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A Natural Driven Membrane Process for Brackish and Wastewater Treatment: Photovoltaic Powered ED and FO Hybrid System

Yang Zhang,[†,#,*] Luc Pinoy,[‡,†] Boudewijn Meesschaert,[§,⊥] and Bart Van der Bruggen[†]

[†]Department of Chemical Engineering, Process Engineering for Sustainable Systems (ProcESS), KU Leuven, W. de Croylaan 46, B-3001 Leuven, Belgium

[‡]Department of Industrial Engineering, Laboratory for Chemical Process Technology, KaHo St.-Lieven, Associated to the KU Leuven as Faculty of Engineering Technology, Technologie campus, Gebroeders Desmetstraat 1, B-9000 Gent, Belgium

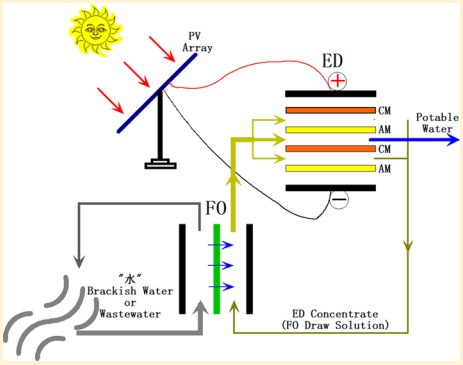
[§]Department of Industrial Sciences and Technology, Laboratory for Microbial and Bio-Chemical Technology, Katholieke Hogeschool Brugge-Oostende, Associated to the KU Leuven as Faculty of Engineering Technology, Zeedijk 101, B-8400 Oostende, Belgium

[⊥]Department of Microbial and Molecular Systems, Centre for Surface Chemistry and Catalysis, KU Leuven, Kasteelpark Arenberg 23, B-3001 Leuven, Belgium

[#]Separation and Conversion Technology, Flemish Institute for Technological Research (VITO), Boeretang 200, B-2400 Mol, Belgium

Supporting Information

ABSTRACT: In isolated locations, remote areas, or islands, potable water is precious because of the lack of drinking water treatment facilities and energy supply. Thus, a robust and reliable water treatment system based on natural energy is needed to reuse wastewater or to desalinate groundwater/seawater for provision of drinking water. In this work, a hybrid membrane system combining electrodialysis (ED) and forward osmosis (FO), driven by renewable energy (solar energy), denoted as EDFORD (ED-FO Renewable energy Desalination), is proposed to produce high-quality water (potable) from secondary wastewater effluent or brackish water. In this hybrid membrane system, feedwater (secondary wastewater effluent or synthetic brackish water) was drawn to the FO draw solution while the organic and inorganic substances (ions, compounds, colloids and particles) were rejected. The diluted draw solution was then pumped to the solar energy driven ED. In the ED unit, the diluted draw solution was desalted and high-quality water was produced; the concentrate was recycled to the FO unit and reused as the draw solution. Results show that the water produced from this system contains a low concentration of total organic carbon (TOC), carbonate, and cations derived from the feedwater; had a low conductivity; and meets potable water standards. The water production cost considering the investment for membranes and solar panel is 3.32 to 4.92 EUR m^{-3} (for 300 days of production per year) for a small size potable water production system.



INTRODUCTION

Because of population growth, the expansion of urban and industrial areas, and the increase in living standards, water has become a limited resource in many parts of the world.[1−5] On the other hand, water pollution and climate change severely impact global water security.[5,6] This situation is even more crucial in arid and semiarid areas.[7] Furthermore, in remote areas and on islands, there is often a lack of power and water supplies. Thus, available renewable natural energy should be considered for desalination and wastewater recycling.

To promote water security, water and wastewater treatment technologies are essential to improve the water efficiency and to close the water cycle by means of water reuse and wastewater reclamation. The development of water technologies also helps to purify contaminated surface water and groundwater as well as to desalinate brackish water and seawater to fresh water.[2−4] Among these water technologies, membrane technology is an emerging and promising one and has been taking an important role to ensure the water quantity and quality.

Generally, pressure-driven membrane processes such as nanofiltration (NF) and reverse osmosis (RO) need adequate pretreatment to avoid scaling and fouling. Those pretreatment processes lead to higher investment and operational costs. Furthermore, an inappropriate concentrate disposal results in a threat to the environment and the eco-system.[8−10]

Sustainable development of resources requires a well-elaborated interplay on the water-energy nexus. A combination of membrane processes and renewable energy is a trend for water treatment and desalination.[4,11−16] Photovoltaic (PV)

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powered systems are a good option, because most of the arid and semiarid areas have abundant solar resources. Recently, various PV driven membrane systems have been investigated and experimented. Schäfer and co-workers[13,14] studied a PV driven membrane system (UF-RO/NF) to desalinate brackish water (5300 mg L^{-1} TDS; 8.29 mS cm^{-1}) in central Australia. Results show that a good quality of water (average conductivity 280 μS cm^{-1}) with a water recovery of 28% can be obtained by using a BW-30 membrane with 2.3 kWh m^{-3} energy consumption.

