Renewable energy powered membrane technology: Safe operating window of a brackish water desalination system

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A B S T R A C T

The safe operating window (SOW) of a renewable energy (RE) powered membrane filtration system for brackish water desalination is determined. The SOW is constrained by several factors: (i) operating limits of pump motor (pressure and flowrate), (ii) maximum recommended recovery, and (iii) the osmotic pressure of the feedwater. The membranes (and brackish feedwater salinities) used were BW30 (5500 and 10,000 mg/L), aged BW30 (5500 mg/L) and NF90 (5500 and 2750 mg/L). At lower salinities (2750 5500 mg/L) the main constraint was maximum recovery (30%), while at higher concentrations (10,000 mg/L) osmotic pressure played a more limiting role. The optimum operating strategy is 'constant recovery'. This produces the highest flux at a given power consumption and thus the lowest specific energy consumption (SEC) while maintaining good retention. However, this operating strategy can be difficult to implement. Therefore, 'constant set point' mode is recommended for this system in order to provide a robust and effective solution, despite a minor reduction in performance. This approach is attractive for being powered by a wind turbine or solar energy (photovoltaics) given the low SEC ($\sim$ 3 kWh/m^3) that enables operation over a very wide power range (70 280 W) in order to achieve the desired pressure range (5 11.5 bar). Overall, the SOW methodology can be used in the performance evaluation of a wide range of membrane filtration systems.

Keywords:
Brackish water
Reverse osmosis
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System performance
Safe operating window

1. Introduction

The energy water nexus experienced in remote areas means that the lack of safe drinking water is exacerbated by the scarcity of electricity that is required to power water purification systems [1]. The flow on effect of energy shortages and the impact of climate change on water supply have major implications for rural poverty, as described by the United Nations Millennium Development Goals [2]. The development of low pressure reverse osmosis (RO) and nanofiltration (NF) membranes [3] has triggered significant interest in applying membrane desalination as a cost effective strategy for desalination of brackish groundwater. Thus, great potential exists for decentralised renewable energy powered membrane (RE membrane) systems for overcoming the dearth of infrastructure and providing potable water in off grid locations, from brackish groundwater sources in both developed and developing countries [4].

Integrated RE membrane systems can avoid fossil fuel dependency and the subsequent greenhouse gas emissions, as well as ultimately lowering energy and water costs [5]. Such systems are also being considered for emergency water supply [6]. Although membrane filtration is sometimes regarded as being both a capital and energy intensive technology, the energy consumption is predicted to decrease significantly in the coming years due to advances in membrane technology [7]. Already, RE membrane systems can be a cost competitive clean water supply option for developing countries [8]. The potential for developing high permeability membranes for low recovery in brackish water desalination systems has been reported [9]. One of the key barriers to the widespread implementation of RE power systems is the lack of a cost effective means of storing enough electricity to enable sufficient power to be provided to a load during cloudy or calm periods [10]. Traditionally, small wind and solar power systems have relied on using lead acid batteries for energy storage; however

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performance, maintenance and safety challenges of implementing this technology in remote locations remain [11]. However, via a paradigm shift, the realisation of directly connected RE membrane systems that possess no energy storage components can allow the performance to vary with resource availability and actually realise *more robust* systems [12,13]. Nonetheless, the challenge of operating under fluctuating power conditions is not trivial. Indeed, in some ways, it goes against many of the 'design rules' used by RE and membrane filtration engineers alike: that a stable power source is required in order to achieve constant flow and pressure [14]. While it has been demonstrated that RE membrane systems can function from a varying wind or solar resource, a significant lack of knowledge exists around what the actual constraints are in determining the performance of such systems and the best strategy for operation.

Therefore, the motivation for this research is to experimentally demonstrate, for the first time, a safe operating window (SOW) for a RE powered reverse osmosis (RO) system and to determine the optimum operating strategy for variable power operation. Operating within the SOW is technically desirable as it will enable maximum potable water production at minimal cost, while reducing the risk of performance degradation caused by high recovery operation. The method developed can be applied to any other membrane system and demonstrates the possibility of operating without energy storage. The SOW concept was first proposed by Feron [14] for the transient operation of wind powered seawater RO systems, observing that the operation is expected to encounter both intermittency (period of calm or darkness) as well as fluctuations in power according to the instantaneous wind speed or solar radiation. It was concluded that irregular operation would not cause any major problems as long as the cycling on/off of the plant was controlled such that the rate of pressure change and the frequency of cycling did not cause any damage to the membranes.

The SOW originally proposed by Feron was a curved sided quadrilateral that is derived from the constraints from the membrane characteristics, which were defined as follows [14]:

i. maximum feedwater pressure: as determined by the mechanical strength of the materials used in the membrane;
ii. maximum concentrate flowrate (or crossflow velocity): limited by mechanical deterioration at high concentrate flowrates;
iii. minimum concentrate flowrate: risk of water quality and recovery dependent scaling and fouling due to concentration polarisation; and
iv. maximum permeate concentration: defined by water quality guidelines. Feron [14] set this as 500 mg/L of total dissolved solids (TDS). The World Health Organisation (WHO) [15] notes that water with a TDS $>$ 1000 mg/L is unpalatable. Therefore, a sodium chloride (NaCl) concentration of 1000 mg/L was used as the target value. Low pressure can cause the permeate to exceed the target value as the salt concentration in the permeate is inversely proportional to the difference between the applied pressure and the osmotic pressure gradient.

In essence, power fluctuations will affect pressure and feed flowrate the combination of which will determine recovery and concentration polarisation, which in turn affects both fouling/scaling and permeate quality. Generally, when not only seawater is concerned, how a system responds to those parameters depends on the feedwater quality.

Feron [14] proposed two recommendations to allow wind membrane seawater plants to deal with a variable wind resource: (i) vary the membrane area; or (ii) allow transient operation within the constraints of the SOW. The conclusion at that time was that neither option was economically beneficial as it involved either under utilisation of expensive membrane area or a relatively minor increase in productivity for the increased complexity of the plant. While the work of Feron [14] has since been noted by several authors [16 19], as yet there has been no detailed experimental investigation or verification of an operating strategy for transient operation of wind membrane plants within a SOW. Miranda and Infield [19] modelled a wind membrane system for seawater desalination that included both a medium and high pressure displacement pump to allow independent control of the feed flowrate and pressure at any point within the SOW according to the available wind speed. However, further details on how this operating strategy could be applied were not provided, the testing was limited, and the requirement for having two pumps, motors and inverters would prove costly and reduce robustness. Moreno and Pinilla [17] used ROSA software [20] to determine the operating limits for a wind powered seawater desalination plant. Minimum concentrate flowrate and the maximum feed flowrate were identified and the minimum operating pressure and feed flowrate required to produce adequate permeate quality determined. Experiments were aimed at verifying the ROSA analysis over a limited range and under steady state conditions only.

Pohl et al. [16] used ROSA to investigate the use of four different operating strategies for transient operation of a RO system within a SOW. The simulations were performed using DOW SW30HR modules and 'standard' seawater [21] at 25 °C. The SOW was determined based on the manufacturer's data used as inputs to the constraints of Feron [14] above. Operating strategies investigated were [16]: (i) constant feed pressure, (ii) constant permeate recovery, (iii) constant feed flowrate, and (iv) constant concentrate flowrate. Constant recovery was found to be the optimum operating strategy based on the criteria of low specific energy consumption (SEC), production over a broad load range, good permeate quality, and low pressure variation. Operating the RO plant with constant feed pressure, as used in many conventional plants, resulted in low SEC but exhibited a narrow load range, which is unsuitable for transient operation. Hence, the wide load range necessary for transient operation could only be achieved by variation of feed pressure. However, at this point it should be noted that the impact of pressure variations on the performance and lifetime of the membrane module is largely unknown and requires further investigation [22]. The results of Pohl et al. [16] were not verified by practical experimentation and focussed purely on the membranes, while the performance curves for pumps and motors were not considered. Therefore, it is essential to determine an appropriate method of implementing chosen operating strategies and the mapping out the SOW.

Previous research by the authors resulted initially in the development of a photovoltaic powered brackish water membrane desalination system [11,23], and subsequently extended to investigate the performance of such systems under both fluctuating [12] and intermittent [24] wind conditions. In addition, the potential of supercapacitor energy buffering was studied under controlled sinusoidal fluctuations of simulated wind speed [25]. This same system is used here to investigate best operating strategy and determine a SOW methodology, taking into account module choice and feed concentration.

2. Materials and methods

2.1. Wind membrane system

The wind powered brackish water nanofiltration (NF) or RO membrane system utilised here has been extensively described in a previous paper [12]. The key component of this system is a 300 W DC progressive cavity pump (Mono Sunsub SM022), which draws water through a polypropylene 1 μm microfilter (SupaGard, 1.2 L) with suction pressure of ~0.3 bar before pumping it through the

NF/RO membrane (up to 12 bar). All parameters (pressure, flow rate, conductivity, temperature, pH, current, voltage) were recorded using a datalogger (dataTaker DT800) at a rate of 1 Hz, while LabVIEW was used for viewing instantaneous system performance and data processing. Water temperature was 13.5 ± 1.0 °C and pH was at 6.8 ± 0.2. Both permeate and concentrate streams were recycled back into the feed tank. In this work, the wind membrane system was driven by connecting the wind turbine generator (FuturEnergy, rated power 1 kW at 12.5 m/s, 48 V_{DC}) to a wind turbine simulator to allow precise control of the desired wind regime. The same system has also previously been powered by photovoltaic panels [11]. A detailed description of all sensors used as well as a schematic diagram of the system can be found in Richards et al. [26].

2.2. Water quality/chemicals/analysis

Feedwaters were prepared using deionised water and general purpose grade NaCl (Fisher Scientific, UK) at three salinities: 2750, 5500 and 10,000 mg/L NaCl. Electrical conductivity (*EC*, S/cm) of feed, permeate and concentrate was measured using conductivity electro des and converted into NaCl (mg/L) using a conversion factor k=0.625, as measured using NaCl dissolved in deionised water at 13 °C.

2.3. Membrane type and characterisation

All membrane specific parameters transmembrane pressure (TMP), flux (J), recovery (Y), retention (R), and SEC were calculated using previously defined relationships for this system [11,23]. The usability index (UI) a dimensionless indicator of good system performance (high flux with a permeate quality that meets the required guideline values) was determined using the method described in Park et al. [12]. A positive UI value indicates good system performance, zero implies no flux, while a negative value means that the permeate concentration is not meeting the guideline value.

