared to the directly-driven system without energy storage [2], the use of supercapacitors to buffer these wind fluctuations (Figure 8) with a 1 min period of oscillation resulted in an 85 % increase in average flux and 40 % improvement in the quality of permeate produced over 10 min. This was a result of the improved power quality supplied to the membrane system as a result of the supercapacitors buffering the fluctuations and providing constant power. Note that turbulent wind speed fluctuations most commonly occur with a 1 min period of oscillation [6], which highlights the effectiveness of using supercapacitors for this purpose. The increase in permeate quality was sufficient to produce good quality drinking water (<600 mg/L) according to the WHO guidelines [44]. The use of supercapacitors enabled the expansion of the safe operating window for producing good quality permeate from ~9 m/s (no energy storage) to any wind speed where the SOC of the supercapacitor bank was above the unusable limit (27 %). However wind speeds of >7 m/s were required for charging of the supercapacitor bank, therefore lower wind speeds were not sufficient for operating the system for more than ~5 min (Figure 6). While the smallest supercapacitor bank was adequate for absorbing the whole range of short term wind fluctuations over the operating range of this system, increasing the size of supercapacitor storage would provide power for longer periods of intermittency. This would be a trade-off between the benefits of increasing the storage time versus the added cost of supercapacitor capacity and would depend on the particular system and wind resource.

Further work is required to examine the effect of real wind speed data on the wind-membrane system performance and the overall improvements in water quality and quantity. Testing under actual wind conditions will help to establish the optimum size of supercapacitor bank for this system and an estimate of the expected lifetime of the supercapacitor modules based on the number of charge/discharge cycles.

In order to investigate the expected productivity of the wind-membrane system over a wind day and to determine the impact of supercapacitors on the cost of water, experiments were performed over 24 hours using real wind data.The wind speed data was obtained from measurements taken near the town of Emden on the North Sea coastline of Germany [8]. This data was measured using an ultrasonic anemometer at 20 m hub height and a sampling frequency of 4 Hz over 275 hours in October 1997. The data was adjusted using the log law to make it applicable for a small wind turbine system by reducing the hub height from 20 m to 8 m [50]. A 24 hour segment of the wind speed data exhibiting a wide range of wind speeds with distinct high and low regions, turbulence and gusts was chosen to provide a realistic but challenging test for the wind-membrane system. The average wind speed over the 24 hour period was 6 m/s with a wide range from 0 – 20 m/s. The wind-membrane system produced 0.79 m^3/day over the 24 hour period without supercapacitor storage, while the permeate production was 0.93 and 1.15 m^3/day for the 4x1 and 4x3 banks, respectively.

The expected lifetime of the supercapacitor banks is important, as any improvements in short-term performance should not be made at the expense of increased maintenance and cost of water. The performance of supercapacitors degrades over time according to the variation of voltage and the ambient temperature [24]. This degradation follows an exponential decay rather than a failure to indicate the end of lifetime. The standard lifetime measurement used in industry is a 20 % decrease in capacitance and/or a 200 % increase in the internal resistance of the supercapacitor. The cycle lifetime for these supercapacitors was given as 500,000 cycles (at 25 °C), measured as cycles from the rated voltage (60 V_{DC}) to half of the rated voltage, resulting in a 20 % decrease in capacitance (Table 1). To give an indication of the expected lifetime of the supercapacitors, the number of cycles was calculated over the 24 hour period. One cycle was taken to be a round trip voltage change of 60 V_{DC}, and this was averaged over two experiments, as the 24 hour experiment was repeated. The 4x1 supercapacitor bank underwent 156 cycles and the 4x3 supercapacitor experienced 112 cycles over the 24 hour period, giving a lifetime range of 8.8 – 12.2 years. These values correspond well with the literature, where typical lifetimes of 8 – 12 years have been given for supercapacitors used in wind energy applications [30, 14].

Preliminary calculations for the cost of water can be made based on these productivity figures over 24 hours and the capital cost of the membrane system ($15,840) over a 20 year lifetime [51]. The cost of each supercapacitor was $120 in July 2008, therefore the 4x1 bank cost $480 and the 4x3 bank cost $1440. Assuming a supercapacitor lifetime of 10 years, the banks would require replacement once during the lifetime of the membrane system. Using the productivity over the 24 hour period, the cost of water would be 7.5 $/m^3 with no storage, 6.5 $/m^3 with the 4x1 supercapacitor bank and 5.5 $/m^3 with the 4x3 bank over the lifetime of the system. This reduction of 13 – 26 % in the cost of water is significant and highlights the benefit of using supercapacitors for energy buffering of wind-membrane systems.