However, solar power has an important drawback for an RO (or NF) system, i.e., it fluctuates due to weather changes and clouds cover. This brings harm to the pressure driven membrane system due to the back-pressure effect. This undesired power fluctuation may reduce the lifetime of membrane and yield an unstable quantity and quality of permeate.[13,14] An installation with batteries can improve the stability but it also highly increases the investment and maintenance cost, and it lowers the energy efficiency.[15] Furthermore, biofouling of RO membranes is another drawback for long-term operation of a PV driven RO system.[15]

A PV driven electrodialysis (ED) system is an alternative configuration for desalination, which avoids the drawbacks in the PV-RO system: no pressure is needed, and the system is thus operated in a stable way; biofouling does not have a dominant affect on the ED performance and the foulants can be removed by chemical cleaning since ion exchange membranes have a good tolerance for acids and bases. Ortiz et al. [16] studied brackish water desalination by a PV driven pilot scale ED system located in Alicante, Spain. The results show that a power consumption of 0.92−1.69 kWh m^{-3} is needed to desalinate the water with a TDS (total dissolved solid) ranging from 2329 until 5011 g m^{-3} to a potable quality (TDS < 400 g m^{-3}).

ED seems to be a good option as a desalination unit combined with PV as the power source; however, it can only remove salts and a small amount of charged organic compounds, and most of the uncharged compounds remain in the water. This is one of the main drawbacks of ED application for desalination, especially when the water (e.g., wastewater, polluted groundwater, or brackish water) contains organic pollutants.[17] Previous studies show that ED can only remove approximately 10% of the TOC in a RO concentrate from a wastewater treatment plant.[18] In view of system integration, it is required to have a unit to remove those contaminants prior or after the ED unit. As a salinity gradient driven dense membrane process, forward osmosis (FO) can be a novel option as a barrier prior to ED.

FO is an osmotic pressure-driven process that moves the water across a selectively permeable membrane.[19] FO has a high rejection of a wide range of contaminants[19−22] and a lower fouling tendency than pressure driven membranes.[23−25] Linares et al. [20] studied the rejection of 13 organic micropollutants (spiked into wastewater) by using clean and fouled FO membranes. Seawater was used as the draw solution and each experiment was carried out for 24 h. The results show that a moderate to high rejection was obtained for both hydrophilic and hydrophobic neutral compounds (44−95% and 48−92%, respectively), and a high rejection was found for hydrophilic ionic micropollutants (96−99%). Positive results were also obtained by Xie et al.[21] They investigated rejection and adsorption of hydrophobic contaminants (bisphenol A, triclosan and diclofenac); the results indicate that those hydrophobic contaminants adsorbed to the membrane during the initial 2−3 h, and the rejection with the FO membrane was over 95% for all the contaminants in the initial 2 h. Butler et al. [22] investigated the rejection of heavy metals by FO. They obtained a maximum rejection at pH 5 of 99.5, 99.5, 99.9, and 99.5% for chromium, copper, lead and arsenic, respectively with 2.4 LMH (liter per square meter membrane per hour) water flux.[22] However, some obstacles have to be solved to bring FO process to full scale applications.[26,27] One of the main drawbacks on FO process to produce potable water is the recovery of draw solution. Most of the recent investigations were focus on using less energy intensive methods (by using various kinds of draw solutes) to recover draw solutions.[28−30] However, the use of renewable energy to recover draw solution has drawn much less attention. Moreover, a systematic investigation on FO integrated renewable energy driven system has not been reported.

In this paper, a novel photovoltaic (PV) driven FO-ED system, denoted as EDFORD (ED-FO system by Renewable energy Driven) is investigated to produce high quality (potable) water from secondary wastewater effluent or brackish water. In view of the energy balance, solar energy is transformed into a chemical potential (osmotic energy) by an ED process, and then that the osmotic potential draws water through the FO membrane. With respect to the cost, osmotic pressure build-up, toxicology ,and environmental impact, NaCl is chosen as the draw solute. A schematic diagram of the concept can be seen in Figure 1: NaCl is used as a medium to "carry" water from the brackish water or wastewater to the ED-unit and water is "released" by using solar energy to remove the salts with the ED unit. NaCl is circulated in this system, and hence no waste concentrate is discharged into the environment.