Two different types of brackish water NF/RO membranes (Dow Filmtec) were used, namely a brackish water RO module, BW30 4040 and a NF90 4040 nanofiltration module [21]. Both a new and a 6 year old BW30 membrane (referred to as "aged") were experimented with in order to examine the affect of membrane aging on performance degradation and SOW. The aged BW30 membrane was used for field trials in the Australian outback in 2005 [11,23] and extensive lab testing between 2008 and 2011. Frequent cleaning (daily during field trials) will have accelerated aging. All membrane modules had a surface area of 7.2 m^2. The performance characteristics of the three membranes are given in Table 1, with the set point described in the following section.

2.4. Methodology for SOW determination

The determination of SOW and its constraints requires knowl edge of all possible system operating scenarios. Main system inputs are feed pressure and flowrate (hydraulic power) as well as membrane type and feedwater quality. The hydraulic power is defined by

$$P_{\text{hydraulic}} = \Delta p \times Q, \tag{1}$$

where Δp is the pressure difference (Pa) between the discharge and suction sides of the pump and Q is the flowrate (m^3/s). The electric power consumption of the pump motor ($P_{\text{pump motor}}$) is then related to Eq. (1) via

$$P_{\text{pump\_motor}} = \left(\eta_{\text{pump}} \times P_{\text{hydraulic}}\right) \times \eta_{\text{motor}}, \tag{2}$$

where the term in parenthesis represents the mechanical power applied to the pump shaft, while η_{pump} is the pump efficiency (typically 43%) and η_{motor} is the motor efficiency (taken to be 85% for a brushless DC motor).

The main outputs of the SOW are productivity (flux and recovery) and desalination efficiency (retention and SEC). The SOW requires the relationship between input and output para meters over the whole operating range, which was determined experimentally. In order to have a baseline for performance comparison under fluctuations energy conditions, a membrane system 'set point' was determined at the start of each experiment. This was achieved by setting the pump motor power to a constant value of 240 W and adjusting the regulating valve on the concen trate stream to realise a TMP of 10 bar at a feed flowrate of 300 L/h [12]. Subsequently, during experiments to map out system perfor mance, the power was increased from 45 to 280 W (10 steps) and the set point of the regulating valve adjusted to achieve a pressure of 4 12 bar (or the maximum bounds of operation). Operation at each step was maintained for 20 min to achieve steady state conditions. With these additional experimental constraints, which were not considered by Feron [14], the resulting form of the SOW is now a curve sided pentagon as shown in Fig. 1.

Specifically, the following steps were followed in order to determine the SOW:

i. Experiments were performed to map out the whole system operating range for key input parameters: power, feed pressure and feed flowrate as described above (see Fig. 2).
ii. The operating range of the membrane system was plotted according to the input parameters of TMP and feed flowrate (Fig. 2A) to form the basis of the SOW (see Fig. 3). The best method of plotting the operating window was to plot feed flow rate over TMP using the lines of constant set point and providing a platform to plot other relations on top.

Table 1
Membrane performance characteristics (standard set-point conditions of 240 W pump motor power, TMP 10 bar, feed flowrate 300 L/h, feedwater with concentration 5500 mg/L NaCl and temperature 13.5 ± 1.0 °C).

Module	Retention (%)	Recovery (%)	Permeate flowrate (L/h)	Flux (L/m^2 h)
New BW30	97.0	28	72	10.0
Aged BW30	92.0	30	90	12.5
NF90	91.6	45	135	18.8

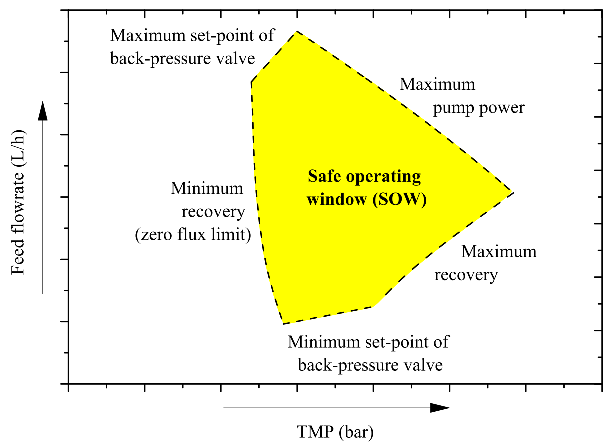

Fig. 1. Graph outlining the principle of the experimentally determined SOW of a membrane system constrained by (clockwise from left hand side): minimum recovery (zero flux limit), the maximum set-point of the back-pressure valve, the maximum pump power, maximum recovery and the minimum set-point of the back-pressure valve.

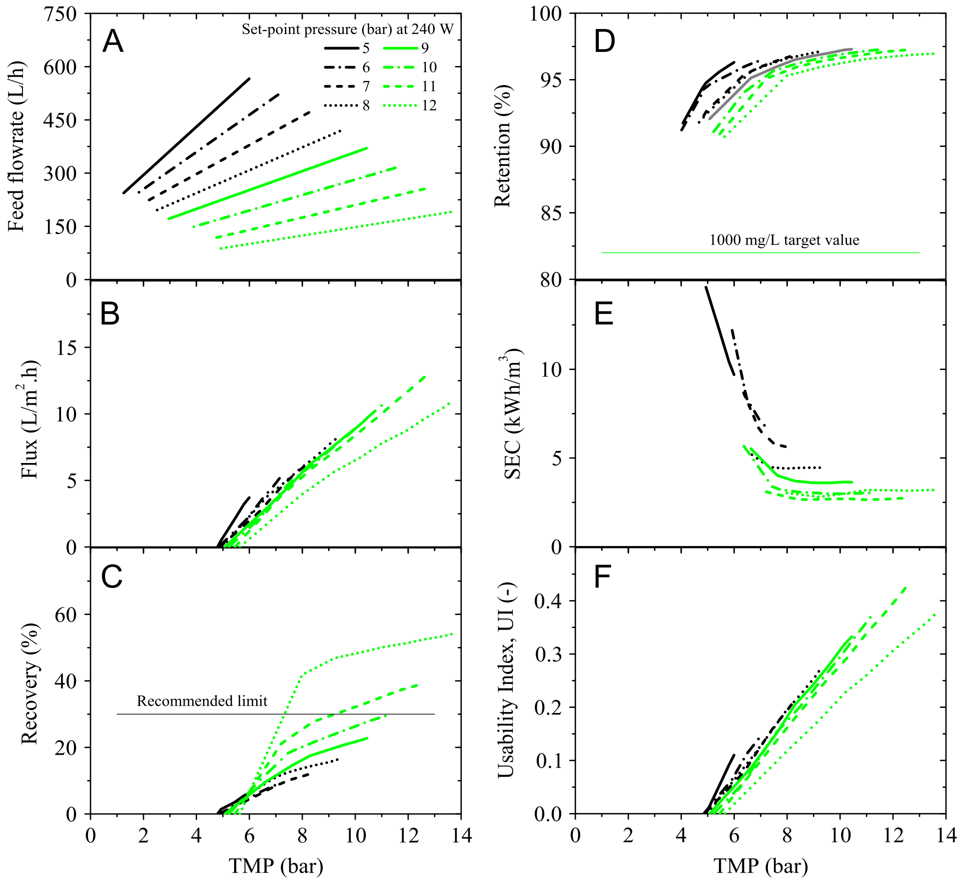

Fig. 2. Steady-state performance of membrane system at 240 W mapped out over whole operating range as a function of set-point pressure (new BW30, 5500 mg/L NaCl).

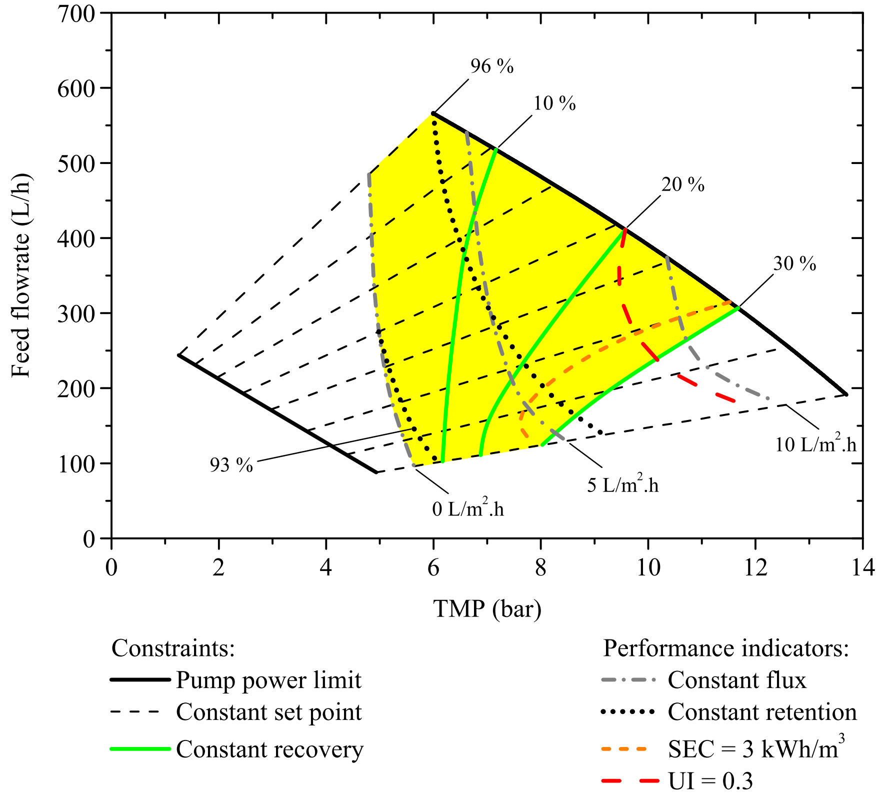

Fig. 3. SOW (shaded area) showing constraints to safe operation and performance indicators (new BW30 module, 5500 mg/L NaCl).

iii. Lines corresponding to the limitations of the pump power on TMP and feed flowrate range were plotted onto the SOW in Fig. 3.
iv. Based on the relationship of recovery to TMP and set point pressure (Fig. 2C), lines of constant recovery were added to Fig. 3. For example, to plot the 30% recovery line, the 10, 11 and 12 bar set point lines in Fig. 2C were used to find the TMP at 30% recovery. This was then plotted onto the SOW using the TMP and corresponding set point line.
v. The relationships of flux, retention, SEC and UI to TMP and set point pressure were used to add constant lines to the SOW as described above for recovery.
vi. The boundaries of the SOW in terms of pump power, zero flux, 30% recovery and the maximum and minimum set point pressure lines were used to determine the SOW shaded in yellow (Fig. 3).

