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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.

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