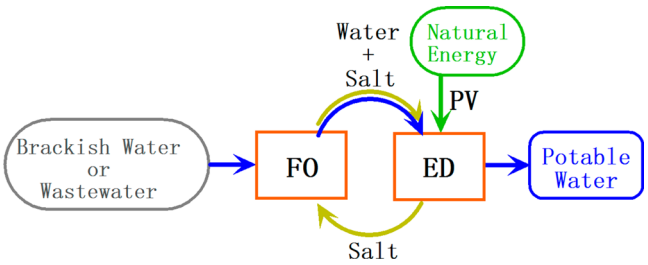

Figure 1. Conceptual diagram on salt-mediated water production by EDFORD system. In view of the energy balance, solar energy is transferred to chemical potential (osmotic energy) by ED process then draws the water through the FO membrane.

The PV driven FO-ED system can treat streams not applicable to standard NF/RO/ED without pretreatment; and it can have better performance and lower energy consumption. The system has a better stability and is very suitable to supply water to a small community and to produce water for infiltration in arid and semiarid areas to close the fragile water cycle.

METHODS AND MATERIALS

FO Membrane and the Apparatus Setup. A flat-sheet configuration with FO membranes (110707 ES-1) kindly supplied by HTI (Albany, USA) was used in this study. Each FO membrane had an effective area of 0.0064 m^2 (8 cm*8 cm). To obtain a decent FO membrane surface area, 27 pieces of FO membranes with 26 silicon rubber spacers (PCCell GmbH) of

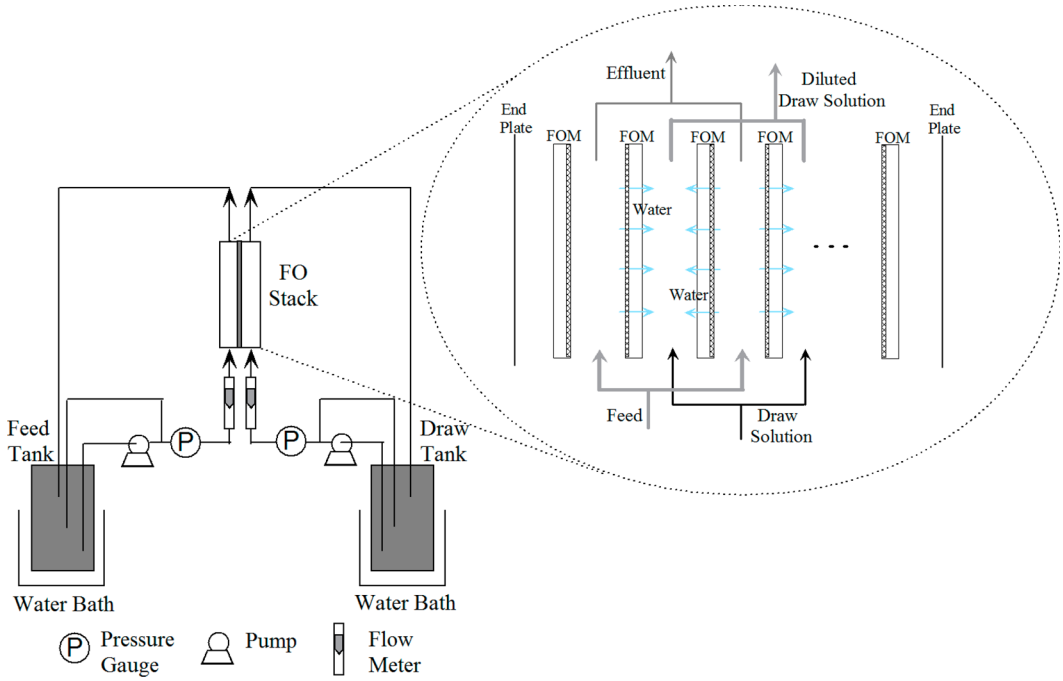

Figure 2. Configuration of ED-64-004 stack as a FO stack (FOM, forward osmosis membrane) and the system setup for FO experiments.

0.5 mm thickness (with plastic woven mesh to separate membranes and to provide turbulence at lower bulk velocities) in between were installed into a PCCell ED-64−004 stack (Heusweiler, Germany). The compartments formed by the FO membranes and the end plates were sealed. Thus, the total membrane surface area was 0.16 m^2. The membrane active layers faced the feed solution. A schematic diagram of the stack configuration can be found in Figure 2.

The FO system setup can be also seen in Figure 2: feed and draw solutions were pumped from the vessels with 20 L solution through the FO stack by using centrifugal pumps, with a constant flow rate of 30 $L.h^{-1}$, measured by the flow meters. A bypass was used to adjust the flow rate through the stack and to have a good mixing in the tank. A water bath was used for each tank to keep a constant temperature (22 ± 3 °C). The volume change in the feed tank was measured as the weight difference in the feed and measured by a digital scale SBS-PW-302E (30 kg ± 2 g, Steinberg Systems, Germany).