3. Results and discussion

3.1. Mapping out wind membrane system performance

An example of mapping out the steady state performance as a function of TMP is shown in Fig. 2 for the new BW30 membrane and 5500 mg/L NaCl feedwater. Feed flowrate increased linearly with TMP (Fig. 2A), but at higher set point pressures the feed flowrate reduced as the positive displacement pump could not maintain high flowrates at high TMP. Flux commenced after the osmotic pressure of 4.36 bar is overcome (Fig. 2B) and increased with TMP. Some concentration polarisation (CP) was observed at high TMP, indicated by the departure from linearity. Recovery at higher pressures (Fig. 2C) was greater than the desired 30% limit for the 11 and 12 bar set point pressures; however, the 10 bar set point line yielded the second highest flux of 11.5 L/m^2 h at a TMP of 11.5 bar and with recovery of 30%. Therefore, this would be a better set point pressure at which to operate the system. The knee in the recovery data is caused by the decreasing slope of the flux combined with the significantly lower feed flowrates at higher TMPs (as can be seen in Fig. 1A and B). Retention (Fig. 2D) of the new BW30 membrane was well above the minimum required to meet the target permeate concentration value over the whole operating range, and increased with TMP. SEC (Fig. 2E) decreased with increasing TMP to a minimum value of 2.6 kWh/m^3 at the 11 bar set point pressure setting. Although the 11 bar set point line yielded the best overall performance in terms of UI (Fig. 2F), the set point pressure of 10 bar provided the highest UI within the recommended recovery limit of 30% (Fig. 2C). Therefore, this would be the optimum set point for the wind membrane system to maximise the performance within target limitations for this particular membrane and feedwater.

Other combinations of membrane module and feedwater concentration new BW30 with 10,000 mg/L NaCl, aged BW30 with 5500 mg/L NaCl, and NF90 with feed concentrations of 5500 and 2750 mg/L NaCl are presented in the supplementary information (Figs. S1 S4). Maximum flux and minimum SEC were achieved under similar TMP and feed flowrate conditions for each membrane and feed concentration. This is highlighted by the fact that the set point lines that achieved maximum performance in terms of flux and SEC were all in the range 9 12 bar. However, due to operation at low feed flows (the maximum for both BW30 and NF90 modules is 3.6 m^3/h) the maximum retention was achieved at lower TMP and higher feed flowrates with set point pressure lines of 6 9 bar. Higher crossflow velocity increases the SEC. This highlights the trade off that needs to be made between maximising the retention versus operating at higher flux and SEC albeit with a slightly lower retention. This decision depends on the feedwater characteristics, with higher feedwater salinities requiring higher operating pressure and crossflow velocity.

3.2. SOW as a function of membrane type and feed concentration

3.2.1. Establishing the SOW

The results from Section 3.1 were used to define the SOW of the wind membrane system and to determine the main constraints of operation. The methodology for determining the SOW can be used for optimising the performance of any membrane system (whether powered by RE or grid electricity) and is described in detail in the supplementary information. The SOW for the new BW30 module with feedwater concentration of 5500 mg/L NaCl was mapped out in terms of TMP and feed flowrate. The lines in Fig. 3 correspond to, firstly, the operating constraints (pump power limits, recovery limit and constant set point line relating TMP to flowrate) and, secondly, to performance (constant flux, constant retention, SEC and UI). The performance lines: (i) illustrate the impact of TMP and feed flowrate on performance; (ii) show the best operating region within the SOW, and (iii) allow performance comparison between the different SOWs (comparing Fig. 3 and Figs S4 S8). The main constraints that define the SOW were categorised as follows:

i. Pump motor power: the available power limited the values of both TMP and feed flowrate achievable, besides determining the relationship between the two parameters as shown by the constant set point lines. The helical progressive cavity pump used in this work had a maximum rated power of 300 W and the system operated using a minimum of 45 W. This restricted the operating limits to TMP to 1.4 13.7 bar and a feed flowrate of 90 570 L/h.
ii. Osmotic pressure: this must be overcome by the pump to produce flux depending on the feedwater concentration, membrane module and the recovery. Higher feedwater concentrations, membranes with greater permeability, and increased recovery all result in increased osmotic pressure. The osmotic pressures at 13 °C for the 2750, 5500 and 10,000 mg/L NaCl feedwaters are 2.18, 4.36, and 7.92 bar, respectively. The minimum TMP required for the new BW30 module to produce flux with feedwater of 5500 mg/L NaCl is shown by the zero flux line in Fig. 3. The impact of increasing the recovery on the osmotic pressure is demonstrated by the increased TMP required to produce flux at low feed flowrates. The minimum pressure required to produce water was 4.8 bar, 4.3 bar and 3.9 bar for new BW30, aged BW30, and NF90 membranes, respectively. At 10,000 mg/L NaCl, the new BW30 produced permeate at 8.4 bar, while the NF90 worked from 2.2 bar at 2750 mg/L NaCl. This highlights the impact of reduced osmotic pressure when using membranes with increased permeability.
iii. Permeate quality: the feedwater concentration determines the minimum retention required to meet the 1000 mg/L target value. This is also dependent on the type of membrane module and operating conditions. The retention was not a constraint for the BW30 membrane with the 5500 mg/L NaCl feedwater (Fig. 3). However, for the aged BW30 (Fig. S6) and NF90 (Fig. S7), the SOW was constrained at low pressure and feed flowrate (low recovery) by the minimum retention (82%) required to produce permeate to meet the target value. Thus, retention degrades with time, while lower retention NF membranes will have a narrower SOW.
iv. Recovery: Although high recoveries with brackish waters are achievable under certain conditions [27], in the case of small scale systems designed to operate without chemical additions, the maximum recovery to prevent scaling and fouling is typically recommended to be in the range of 20 30%

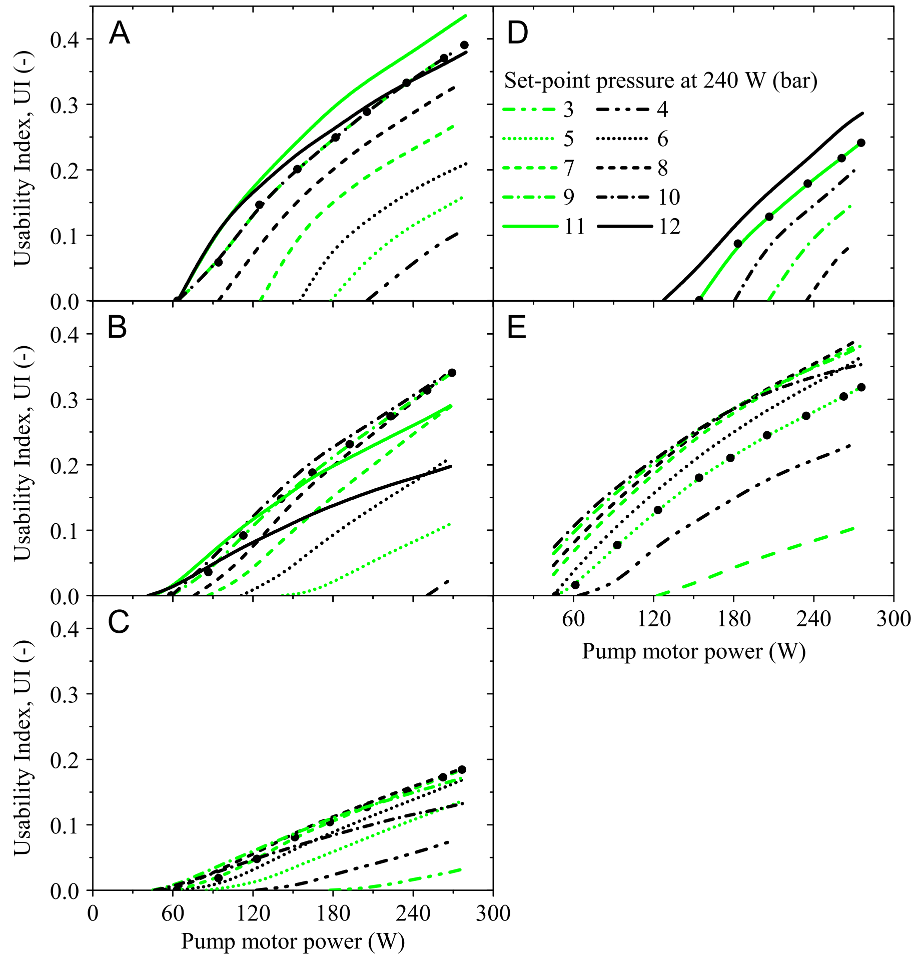

Fig. 4. Determination of most suitable UI within the SOW according to membrane module and feedwater concentration (A–E). The optimum set-point pressure for each combination of membrane and feedwater salinity is shown by the solid circle symbol (•). (A) New BW30: 5500 mg/L, (B) Aged BW30: 5500 mg/L, (C) NF90: 5500 mg/L, (D) New BW30: 10000 mg/L and (E) NF90: 2750 mg/L.

[21,28,29]. There is also an impact on power consumption, with lower SEC values occurring at low recoveries (in the range 20 30%) [9]. In this work, the maximum recovery of 30% was chosen for the synthetic NaCl feedwater and Fig. 3 demonstrates how this restricted the SOW at high pressure and low flowrate. The main impact of the limiting recovery was the reduced flux that could be achieved (Figs. S6 S8). In applications with more complex feedwater composition this depends on the presence of likely foulants and scalants. Thus, a detailed study of the specific feedwater characteristics would be essential before the actual limiting recovery was determined and implemented in a small community based system.

v. Membrane: The mechanical limitations restrict the maximum hydraulic loads (feed pressure and flowrate) due to potential damage caused by excessive mechanical stresses on the mem brane module [21]. However, the maximum ratings for the BW30 module were feedwater pressure of 41 bar, feed flowrate of 3600 L/h and pressure drop of 1 bar [21] and therefore posed no limitation on the SOW. The manufacturer recommends the pressure to be increased gradually over a period of 30 60 s, which corresponds to a maximum rate of change of 82 bar/min. To date, the most rapid simulated wind energy fluctua tions achieved over a period of 15 s resulted in a rate of change of 54 bar/min [12], and thus mechanical damage is not expected due to short term performance variations.