As mentioned in the introduction, supercapacitors are an efficient and cost effective source of power, but an expensive source of energy. Therefore, they are most appropriate for energy buffering over short periods of time, on the order of several minutes. For providing power over longer periods of time (10 – 15 min) high power batteries would be more appropriate [27]. The current cost of supercapacitor energy storage is 10 – 20 $/Wh, while the cost of high power batteries is in the region of 1 $/Wh [52]. There are numerous developers of supercapacitors (SAFT (France), NESS (Korea), PowerCache (Maxwell, USA)) who are looking at ways to increase the energy density and reduce the cost of these devices [53].

4. Conclusions

The suitability of supercapacitors to expand the safe operating window of a wind-membrane system was examined in a systematic manner. The supercapacitors were able to provide sufficient energy during periods of no wind (intermittency) and enhance the power quality delivered to the membrane by absorbing turbulent wind (fluctuations). As a result, system shut-down and compromised permeate quality due to reduced TMP were avoided. The use of supercapacitors to provide constant power resulted in a 40 % increase in the average flux and 15 % increase in permeate quality under intermittent operation over one hour. The improvements in the average flux and permeate quality under fluctuating conditions due to increased power quality were 85 % and 40 %, respectively. While the SOC of the supercapacitor bank was above the minimum threshold value of 27 %, the membrane system operated as under steady-state conditions regardless of the wind speed and power output from the wind turbine. Once the threshold SOC was reached then the supercapacitors were no longer providing power and the membrane system either shut down or was directly subjected to the wind speed fluctuations from the wind turbine. Wind speeds of >7 m/s were required to provide a net surplus of energy and increase the SOC of the supercapacitor banks when the membrane system was operating, otherwise the energy was gradually discharged. The length of run-time provided by the supercapacitors during intermittent periods was dependent upon the size and therefore the capacitance of the supercapacitor bank. The maximum period of intermittency that could be buffered was 4 min by the largest bank. More storage could be provided by adding further rows in parallel, but this would not be the optimum use for supercapacitors as they are a cheap and efficient source of power but an expensive source of energy. The supercapacitors were very effective at absorbing oscillations over a wide range (15 s – 20 min) and are therefore considered to be ideal for integration into membrane systems powered by renewable energies for reducing the number of system re-starts and providing higher average water quality and quantity.

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Table 1 Supercapacitor specifications [24].

Specification	Value
Capacitance, C_{module} (F)	58
Rated voltage, V_R (V_{DC})	15
Operating temperature range (°C)	-40 to +65
Life test (years)	10 years at rated voltage and 25 °C
Cycle test (cycles)	500,000
Maximum energy (Wh/kg)	3.63
Power density (W/kg)	3,000
Leakage current (mA)	1.0
Internal resistance (mΩ)	19.0
Dimensions (mm)	216 x 69 x 38
Mass (kg)	0.566

List of figures

Figure 1 Schematic diagram of the supercapacitor bank attached to the wind-membrane system including wind turbine simulator, control electronics, motor controller and membrane system load with current sensors I1 – 13 and voltage sensors V1 – V2.

Figure 2 Energy available from the supercapacitor bank according to the charge voltage and the size of bank (determined by number of parallel rows).

Figure 3 Charging time for the supercapacitor bank related to the available wind speed and the size of bank.

Figure 4 SOC of the supercapacitor bank charged by the wind turbine simulator over wind speed range 4 – 14 m/s with no power being drawn from the system; (A) 4x1; (B) 4x3 bank.

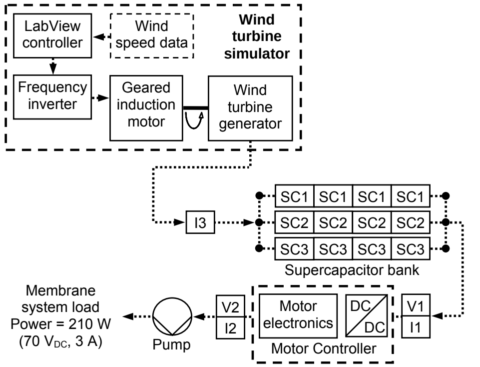
Figure 5 SOC of the supercapacitor banks discharged by membrane system at 240 W with no additional power being provided by the wind turbine simulator.

Figure 6 SOC of the 4x1 supercapacitor bank connected to wind turbine simulator and membrane system over wind speed range 4 – 14 m/s.

Figure 7 Wind-membrane system performance using 4x3 supercapacitor bank under intermittent operation with off time 0.5 – 5 min and feed water concentration 5500 mg/L NaCl.

Figure 8 Wind-membrane system performance using 4x1 supercapacitor bank under oscillating wind speed fluctuations (average 7 m/s) with periods 15 and 20 min and feed water concentration 5500 mg/L.