Ion-Exchange Membranes and ED Apparatus. A Berghof 500 ED (Eningen, Germany) installation was used in the ED experiments. The setup consisted of three separated circuits with three 4 L vessels for the diluate, the concentrate and the electrolyte rinsing solution. The ED stack consisted of 5 cell pairs with an effective surface area of 58 cm^2 (i.e., total effective surface area is 0.029 m^2) for each membrane. More details can be found in previous work.[18] The initial ED diluate was the "diluted draw solution" from the FO, and the desalinated diluate denoted as the "ED product" has less than 10 mmol L^{-1} NaCl as the target (TDS < 600 mg L^{-1}, Guidelines for drinking water quality, WHO [31]). The initial ED concentrate was also the "diluted draw solution" from the FO. The final ED concentrate was recycled to the FO system as the draw solution. This water flowchart can be seen in the graphical abstract.

Prior to PV powered-ED experiments, the ED was powered by using a constant voltage of 8 V by a DC power source (ES 030−5, Delta Elektronika, The Netherlands) to normalize the operational conditions. Both modeled water (deionized water + NaCl) and real draw solutions from the FO experiments were used as the diluate and the concentrate. Current efficiency, energy consumption, and salt flux were calculated according to the data obtained from the experiments.

Photovoltaic Array and the Experiment Location. A monocrystalline photovoltaic array was kindly supplied by Soltech (Heverlee, Belgium). Four panels were connected in parallel and used for the experiments and 1 panel was tested as the reference to determine solar irradiation. Each panel has an effective surface area of 0.0648 m^2 (18 cm × 36 cm) with a voltage output of around 8−9 V in sunlight. The PV array was fixed on a hard board and faced to the south direction (5°), with a 55° angle against the ground surface. The experiments were conducted in an open area in Heverlee, Belgium. The PV array efficiency was calculated by comparing the measured value with the maximum value obtained from the manufacturer.

Experimented Water, Sample, and Data Analysis. In the FO experiments, the initial draw solutions were NaCl solutions with a concentration of 0.2, 0.5, or 1.0 mol L^{-1}. These draw solutions were either made by analytical grade NaCl dissolved in deionized water, or came from the ED concentrate stream, which will be specified in each experiment. The wastewater used in the experiments was collected from the secondary effluent from a wastewater treatment plant owned by Aquafin (a wastewater treatment company in Flanders, Belgium), and was treated by a submerged UF unit (Zenon, Canada) by IWVA (a water company in Belgium) in Wulpen, Belgium. A synthetic brackish water in this work was made by using DI water with dosing of 0.03 mol L^{-1} NaCl, 0.025 mol L^{-1} $NaHCO_3$, 0.004 mol L^{-1} $MgSO_4$, and 0.01 mol L^{-1} $CaCl_2$ (chemically pure).

TOC and ionic carbon were analyzed by a Shimadzu TOC Analyzer-5000 A (Kyoto, Japan). Cations were measured by inductively coupled plasma mass spectrometry (ICP-MS, Thermo Scientific X Series, USA). The NaCl concentration was calculated by measuring the conductivity of the solution.

The linear correlation coefficient between the NaCl concentration and the conductivity was 0.9991.

FO Membrane Water Flux. The FO membrane water flux was measured as the weight difference in the feed solution, and was monitored by using a digital scale. The unit of FO membrane water flux is LMH. Since the experiments were performed in batch, the water flux drops with the dilution of the draw solution. The FO membrane flux is calculated by a weight difference during a time interval

$$J_{FO} = \frac{\Delta W_{feed}}{\rho A_{FO} \Delta t} \quad (1)$$

where ΔW_{feed} is the weight difference of the feed solution, ρ the water density (here taken as 1000 g L^{-1} since the maximum salt concentration in this work was 1.0 mol L^{-1}), A_{FO} the FO membrane effective surface area and Δt the time interval.

Normalized FO Water Flux (LMH L mol^{-1}). A normalized FO water flux was used to show the water flux in a normalized condition (with 1.0 M NaCl draw solution). This is calculated by

$$J_{nor} = \frac{J_{FO}}{C_{draw}} \quad (2)$$

where C_{draw} is the concentration of the draw solution.

Current Efficiency (%) of ED Process. The current efficiency is the fraction of the current that is used to transfer ions from the diluate to the concentrate. The current efficiency (η) can be calculated as

$$\eta = \frac{z\left(C_0 \frac{W_0}{\rho} - C_t \frac{W_t}{\rho}\right)F}{n\bar{I}t} \times 100(\%) \quad (3)$$

where C_0, C_t is the initial and the final concentration of the ion during a time period (t), W_0, W_t is the initial and the final weight of the feed during a time period, F is the Faraday constant, n is the number of cells in the ED stack, and $\bar{I}$ is the average applied current during time period t.

Desalination Energy Consumption (mol kWh^{-1}) by ED. The desalination energy consumption is represented by the molar amount of migrated ions divided by the electricity consumed by ED. It is calculated by the following equation

$$\kappa = \frac{C_0 \frac{W_0}{\rho} - C_t \frac{W_t}{\rho}}{U\bar{I}t} \quad (4)$$

where U is the applied voltage (constant during the experiments).

