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Renewable energy powered membrane technology: Impact of solar irradiance fluctuations on performance of a brackish water reverse osmosis system

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ABSTRACT

Fluctuations in solar irradiance were varied in frequency and magnitude to investigate the performance of a directly-connected solar energy powered reverse osmosis (RO) membrane system. Typically, the system produced acceptable quality water with constant solar irradiances ranging from 400 to 1200 W m^{-2}. Low average motor powers were encountered during fluctuations, however, in many cases, good performance was still realised, even at solar irradiance values that were equivalent to <400 W m^{-2}. This counter-intuitive result arises from the effect of averaging the motor power, with periods of high solar irradiance compensating for the under-performance at times when the system was off. Overall, even though the permeate flux was often low when operating under fluctuating conditions, the RO system continued to deliver satisfactory quality water and at a low specific energy consumption (SEC). Temporal studies revealed that a disruption of the concentration polarisation layer occurs via a naturally induced backwash for steps in the solar irradiance as low as 100 W m^{-2}. This suggests that a renewable energy powered RO filtration system could benefit from being operated from a fluctuating energy source. Furthermore, the operating conditions during the first couple of minutes after a system shutdown event is shown to be very important, with: (i) shorter off-periods resulting in good performance being achieved quicker, and (ii) short-term power availability dramatically improving system performance. These findings indicate that a renewable energy powered RO system can operate well from a fluctuating energy source, in particular when additional power – for example, via supercapacitor energy buffering – is available to boost the system after a shut-down period.

1. Introduction

The lack of potable water has been described as being one of the major problems in the developing world, particularly in remote areas [1]. Small-capacity water systems are often more cost effective than water transportation in these isolated regions [2–4]. The most important factor for the success of small-capacity systems is simplicity in design as well as robust and reliable operation. Reverse osmosis (RO) membrane desalination technology has been demonstrated to be an efficient and reliable water treatment solution for such applications [5–7]. In remote regions that lack access to an electricity grid or that have an unreliable connection, systems powered by renewable energy (RE) offer a distinct advantage as they are energy independent. In recent years, there have been many reviews of renewable energy powered membrane filtration (RE-membrane) systems [8–13]. In particular, the applicability of photovoltaic (PV) power has been widely demonstrated via solar water pumping systems as simple and reliable for rural applications in developing countries [14]. Recently, Ghaffour *et al.* have predicted that with the rapidly falling prices of PV panels, the costs of solar power will very soon compete with that of conventional electricity generators [12]. Therefore, PV-powered RE-membrane systems are one of the most promising solutions in areas of high solar irradiance where brackish groundwater is the only available water source, and particularly where chemical contaminants occur [3,10]. However, the solar resource varies during the day and throughout the year. While solar irradiance values are typically

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regarded as reaching 1000 W m^{-2} on a clear day and the path of the sun can be predicted for different geographic locations, the power for a PV system will experience fluctuations from landscape and weather conditions, including clouds, wind and ambient temperature [15]. In contrast to these fluctuations, manufacturers of nanofiltration (NF) and RO membranes recommend maintaining a constant permeate flowrate to help increase the life of the membrane [16,17].

Reports of RE-membrane systems without any power or pressure/flow stabilising devices can be found in literature. Thomson and Infield describe how their RE-membrane system was not able to perform as expected due to poor weather conditions, low pump efficiency, and electrical losses associated with two direct current to alternating current (DC–AC) inverters [18]. Furthermore, when the system was powered down, the feed flow stopped but the salt ions continued diffusing across the membrane until equilibrium was achieved resulting in contaminated permeate upon restarting the system. To avoid this, the use of an automated valve to reject permeate with high concentration was suggested [18]. Several groups have conducted experimental tests to evaluate the effect of different transmembrane pressures (TMP) in RE-membrane systems [19,20]. Gocht *et al.* conducted preliminary experiments via step response testing with pressures ranging from 10 to 60 bar with rates of change up to ΔTMP = 180 bar min^{-1} and concluded that the transient operation of these systems was possible [19]. Pestana *et al.* demonstrated that higher pressures (an increased driving force) led to an increase in both the permeate flow, and salt concentration in the concentrate flow [21]. To produce the lowest specific energy consumption (SEC), these authors recommended using a control system to obtain the maximum membrane recovery (close to 40%) for the available power. A RE-membrane system tested in central Australia successfully demonstrated the production of 1 m^3 (close to 30% recovery) of high quality water from brackish water – with 5.3 g L^{-1} total dissolved solids (TDS) – over one solar day [22,23], while the same authors further evaluated the safe operating window for the such a system when directly powered by wind energy by testing two different feed waters and different membrane modules [24]. Overall, simpler and more robust RE-membrane systems are desirable for autonomous systems located in remote areas in order to minimise maintenance requirements [3]. Naturally, the challenge is not only technical, with the training of locally-based operators also playing an important role in the long-term success of such a system [3,25].