3.2.2. Impact of feedwater salinity

Increasing the feedwater concentration to 10,000 mg/L (Fig. S5) resulted in: (i) the SOW shifting to higher TMP due to the higher osmotic pressure; and (ii) relaxed the maximum recovery con straint due to lower flux over the operating range. Permeate quality from the BW30 module still met the 1000 mg/L target (Fig. S1C); however, the pressure limitations of the pump and low flux resulted in a relatively high SEC and low UI.

3.2.3. Impact of membrane type

Use of the aged BW30 (Fig. S6) resulted in lower retention restricting the SOW at low values of TMP and feed flowrate. The flux and recovery of the aged BW30 were slightly higher than the new BW30. The SOW for the NF90 with the 5500 mg/L NaCl feedwater (Fig. S7) was also restricted by the minimum retention (82%) required to achieve the 1000 mg/L target value. Due to the higher permeability of the NF90, the SOW was much narrower because of the maximum recovery limitation. With 2750 mg/L NaCl, the SOW for NF90 (Fig. S8) was narrower again, due to the lower osmotic pressure of the feedwater allowing increased flux and therefore recovery.

3.2.4. Experimental versus simulated SOWs

In contrast to Feron [14] and Pohl et al. [16] who did not include pump choice and focused on seawater, in the present study, the retention was only a constraint for the aged BW30 (Fig. S6) and the

NF90 (Fig. S7) membranes with the 5500 mg/L NaCl feedwater at the minimum range of TMP and feed flowrate. This presents an interesting opportunity in the design of small scale brackish water systems in that it may be advantageous to use a membrane with higher permeability at the risk of exceeding the retention limitation at low TMP and flowrate for short periods, thus allowing operation at lower pressure with increased flux and lower SEC, as for the case of NF90 (Fig. S7).

3.3. Optimum operating strategy

3.3.1. Constant set point operating strategy

The system operates along one of the set point lines plotted in the SOW (Fig. 5) according to the available power and the initial set point (position of regulating valve on the concentrate stream). The desired optimum performance was defined as

i. operation within the bounds of the SOW over the whole range of TMP and feed flowrate;
ii. production of the maximum flux and minimum SEC within the bounds of the SOW; and
iii. permeate water quality below the target value.

Therefore, the UI parameter was selected for demonstrating the optimum set point operation for the combinations of membrane module and feedwater concentration (Fig. 4). The optimum set point line was found to be a function of the permeability of the membrane and feedwater concentration. With a feedwater of 5500 mg/L the performance of the new BW30 was the highest within the SOW when operated at a set point of 10 bar (Fig. 4A), while for the aged BW30 and NF90, the optimum set points were 9 bar and 8 bar, respectively. The latter membranes exhibit higher permeability than the new BW30, therefore reaching the 30% recovery limit at a lower TMP and thus limiting the maximum set point.

The optimum set point lines in Fig. 4D and E show the pump motor operating close to its efficient operation limits with 10,000 and 2750 mg/L, respectively. With 10,000 mg/L feedwater, there was no permeate produced below 155 W and the optimum set point within the SOW was 11 bar. With the NF90 and 2750 mg/L, the optimum set point was 5 bar (Fig. 4E). As a result of the low salinity feedwater and high membrane permeability, the maximum recovery was achieved at a TMP of only 4 bar and a feed flowrate of 180 L/h with an 8 bar set point. For lower salinity feedwaters it could be more beneficial to use an NF90 membrane with a pump that provides lower pressure and higher flowrate in order to increase the flux and reduce the maximum recovery. In terms of the RE generator, this may require increasing the voltage output to accommodate a higher flowrate pump motor.

3.3.2. Alternate operating strategies

The next challenge was to investigate whether other operating strategies are viable for maximum performance under variable operation of the wind membrane system, and which of these are the most beneficial in terms of system performance, range of operation and feasible implementation.

The following potential operating strategies considered in Fig. 5 are as follows:

- *Constant TMP (10 bar)*: implemented by varying the feed flowrate. This would involve operating the system at relatively constant current (3.1 3.3 A) by varying the voltage and the regulating valve on the concentrate stream, achieved using automatically actuated valves or a hydraulic accumulator [18,30,31]. This operating strategy would be difficult to implement within the constraints of the SOW while maximising system performance.
- *Constant recovery (28%)*: varying flow and pressure as a function of power is typically achieved in small systems by using a

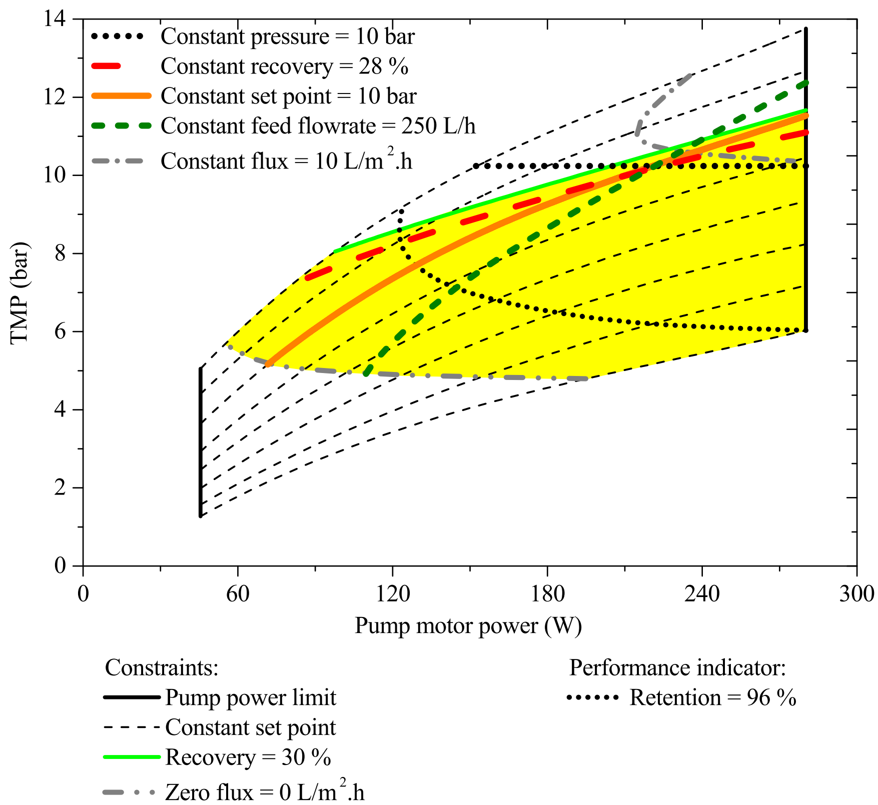

Fig. 5. SOW plotted against pump motor power (new BW30 module, 5500 mg/L NaCl feedwater) showing the various operating strategies that could be used for variable operation in order to maximise flux and retention.

positive displacement pump that provides a fixed ratio of feed and concentrate flow and hydraulic energy recovery [19,28,32]. A recovery of 28% was chosen as this allowed comparison between the various operating strategies, all passing through the point of 10 bar TMP and 250 L/h feed flowrate.

- *Constant set point*: the operating strategy was used for this system, where a set point of 10 bar at 240 W and 250 L/h would be set using the regulating valve on the concentrate stream.
- *Constant feed flowrate (250 L/h)*: implemented by varying the pressure. This would involve keeping the voltage in a relatively narrow range (50 70 V_{DC}) and varying the current and the regulating valve on the concentrate stream. Operation would exceed the bounds of the SOW at high power (> 250 W).

Fig. 5 shows the various possible operating strategies for the new BW30 membrane with 5500 mg/L NaCl feedwater, now replotted as a function of power to better understand the implications for the RE generator. Each of the operating strategies was focused to achieve high flux and low SEC. Also shown in Fig. 5 is a line of constant flux (10 L/m^2 h in this case). This is a common operating strategy for RO systems, whereby the feed pressure is varied over time to allow for changes in feedwater temperature or salinity, as well as flux decline due to fouling. It can be seen that the SOW with this method is quite restricted and therefore it is not considered further in this work.

3.3.3. Performance comparison of operating strategies

With the potential operating strategies defined, the choice of the optimal strategy should satisfy the following criteria:

i. allow the membrane system to operate within the SOW for the maximum amount of time;
ii. optimise the performance in terms of water productivity and retention at low SEC;
iii. operate over a wide power range to utilise the power output from the wind turbine efficiently; and
iv. be robust, cost effective and simple to implement.

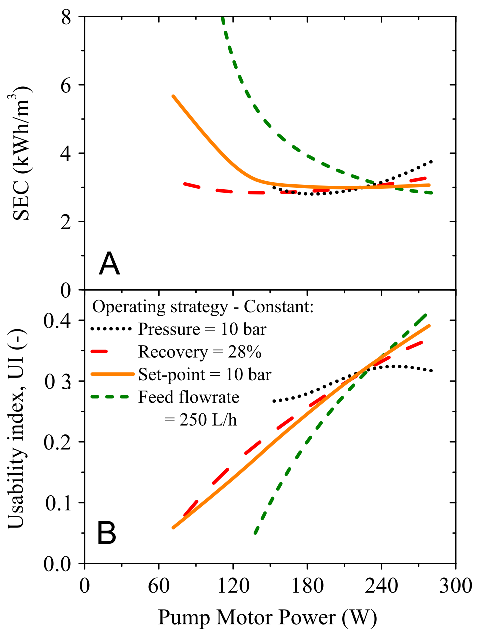

Fig. 6. Performance comparison of operating strategies over whole range plotted as (A) SEC, and (B) UI.