Salt Flux (mol m^{-2} h^{-1} A^{-1}) through Ion-Exchange Membranes in ED. The salt flux of ion exchange membranes in the ED stack, a similar concept as the water flux of water permeable membranes, is represented by the transported ion molar amount divided by the effective membrane area (A_{ED}), the time interval and the applied current.

$$J_{ED} = \frac{C_0 \frac{W_0}{\rho} - C_1 \frac{W_1}{\rho}}{A_{ED} \Delta t \bar{I}} \quad (5)$$

PV Utilization Efficiency and the Panel Efficiency (%). The PV utilization efficiency (λ) is calculated by the utilized electricity power by the ED desalination divided by the actual electricity output from the PV array:

$$\lambda = \frac{UI}{P_{array}} \quad (6)$$

where P_{array} is the power generated from the PV array.

This is different from the PV energy conversion efficiency (panel efficiency). In this work, the PV energy conversion efficiency from the solar light was always measured to be around 14% (13.9−14.7%, shown in the Supporting Information, Table S1).

RESULTS AND DISCUSSION

In the FO-ED system, a water and salt balance can be obtained by optimization of different parameters in the FO and the ED system: the volume of water drawn from the FO equals to the volume produced in the ED (ED diluate); the salt concentration in the ED concentrate equals the concentration in the original FO draw solution. Meanwhile, the salinity of draw solution and the diluted draw solution should be optimized. By using this approach, the system produces a maximum volume of water, while energy used for desalination is minimized (as shown schematically in the Supporting Information, Figure S1).

In this system to convert solar energy to potable water and to the FO draw solution, ED is the central element. Thus, the performance of ED is first presented, from the point of view of the water balance and the energy consumption.

ED Performance and System Salt-Water Balance. ED experiments were performed by using four modeled solutions (synthetic diluted FO draw solution: modeled I, III, and IV, initial concentration 0.2 M, final target concentration 0.4 M, 0.5 and 1.0 M, respectively; modeled II, initial concentration 0.1 M, final target concentration 0.2 M) and two real diluted FO draw solution from the FO unit (0.2 mol L^{-1}, the production of the diluted draw solution by the FO unit will be described in the next section) to calculate energy consumption with respect to different concentration factors. The initial diluate and concentrate were both from the diluted FO draw solution and had the same salt concentration. Therefore the volumes were determined by the final concentrate concentration. The objective for the concentrate concentration was to recover and recycle it as the draw solution. The objective for the concentration of the diluate is that would that low that the diluate would be suited as drinking water. Figure 3 shows the diluate concentration profiles of the modeled and the real diluted draw solutions. As can be seen, all solutions had a low final concentration (below 0.01 mol L^{-1} NaCl, the final

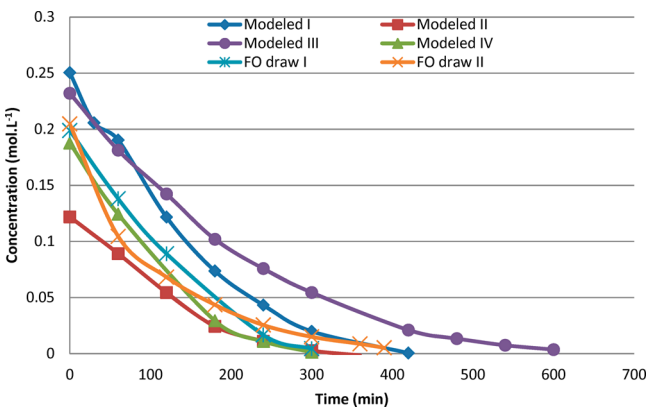

Figure 3. Diluate Concentration Profile As a Function of Time.

Table 1. ED Desalination and Draw Solution Recovery on Modeled Water and FO Draw Solution

water source	diluate/concentrate[a] initial concentration (mol L^{-1})	concentrate[b] final concentration (mol L^{-1})	diluate[c] final conductivity (mS cm^{-1})	current efficiency avg (%)	energy consumption (kWh m^{-3})	desalination energy consumption (mol kWh^{-1})
modeled I	0.2	0.4	0.447	94.9	5.18	38.6
modeled II	0.1	0.2	0.257	94.5	2.97	33.7
modeled III	0.2	0.5	0.519	87	5.37	37.2
modeled IV	0.2	1	0.729	82.4	5.49	36.4
FO draw I	0.2	0.5	0.808	100	4.98	40.2
FO draw II	0.2	0.5	0.877	78.2	5.57	35.9

[a]The initial ED diluate/concentrate is the diluted draw solution from the FO unit, the volumes were determined by the targeted final concentrate concentration. [b]The final ED concentrate is the recovered draw solution for sending back to the FO unit. [c]The final ED diluate is the potable water.

conductivity can be seen in Table 1). All of the concentration–time curves in the ED experiments fit the second-order polynomial simulations with correlation coefficient $R^2 > 0.997$ (except the experiment on FO draw II with $R^2 = 0.967$). Thus, the ED experiment with a constant voltage can generally be simulated by using the second-order polynomial equations. The equations can be found in the Supporting Information, Table S2 of this work.