The classical approach to managing the solar irradiance fluctuations encountered throughout the day is to employ batteries to ensure a continuous and constant supply of electrical power. The performance of several such RE-membrane systems have been reported in the literature [25–29]. In Spain, a containerized NF treatment plant powered by 4.2 kW of PV and two 3.0 kW wind turbines and with 2000 Ah battery capacity demonstrated excellent performance treating reservoir water when compared to a conventional drinking water treatment plant [29]. In Mexico, the battery bank of a PV-powered RO system supplied with brackish groundwater (TDS = 2.2 g L^{-1}) was sized such that it was able to continue providing clean drinking water over a period of four consecutive cloudy days [25]. The efficiency a RE-membrane system in India was enhanced by adding mirrors to the PV panels to concentrate the sunlight and using feedwater to cool the rear-side of the PV modules [30]. The same system utilized a turgo turbine as a simple energy recovery device and relied on a 500 Ah battery to enable the 48 V pump to operate under constant power [30].

However, batteries are observed to reduce the system efficiency, increase both capital and operating costs, demand higher maintenance [22,31] and can exhibit lifetimes as short as 2 years in warmer countries [32], thus making them an undesirable system component. As an energy storage alternative, RE power fluctuations have been smoothed out using mechanical pressure stabilisers [33–35], while simulation tools have been developed to better understand the temporal performance of RE-membrane systems both with [36] without energy storage via battery banks [37]. Park *et al.* concluded that the most challenging factor for RO system performance occurred when the system switched off due to power fluctuations [38] and hence proposed the concept of "energy buffering" via supercapacitors. Fundamentally, batteries store energy electrochemically and the chemical reactions that enable electrons to be extracted into an electrical circuit are slow and, over time, a degradation of the chemical compounds inside the battery will occur. In contrast, supercapacitors store energy electrostatically on the material surfaces, rather than relying on a bulk reaction, enabling much faster charge and discharge times. The lack of material degradation enables supercapacitors to tolerate at least 500,000 charge/discharge cycles, compared to up to 1000 for batteries. Park *et al.* determined that supercapacitors could offer up to 4 min of energy buffering for a RE-membrane system [39] and, subsequently, Richards *et al.* [40] demonstrated that supercapacitors can increase the daily permeate production by up to 40%.

From the point of view of membrane science, unsteady flows were often described as a method to decrease concentration polarisation (CP) and fouling in pressure driven membranes, thus enhancing the system performance [41–45]. Rodgers and Sparks [42] stated that CP layer resistance was minimal during its initial development, but increased rapidly to its steady-state value, with TMP pulsing used to take advantage of the transient development of the CP resistance. Kennedy *et al.* [45] and Rodgers and Sparks [42] demonstrated that membrane flux was improved with increased frequency of pulsed pressure. These studies suggested that fluctuations in power – which are expected in directly connected RE-membrane systems – and consequently in feed flow and TMP, might in fact result in an improved system performance due to reduced fouling and scaling. In addition, the permeate can be drawn into the feed channel if the applied pressure decreases below the osmotic pressure [46–49]. This phenomenon – called forward osmosis or direct osmosis – can be used as a cleaning method (backwash) for flux recovery of membranes that are not severely fouled [49]. This can be accomplished in several ways: by (i) reducing the applied feed pressure; (ii) increasing feed concentration to increase osmotic pressure in the feed above the operating pressure; and/or (iii) increasing permeate pressure [46]. As such, a negative power fluctuation (defined here as being from a higher to a lower value) can lead to flow reversal through the membrane if the pressure drop falls below the osmotic pressure [38], possibly reducing the need for system cleaning in the long-term.

Previous papers from the group have focussed on fluctuations and intermittency encountered when powering the RE-membrane system via a wind turbine [50–52], the potential of supercapacitors for energy buffering [39,40], the definition of a safe operating window (SOW) [24], trace contaminant removal [53,54] as well as field trip investigations [55–58] and socio-techno-economic studies [3,59], the aim of this study was to examine the effects of operating a brackish water RE-membrane system under fluctuating and intermittent solar irradiation. Step response testing was studied systematically by modifying magnitude, frequency and on-time duration of the supplied solar irradiance steps, resulting in key insights into the effect of fluctuations on the performance of brackish water treatment systems.

2. Materials and methods

2.1. System description

The RE-membrane system used in this study (as shown in Fig. 1) has been described previously [40,56], however in this case the