A performance comparison of the operating strategies (data from Fig. 5) are shown in terms of the SEC (Fig. 6A) and UI (B). For the discussion below, a good UI value can be regarded as one that remains well above zero, for example UI ≥ 0.05, over the widest possible range of operating powers. *Constant recovery operating strategy* showed best performance with low SEC (~ 3 kWh/m^3) and a good UI (in range 0.05 0.37) were maintained over the whole operating range. In addition, this strategy fulfilled the desired criteria by having a wide power range (80 280 W) and narrow pressure range (7 11 bar). *Constant TMP operation* had a relatively low SEC and excellent UI of 0.27 0.33, but this was greatly limited by the load range as the power must be > 150 W to achieve 10 bar. In addition, at below 210 W this strategy resulted in operation outside the SOW that resulted in poor overall performance. While this type of operation may be used for large scale systems operated with constant power, with fluctuating power this is not a beneficial strategy. *Constant feed flowrate operation* exhibited the poorest performance highest SEC and lowest UI over the majority of the power range due to low TMP and therefore low flux. This operating strategy would result in a relatively narrow power range (110 280 W) with a wide pressure range 5 12.5 bar and therefore does not meet criteria (ii) and (iii) above. *Constant set point operation* exhibited low SEC (~3 kWh/m^3) above 150 W and good UI (0.05 0.40) being maintained over the whole operating range. A high SEC (up to 6 kWh/m^3) was observed at low power due to the relatively low TMP (5 7.5 bar). This strategy would have a wider power range (70 280 W) and suitable pressure range (5 11.5 bar) and therefore fulfilled the first three criteria for the operating strategy.

Thus, the implementation of criterion (iv) above is now considered for the two most promising operating strategies, constant recovery and constant set point. Constant recovery operation requires either a piston pump [13,28,32,33] or an actuator controlled regulating valve on the concentrate stream to handle fluctuations in power. Apart from additional cost and complexity, the response rate of the valve may result in reduced energy efficiency [16], piston pumps are known to require increased maintenance [34], and the valves in certain pressure recovery devices for small systems are known to perform poorly after longer periods of field operation [35]. Thus these components are not well suited for remote RE membrane installations. Therefore, for the sake of robustness and ease of implementation, the constant set point operating strategy was considered to be the best operating strategy for the current system. This means sacrificing SEC at low power and accepting an additional 2.5 bar variation to the maximum pressure range when compared to constant recovery operation. However, there was no reduction in the average UI and slightly increased performance from the minor reduction of 10 W in the power required to initiate permeate flow. Importantly, choosing constant set point operation does not result in a more complex system, as predicted by [14], and another paper by the authors details the time spent within the SOW when operated using real wind fluctuations [26].

3.3.4. Constant set point operation as a function of wind speed

The expected productivity as a function of average wind speed as an example of RE operation was determined. This is important to determine the feasibility in a specific location according to the available wind resource and feedwater concentration. Fig. 7 shows water productivity, permeate NaCl concentration and SEC as a function of constant wind speed. With 5500 mg/L NaCl feedwater and at moderate wind speed of 7 m/s, the new BW30 membrane could produce 1.0 m^3 of permeate with concentration of 200 mg/L at an average SEC of 3.1 kWh/m^3, while the NF90 module could produce 1.8 m^3 at an average of 450 mg/L and SEC of 2.1 kWh/m^3.

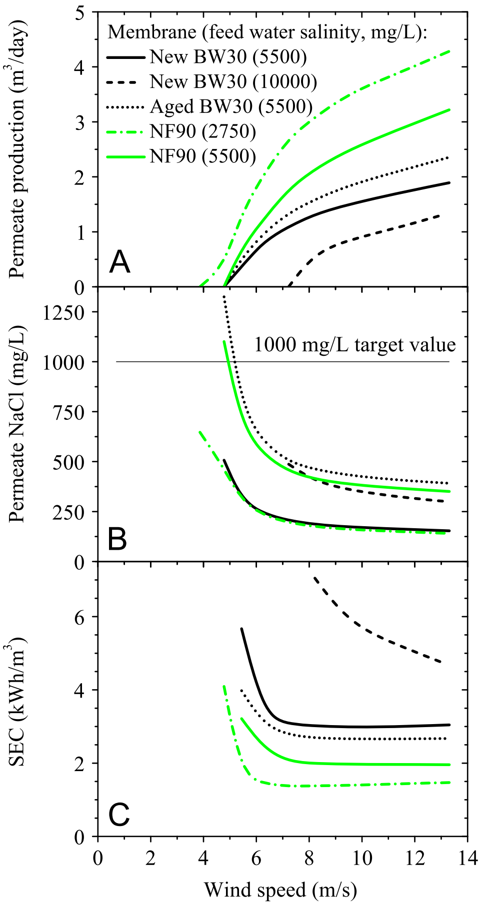

Fig. 7. Performance of wind-membrane system using optimum set-point within SOW for various membrane modules and feedwater concentrations plotted as (A) permeate production, (B) permeate NaCl concentration, and (C) SEC.

Over the entire range of wind speeds, the NF90 membrane produced 70% more water (Fig. 7A), slightly higher permeate NaCl concentration (Fig. 7B), at 35% lower SEC (Fig. 7C) than the new BW30 module. The aged BW30 has increased productivity (~25%), double permeate NaCl concentration, and a lower SEC (13%) than its new counterpart. For NaCl removal, the NF90 would provide lower water costs due to the increased productivity within the SOW; however if there were high concentrations of monovalent ions in the feedwater, then the BW30 may need to be used to increase the retention to achieve a particular guideline value for specific contaminants [36]. A separate paper investigates the performance of a wind membrane system operating under 24 h of high resolution fluctuating wind, including the effectiveness of (i) set point operating strategy and (ii) super capacitor energy buffering, as well as (iii) the fraction of time that the system remains within the SOW [26].

4. Conclusions

The methodology for determining the SOW for a RE powered membrane system is developed. Detailed SOWs are determined for an autonomous wind membrane system using both a BW30 (both new and aged) and NF90 membrane modules with brackish feedwater concentrations of 2750, 5500 and 10,000 mg/L NaCl. At lower salinities, the main constraint to the SOW was the chosen maximum recovery (30%), while at higher concentrations the osmotic pressure played a more dominant role. Different operating strategies were evaluated, with the optimum shown to be constant recovery, which produces the highest flux at a given power consumption and thus the lowest SEC while maintaining good retention. However, since the implementation of this can be difficult in practice, constant set point mode is recommended as the operating strategy for such systems with minor reduction in performance in order to provide a robust and effective solution in remote areas.

Acknowledgements

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Supplementary Information

Renewable Energy Powered Membrane Technology: Safe Operating Window of a Brackish Water Desalination System

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Results and discussion

By increasing the feed water concentration from 5500 mg/L NaCl to 10,000 mg/L, the bulk osmotic pressure of the feed water increased from 4.4 bar to 8 bar. This resulted in a smaller operating range for the BW30 module due to the minimum TMP required to produce flux. This is demonstrated by the minimum set-point pressure line of 7 bar (Fig. S1A) compared to 5 bar in Fig. 1A. As would be expected, the higher osmotic pressure resulted in poorer operational performance. The maximum flux of 10.1 $L/m^2.h$ was achieved with a set-point pressure of 12 bar, however there were no visible effects of concentration polarisation (CP) due to the relatively low recovery (Fig. S1C) compared to the values in Fig. 7.1C. The maximum retention of 97% was achieved by the 11 bar set-point pressure line at TMP of 12.6 bar and feed flowrate of 256 L/h. However, the minimum SEC with the 11 bar set-point line was 4.6 kWh/m^3 which was higher than the minimum of 3.8 kWh/m^3 achieved with the 12 bar set-point line. This demonstrates that higher feed flowrates are necessary to optimise the retention, while higher TMP at the expense of feed flowrate is required to optimise the flux and SEC. However, optimising the flux and SEC is done at the risk of higher recovery (35 – 40% compared to 20 – 25%), which could increase the risk of scaling, and would need to be managed according to the feed water characteristics.

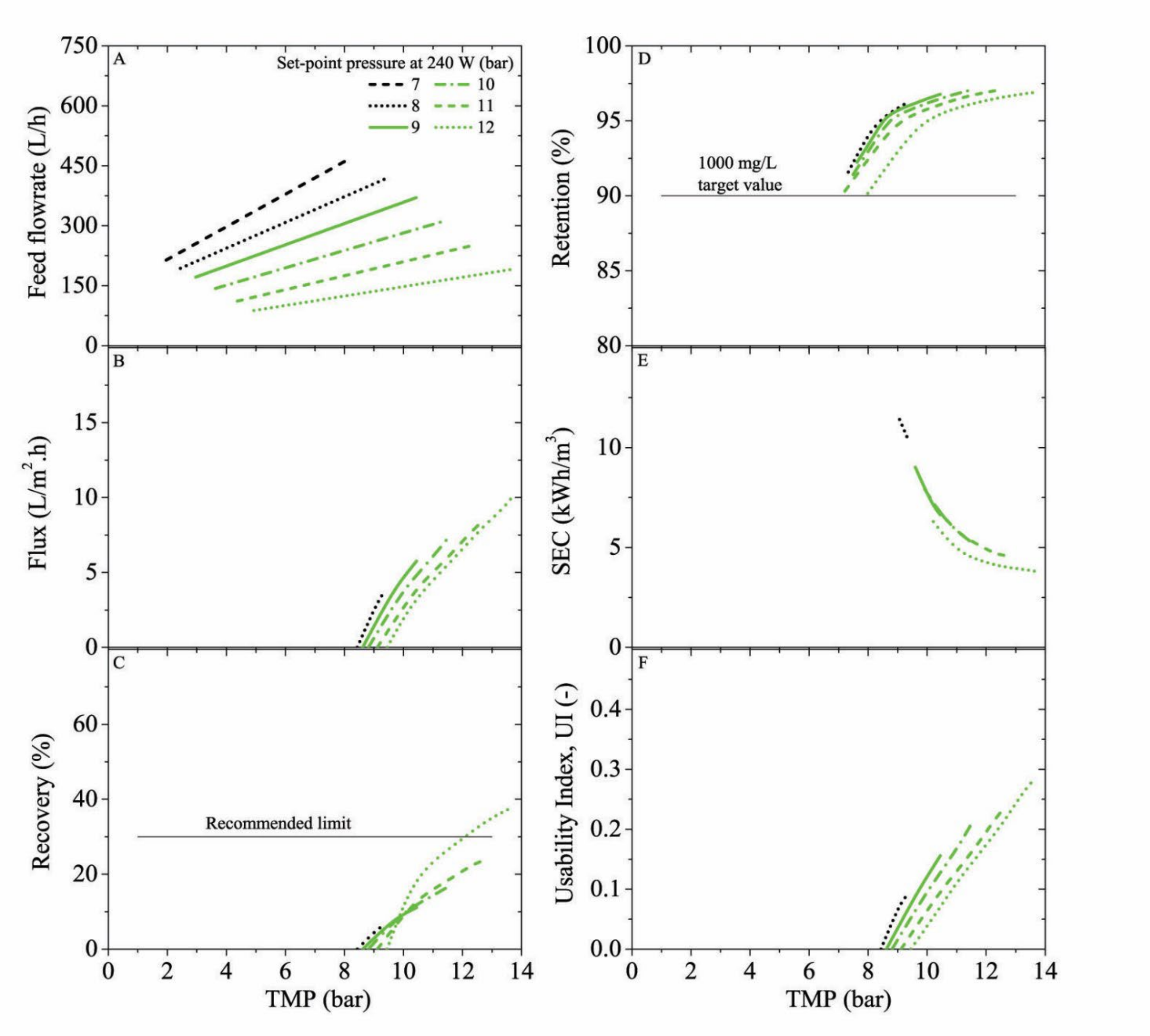

Fig. S1. Steady-state performance of membrane system mapped out over whole operating range according to position of regulating valve on concentrate stream (new BW30, 10,000 mg/L NaCl).