It can be seen from Table 1 that the feed can be desalinated to less than 300 μS cm^{-1} (0.257 mS cm^{-1}) with an average current efficiency of 94.5% and an energy consumption of 2.97 kWh m^{-3} when the initial diluate/concentrate concentration was 0.1 mol L^{-1} NaCl and the recovered draw solution reached a concentration of 0.2 mo L^{-1} NaCl. When the initial diluate/concentrate concentration is 0.2 mol L^{-1}, it takes around 5.5 kWh to produce 1 m^3 of potable water (conductivity <600 μS cm^{-1}) with a current efficiency of around 85%.

The desalination energy consumption (mol kWh^{-1}) is one of the key parameters to connect the ED water production and the salt-water balance of the system. The desalination energy consumption ranges from 33.7 to 40.2 mol kWh^{-1}, as shown in Table 1. This parameter is used to calculate the experimental maximum salt removal rate by PV arrays when coupled with a ED stack, as discussed in the section PV Coupling with the ED System.

FO Water Production and Final Draw Concentration. The water flux of the FO membrane is highly dependent on the draw solution concentration and the hydrodynamic conditions in the FO module.[19,32−34] In this work, 0.2, 0.5, and 1.0 M NaCl solutions were used as the draw solution and deionized water (DI water) as the feed to measure the FO water flux with respect to the draw solution concentration. More details can be found in the Supporting Information, Figure S2, with descriptions. On the other hand, reversal salt flux (salt leakage) from draw solution to the feed was monitored in this work. This information can be found in the Supporting Information, Figure S3, with descriptions. Results show that after 15 h (900 min) operation, feed conductivity increased from 4 μS cm^{-1} to around 500 μS cm^{-1} when 1.0 M draw solution was used. In this case, the salt flux was 0.021 mol m^{-2} h^{-1}. A lower reversal salt flux was observed when lower draw concentration was applied.

Figure 4 shows the correlation between the concentration of the draw solution and the normalized water flux (LMH L mol^{-1}) in the experiments on DI water, synthetic brackish water and wastewater (BW = synthetic brackish water, WW = wastewater) as the feed. It is observed that the higher the concentration in the draw solution, the lower the normalized

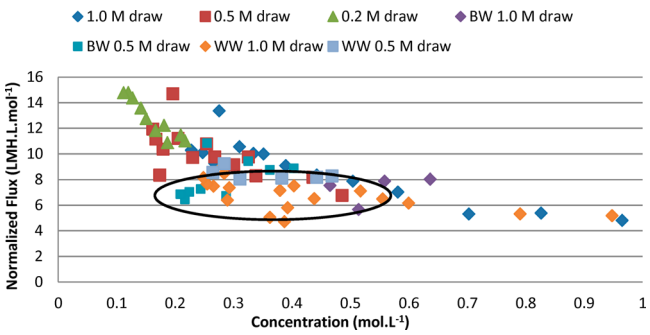

Figure 4. Correlation between draw concentration and the normalized water flux on different feedwater types (BW, synthetic brackish water; WW, wastewater).

water flux. At a concentration in the draw solution of around 0.1 M, the FO membrane shows the highest normalized flux, ca. 15 LMH.L.mol^{-1}. This value is comparable with the flux obtained with a much higher cross-flow velocity (around 16 LMH with a flow rate of 1.5 L min^{-1} on 0.0173 m^2 flat sheet FO membrane by using 1.0 M draw solution).[35] Only 4.5 LMH L mol^{-1} was obtained for the 1.0 M draw concentration. This indicates that with a cross-flow velocity of 30 L h^{-1} for the 1.0 M draw solution, the concentration polarization effect is huge. On the other hand, increasing the cross-flow velocity or reducing the concentration of the draw solution also consumes more pumping energy (requires a higher flow rate or a longer operational time). An optimization of the operational parameters is thus necessary in view of the process economics.

On the other hand, the flux was remarkably lower when the feedwater was synthetic brackish water or wastewater compared with the experiments with deionized water, where the draw solution concentration was below 0.6 M. This indicates that when the draw solution has a lower concentration, the FO flux is more affected by the feed concentration and membrane fouling.