Figure 1



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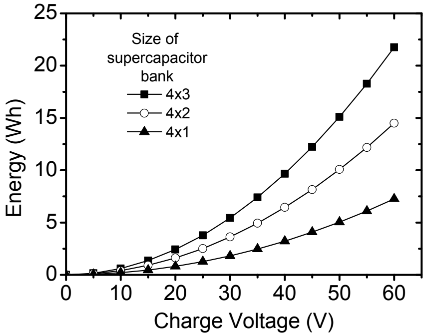

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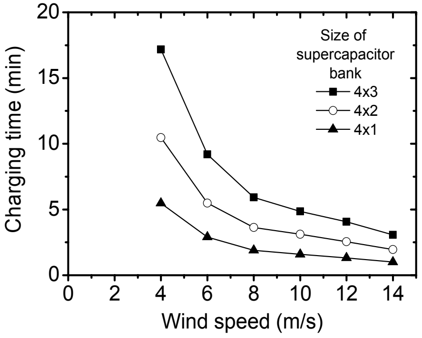

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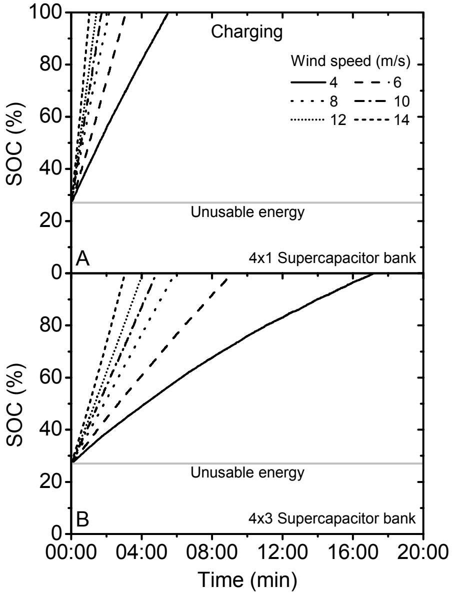

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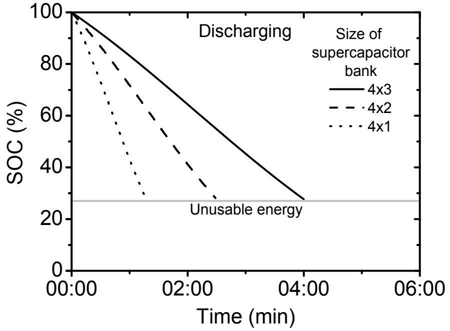

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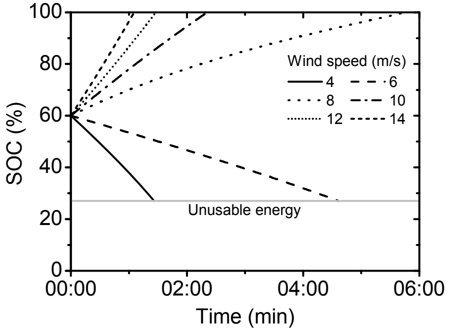

Figure 7

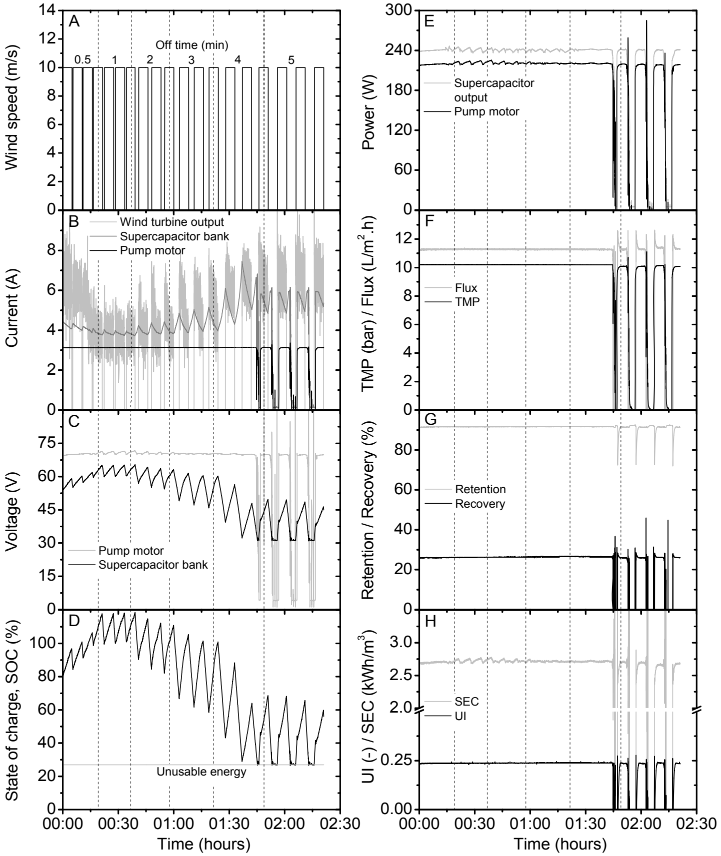

Figure 8