The aged BW30 module had a wider operating range (Fig. S2A) with the 5500 mg/L NaCl feed water than the new BW30 module (Fig. 1A). This is shown by the 4 bar set-point pressure line (Fig. S2A) that was possible with the aged BW30 due to lower osmotic pressure and resistance to flow. The maximum flux (Fig. S2B) of 15.4 L/m^2.h, achieved with the 10 bar set-point pressure line, was 20% higher than the flux achieved with the new module (Fig. 1B). The maximum retention of 92.8% (Fig. S2D) achieved with the 7 and 8 bar set-point pressure lines was significantly lower than the retention of 97.3% achieved with the new module, however the minimum SEC of 2.4 kWh/m^3 was 23% lower.

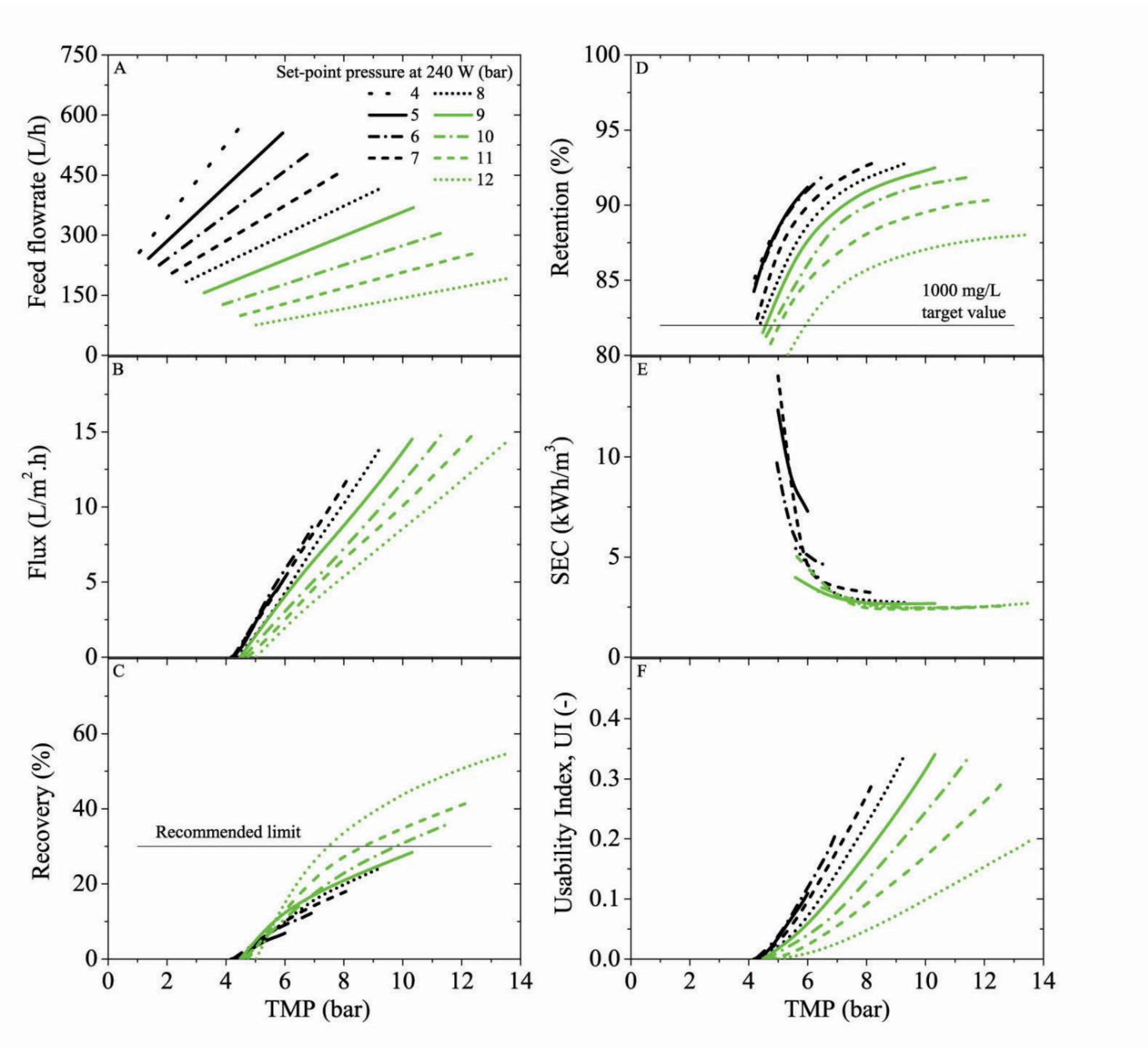

Fig. S2. Steady-state performance of membrane system mapped out over whole operating range according to position of regulating valve on concentrate stream (aged BW30, 5500 mg/L NaCl).

The productivity of the NF90 membrane module (Fig. S3) was significantly higher than with the BW30 (Fig. 1) for the same feed water concentration (5500 mg/L NaCl). This is shown by the maximum flux of 21.6 L/m^2.h (Fig. S3B) achieved with the 9 bar set-point pressure line, compared to 12.8 L/m^2.h with the BW30 module (Fig. 1B). The maximum recovery reached 58 % (Fig. S3C) due to the higher productivity of the NF90 module. The maximum retention of 94.2 % (Fig. S3D) was achieved with a set-point pressure of 7 bar, highlighting the lower operating pressure range required for this membrane. The minimum SEC of 1.6 kWh/m^3 (Fig. S3E), was significantly lower than 2.6 kWh/m^3 with the BW30.

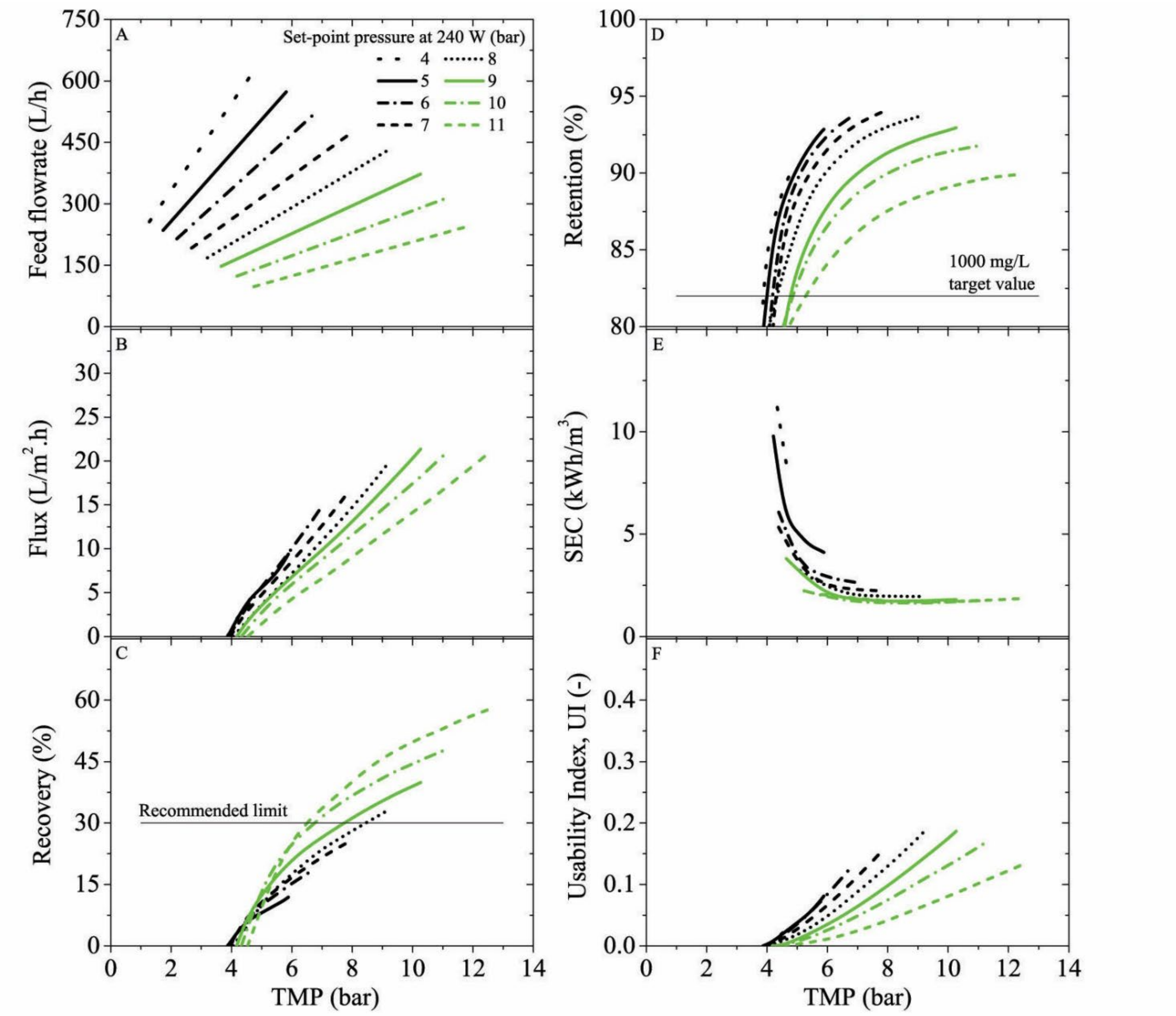

Fig. S3. Steady-state performance of membrane system mapped out over whole operating range according to position of regulating valve on concentrate stream (NF90, 5500 mg/L NaCl).