FO Coupling with the ED System in View of Water Production. 0.5 M NaCl was chosen as the draw solution and FO was coupled with the ED system to produce water and to recycle the draw solution. In the experiments, wastewater was chosen as the feedwater. Through the FO module, the draw solution was diluted from 0.5 to 0.2 M and sent to the ED system for desalination as well as for draw solution recovery. When the draw solution was concentrated up to 0.5 M as the ED concentrate stream, the solution was sent back to the FO as the draw solution. Two sequences of experiments were carried out by using the procedure introduced above (the FO feed was continuously used in the two sequences) and the volume

change in this FO-ED hybrid system can be seen in Figure 5. As shown, 2.8−3.2 L of water was removed from the wastewater

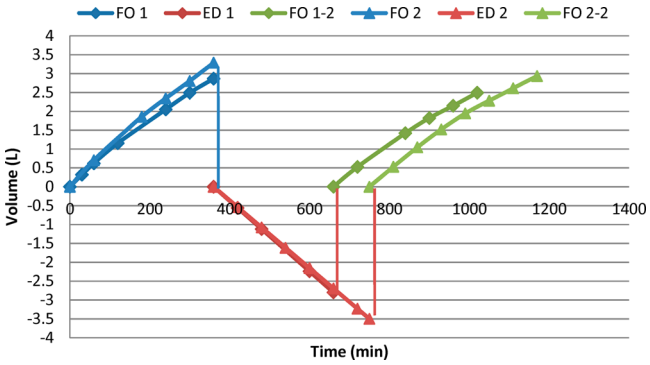

Figure 5. Volume change (water production) in the FO-ED hybrid system during the two sequences of experiments.

by the draw solution in 360 min, and the draw solution was desalinated/recovered by the ED process within 300−390 min. Then the recovered draw solution removed 2.5−3.0 L water again from the wastewater within 360−420 min. The FO flux in the second operation (FO1−2 and FO2−2) was lower than in the first operation (FO-1 and FO-2), this is due to the fact that the feedwater concentration was increased after the first operation (as water was drawn to the draw solution), this leaded to a decrease of FO water flux. However, the membrane was not fouled since the water flux was comparable in FO-1 and FO-2 and in FO1-2 and FO2-2, respectively.

The concentration of organic carbon (by TOC) and carbonate (by ionic carbon) were analyzed in the feed and in the draw solution. It was found that the TOC concentration in the draw solution increased from 1.79 to 1.93 mg L^{-1}, whereas the TOC in the feed increased from 15.94 to 23.84 mg L^{-1}. A slight TOC increase in the draw solution may due to some small organic fractions are able to pass through the FO membrane. The TOC increase in the feed solution is due to the fact that water was drawn from the feed to the draw solution, thus, the feed TOC was concentrated. Meanwhile, the carbonate concentration in the draw solution was negligible (0.67 mg L^{-1} in the beginning and 0.43 mg L^{-1} after two experiments) and increased in the feed from 70.01 to 89.22 mg L^{-1}. This means that small organic compounds and carbonate in the wastewater can hardly pass through the FO membrane. Further analysis is necessary to investigate which organic compounds may potentially penetrate through the FO membrane. According to the literature, the rejection of trace organic compounds by FO is 80−96.5% for charged compounds and 40−90% for noncharged fractions.[36,37]

The concentration of major cations in the FO feed and the draw solution before and after FO-ED-FO experiment was analyzed (see the Supporting Information, Table S3). After two sequences (1020 min), the cation concentration in the FO feed increased by a factor two for Na^+ and Mg^{2+}, and by a factor three for K^+ and Ca^{2+}, because of the volume reduction (loss of water). Meanwhile, the cation concentration in the draw solution only increased 0.0013 mol L^{-1} for K^+, 0.002 mol L^{-1} for Mg^{2+}, and 0.0113 mol L^{-1} for Ca^{2+}. Rejection of other (toxic) inorganic fractions were not measured in this work, but according to the literature, the value should also be satisfactory, e.g., rejection of chromium(III), copper(II), lead(II), and arsenic(V) reaches 99.5, 99.5, 99.9, and 99.5%, respectively.[22]

PV Coupling with the ED System. The PV panel performance is discussed in view of the power output and the power used in the ED for desalination. Figure 6 illustrates the solar irradiation (W m^{-2}), array power output (W), and the power utilized by ED for desalination.

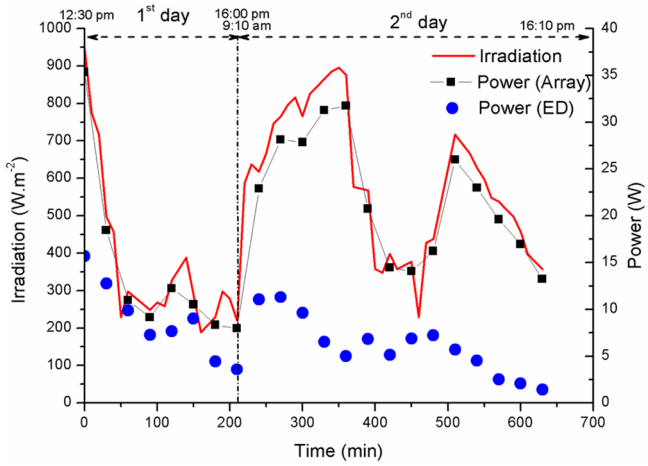

Figure 6. Solar irradiation (W m^{-2}), array power output (W), and the power (W) that was utilized by ED for desalination.