As would be expected, the productivity of the NF90 increased significantly by halving the feed water concentration from 5500 mg/L (Fig. S3) to 2750 mg/L NaCl (Fig. S4) due to reduced osmotic pressure. The maximum flux of 33 L/m^2.h (Fig. S4B), achieved with a 9 bar set-point pressure line, was 53% higher than with the 5500 mg/L NaCl feed water. The lower osmotic pressure of the feed water allowed high recovery up to a maximum of 74 % (Fig. S4C). The maximum retention of 95.5% was achieved with the 6 bar set-point pressure line (Fig. S4D), and the minimum SEC of 0.77 kWh/m^3 with the 10 bar set-point line (Fig. S4E).

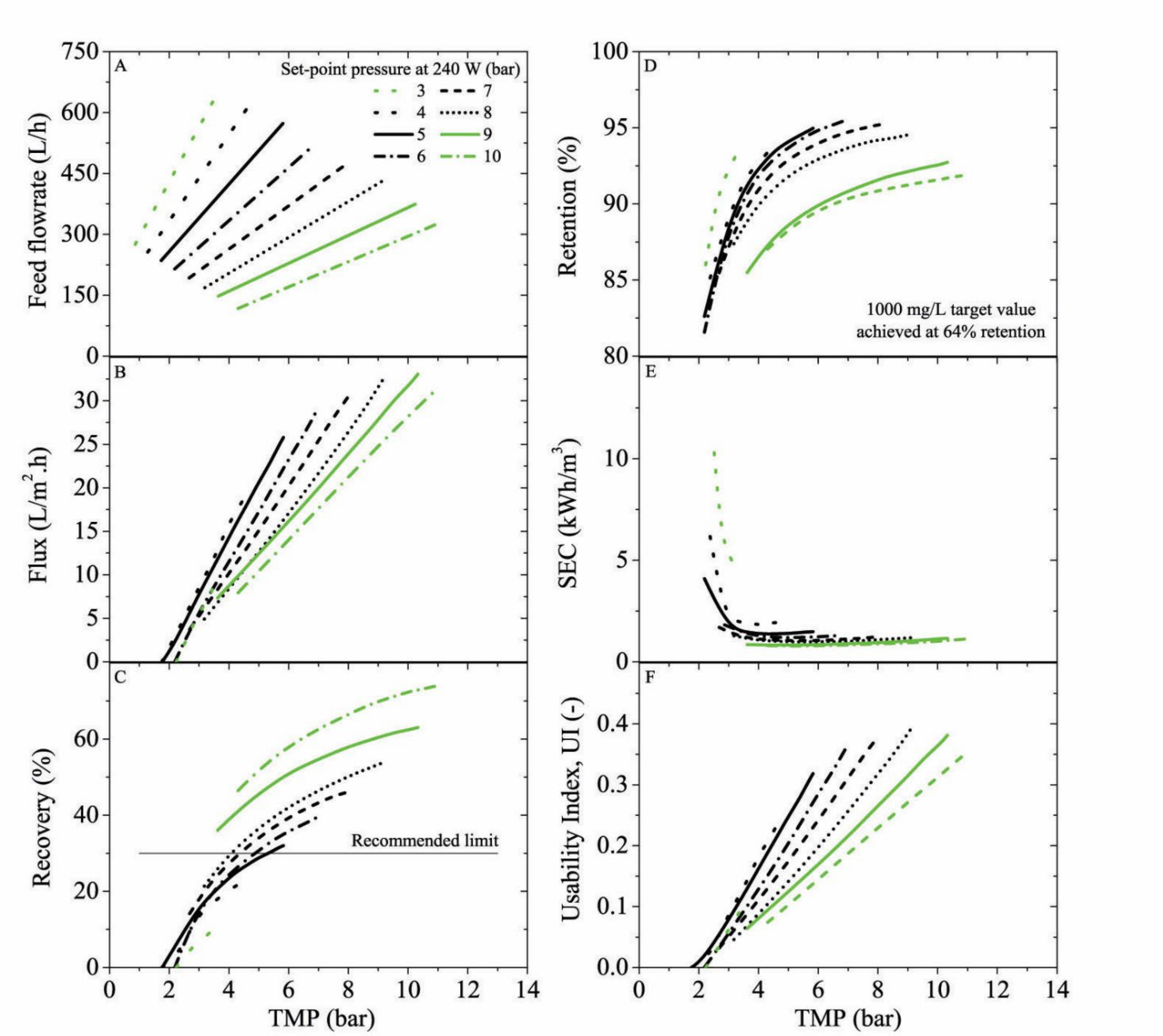

Fig. S4. Steady-state performance of membrane system mapped out over whole operating range according to position of regulating valve on concentrate stream (NF90, 2750 mg/L NaCl).

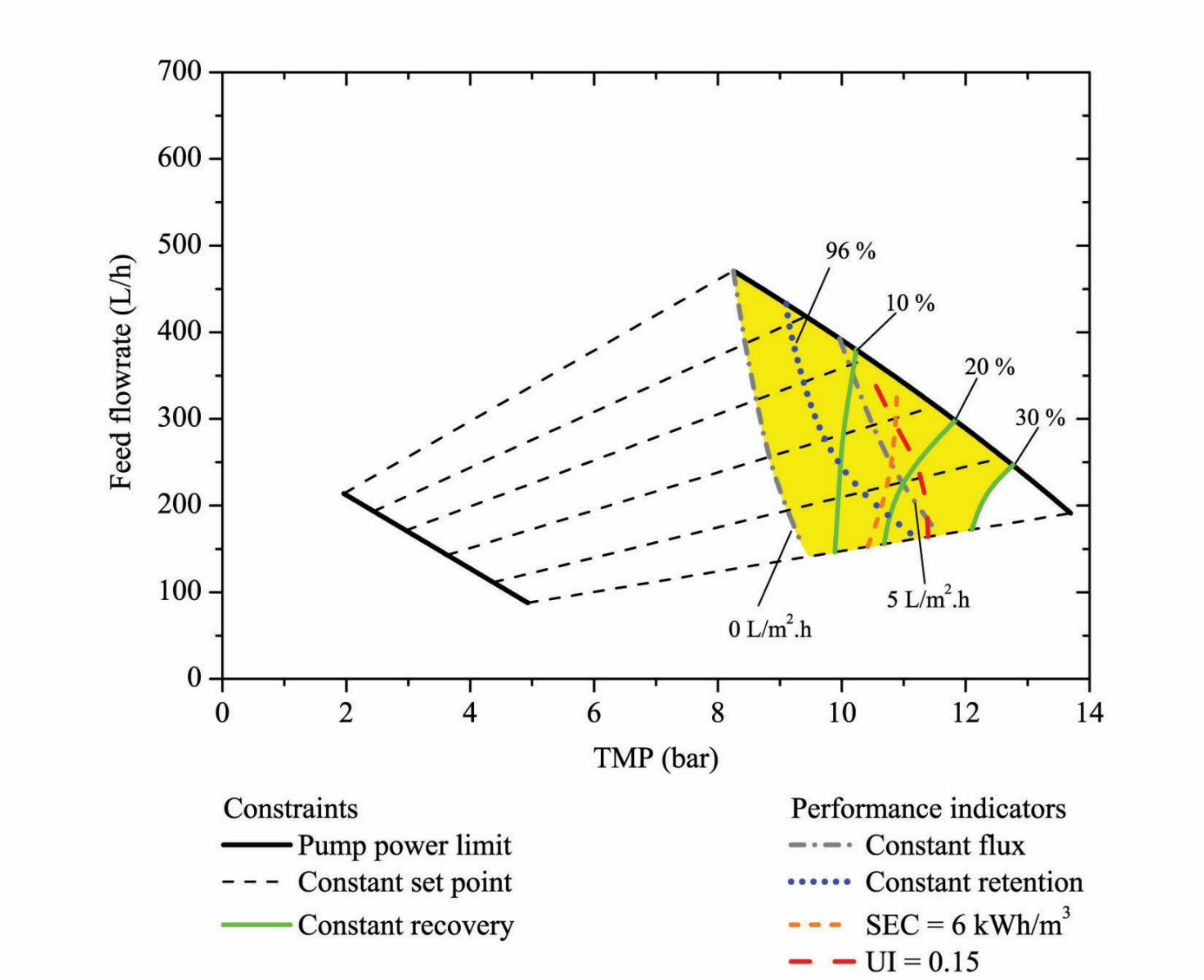

Fig. S5. SOW (shaded area) showing constraints to safe operation and performance indicators (new BW30 module, 10,000 mg/L NaCl).

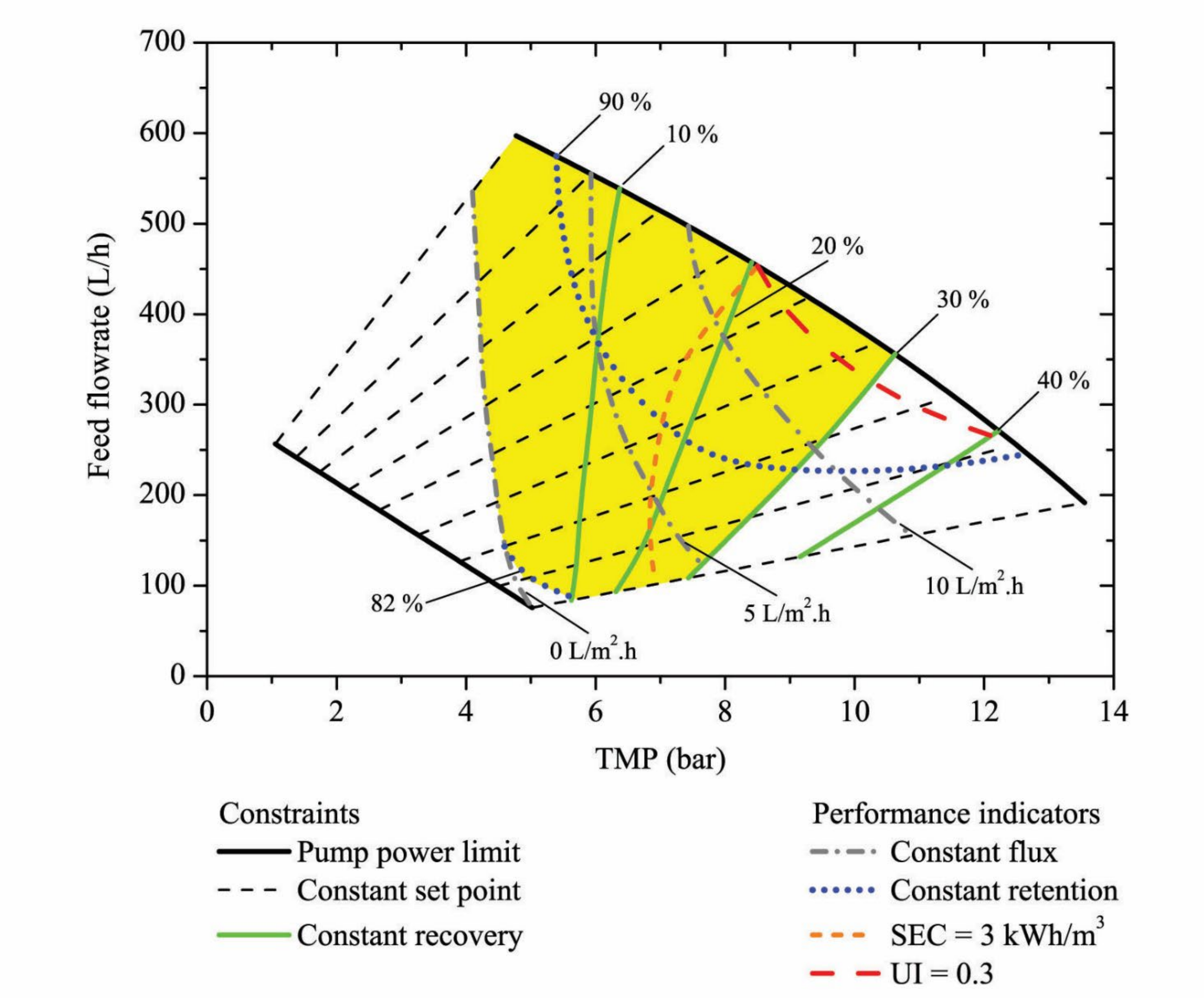

Fig. S6. SOW (shaded area) showing constraints to safe operation and performance indicators (aged BW30 module, 5500 mg/L NaCl).

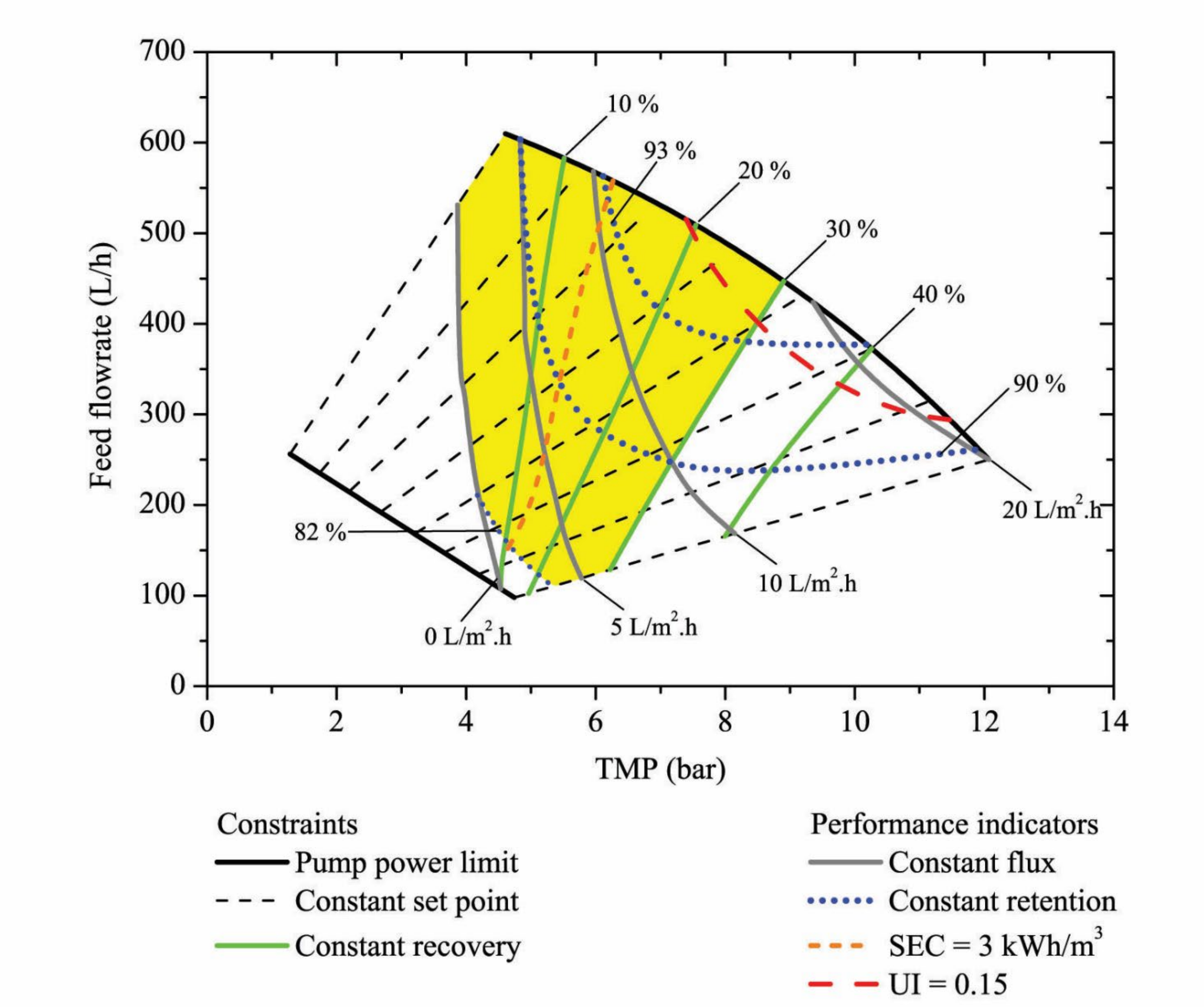

Fig. S7. SOW (shaded area) showing constraints to safe operation and performance indicators (NF90 module, 10,000 mg/L NaCl).

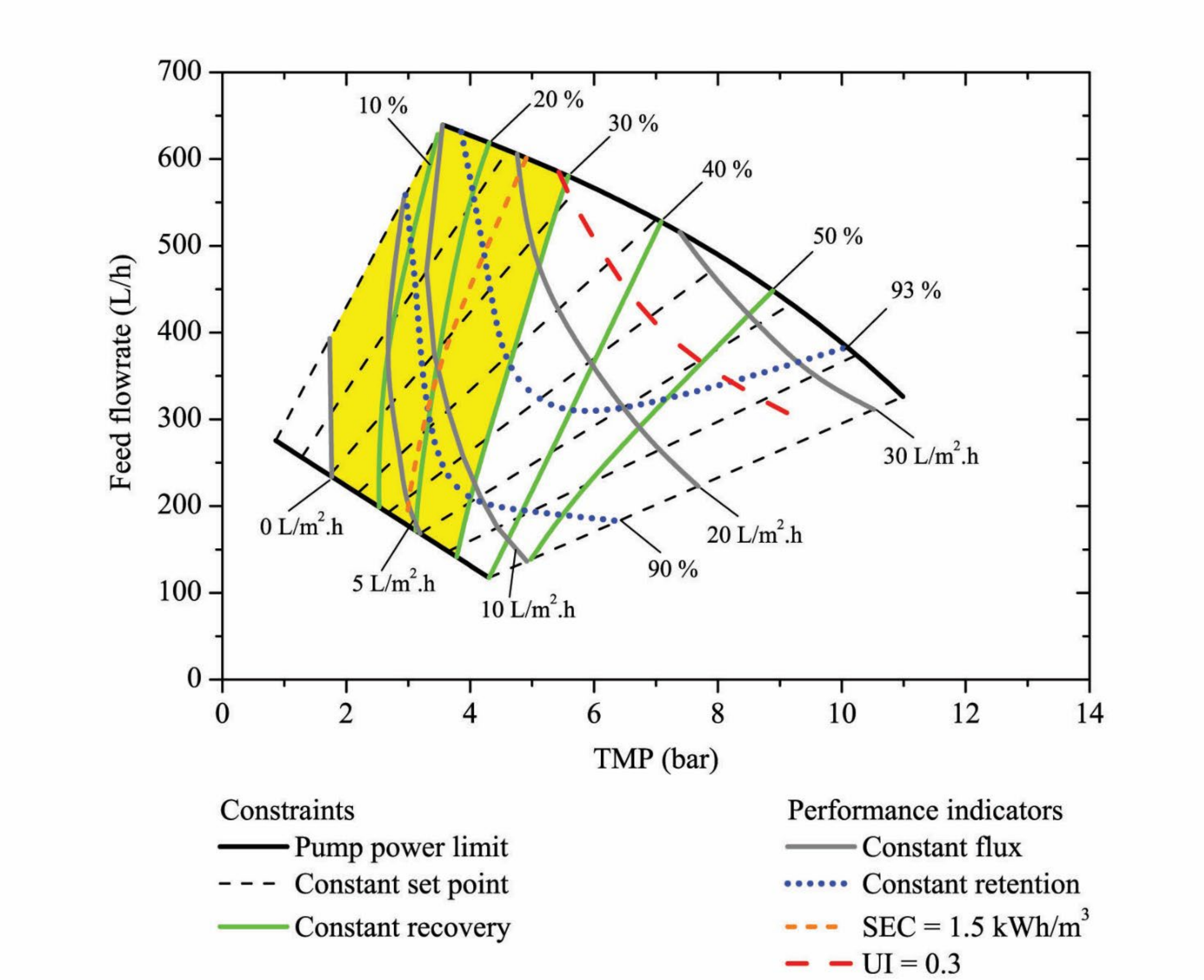

Fig. S8. SOW (shaded area) showing constraints to safe operation and performance indicators (NF90 module, 2750 mg/L NaCl).