The power output fluctuated with the fluctuation of solar irradiation. From 12:30 to 16:00 in the first day, the power utilized for desalination was around 80% on average, but during the second day, the utilization rate was lower, which represents only around 30% on average. This is due to the fact that the diluate was desalinated by ED and hence the concentration decreased with time and so did the current. If the diluate does not have enough conductivity, the lower current efficiency leads to a lower power utilization rate. At low diluate concentration, the resistance of the stack is much higher, hence the energy utilization rate is low, which has been reported by Długołecki et al.[38]

Furthermore, the efficiency of the PV powered ED system and the performance of the ED is elaborated in the Supporting Information, Page S9 and Figure S3. According to the information, although the solar power fluctuated due to weather and time changes, the diluate conductivity continuously decreased and no large effect was observed for the ED desalting performance. A double peak on the efficiency can be found in Supporting Information, Figure S3. This is due to the effect of the diluate concentration and the solar irradiation strength. A maximum of 90% of solar power was used in this experiment. Further studies should be done to fit the diluate concentration and change in solar strength during the day. In this way, system efficiency and energy utilization rate can be optimized.

Economical Analysis on the EDFORD System. The average electricity generation for these 4 panels was around 15 W.h. Thus, the electricity generation from 1 m^2 of photovoltaic panel in daily average irradiation 4.8 kWh m^{-2} day^{-1} in 1 h is 57.9 W h m^{-2}, and in one day the generated electricity is 463 W h m^{-2} (irradiation period assumed to be 8 h). As calculated from the experiments, the ED desalination energy consumption is 35 mol kWh^{-1}, thus, the theoretical (100% current efficiency) daily (8 h) water production from a 0.2 mol L^{-1} diluted draw solution is 81 L.m^{-2} photovoltaic panel, i.e., 65 L of water production if the current efficiency is 80%. If the diluted draw

Table 2. Surface of the Membranes and the Solar Panels Needed to Produce 130 L of Drinking Water Per Day

initial draw (mol L^{-1})	final draw (mol L^{-1})	average FO flux (LMH)	ED salt flux[a] (mol m^{-2} h^{-1} A^{-1})	ED membrane surface (m^2)	panel area (m^2)	FO membrane surface (m^2)
1	0.2	3.52	6.30	1.03	2	1.54
0.5	0.2	2.92	5.11	1.27	2	1.85
0.2	0.1	1.9	5.91	0.55	1	2.85

[a]Assuming the applied current in average is 0.5 A, 8 h per day.

solution is 0.1 mol L^{-1} NaCl, the water production reaches 130 L day^{-1}, which is sufficient for residential water use for one capita. Assuming the FO unit works 24 h daily, the membrane surface area can be calculated from the targeted water production volume.

According to the assumption of 130 L day^{-1} of drinking water production, Table 2 shows the calculated FO membrane surface area, ED membrane surface area and the PV panel area in the EDFORD system. This assumption is based on an average solar irradiation of 8 h per day.

As shown in Table 2, a similar membrane surface area and panel area is needed when the initial draw solution is 1.0 or 0.5 M, with in both cases a final draw concentration of 0.2 M. However, only half the ED membrane surface and a smaller panel area are needed if the initial draw solution is 0.2 M and the final concentration is 0.1 M; the FO membrane surface that is needed is however doubled. Considering that the cation exchange membrane and anion exchange membrane cost is 200 EUR m^{-2} each, the solar panel cost is 800 EUR m^{-2}, the FO membrane cost is 80 EUR m^{-2}, and supposing that the ion exchange membrane and FO membrane lifetime is 5 years, the solar panel lifetime is 20 years, then the water production cost can be estimated as 3.32 to 4.92 EUR m^{-3} (for 300 days of production per year) for this small size potable water production system.

■ ASSOCIATED CONTENT

Supporting Information

Details of the PV experiment: irradiation, output, and the efficiency (Pages S2 and S3 and Table S1); water and salt balance in the FO-ED system (Page S4 and Figure S1); correlations between the diluate concentration and the experiment time in ED experiments with a constant voltage of 8 V (Page S5 and Table S2); FO water flux with respect to the draw concentration (Page S6 and Figure S2); reversal salt flux (salt leakage) (Pages S7 and Figure S3); major cations in the FO feed and the draw solution before and after FO-ED-FO experiment (Pages S8 and Table S3); performance of PV powered ED (Page S9 and Figure S4). This material is available and free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: + 32 14 335744. Fax: +32 14 321186. E-mail: yang.zhang@vito.be.

Author Contributions

The manuscript was written through contributions from all of the authors. All of the authors have approved the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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