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Pre-desalination with electro-membranes for SWRO

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ABSTRACT

Although seawater reverse osmosis (SWRO) is currently the only non-thermal desalination process in practical use, its characteristics make it difficult to approach the ideal reversible process. SWRO has a low water recovery (determined by the osmotic pressure) and relatively high energy consumption. A breakthrough in development of SWRO membranes can not be expected; at maximum a recovery of 60% could be obtained with membranes that can stand ultra-high pressures. In our project, an alternative development of desalination is introduced in which the osmotic pressure difference is reduced prior to SWRO with the use of electro-membranes, as in electrodialysis (ED). ED has distinctive and complementary assets when compared to SWRO. ED enables an operation close to the reversible limit, at least to the first extent of the desalination process. ED is an ideal pre-desalination step as: (i) the water recovery is not limited by a driving force (e.g., pressure), (ii) the specific energy consumption is directly proportional to the salt removal, (iii) the process economy allows low ionic fluxes and thus low irreversible losses, (iv) the system can be operated with infinitesimal changes in salinity (a pre-requisite for reversibility), and (v) the pre-treatment efforts can be kept limited. In this paper we compare a hybrid ED-SWRO scheme with state-of-the-art desalination schemes with respect to costs and energy consumption.

Keywords: Electrodialysis; Seawater desalination; SWRO; BWRO

1. Introduction

Desalination of seawater and brackish water could significantly contribute to the global problem of water scarcity [1]. It is, however, often considered being too energy-consuming and too expensive. Seawater reverse osmosis (SWRO) is currently the only non-thermal technique for seawater desalination. In a SWRO system, water is forced through a semi-permeable membrane from the seawater side ('concentrate') to the fresh water side ('permeate') of the membrane by applying a pressure in excess of the osmotic pressure. SWRO has a low water recovery (determined by the osmotic pressure, max. 50%) and relatively high energy consumption (3–5 kWh/m^3).

The question is if there is a way in which a change can be made from "a low water recovery determined by the osmotic pressure" towards "a higher recovery determined by the chemical composition (scaling)" [2], together with a lower energy consumption. A real breakthrough in the development of high-pressure SWRO membranes, however, can not be expected; at maximum a recovery of 60% could be obtained [2,3]. The maximum applicable pressure (and thus water recovery) is inherent to the membrane structure (thin film composites). These

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membranes suffer from so-called mechanical compaction at high pressures [4].

In this paper, we present a hybrid desalination scheme and we compare this hybrid scheme with state-of-the-art (non-thermal) desalination schemes with respect to costs and energy consumption. Our main aim is to quantify the potential benefits of the proposed hybrid desalination scheme, especially the energy consumption and pre-treatment requirements of the different schemes on a model base.

2. A new hybrid desalination scheme

Any desalination system will be most energy efficient if it involves a reversible thermodynamic process, which is independent of the techniques and mechanisms used. It can be calculated that the lower limit of specific energy consumption for seawater desalination is 1.4 kWh per m^3 of fresh water produced (seawater with a 3.2 wt% salinity, at $T = 293$ K). The water recovery is in this case 80%, which means that each m^3 of fresh water is produced from 1.25 m^3 of seawater. This small surplus of seawater is assumed to be necessary to prevent precipitation of sparingly soluble salts when fresh water is extracted from the system ('scaling'). These numbers for energy consumption and water recovery could be used as the ideal standard for each desalination process.

SWRO has at least five interrelated characteristics that make it difficult to approach the ideal standard of a reversible desalination process (Table 1). An alternative direction for a further development of desalination is to reduce the osmotic pressure difference prior to SWRO, i.e., to reduce the salt concentration of the feed water with a (pre-) desalination step prior to the use of pressure-driven membranes. A pre-desalination may include electro-membranes, as in electrodialysis (ED). In an ED system, ions are forced through ion-selective membranes from the seawater side of the membrane ('concentrate') to the fresh water side ('diluate') by applying an electrical potential difference in excess of the salinity-gradient emf.

It is innovative to suggest ED as an alternative pre-desalination technique. It is commonly accepted that ED as a desalination process is less energy efficient than reverse osmosis (e.g. [5–7]), although few researchers recognize that the ED lacks a good design for seawater desalination (e.g. [8]). Therefore, ED is proposed here in a hybrid process scheme including SWRO. In such case ED will not cover the entire process of desalinating, i.e., from seawater quality to fresh water quality, but only within that extent of the desalination process in which it has the best characteristics. To our opinion there are some overlooked distinctive and complementary assets of ED linked to the five mentioned characteristics of SWRO (Table 1). Furthermore, it should also be mentioned that innovative ED concepts may be included: low-cost ED membrane and electrode materials, optimised electric and hydrodynamic configurations, and fouling-preventive operations.

3. Assumptions for evaluation

3.1. Assessed desalination schemes

The main goal was to quantify the potential economical benefits of the proposed hybrid desalination scheme when compared to other desalination schemes. The assessed desalination schemes are given in Fig. 1. The schemes include:

- Ideal reversible desalination (technology not defined);
- State-of-the-art desalination with seawater reverse osmosis (SWRO);

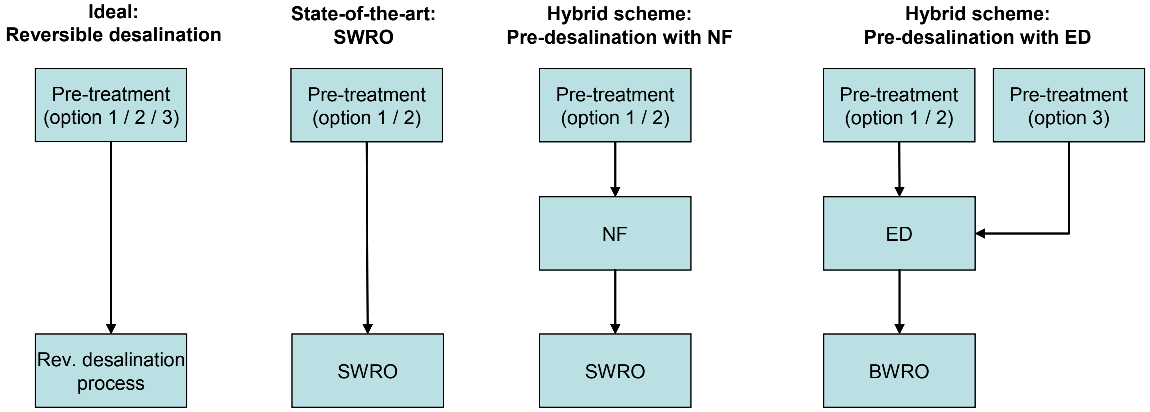

Fig. 1. Assessed desalination schemes, including pre-treatment, pre-desalination step (if any), and desalination step, excluding permeate polishing; SWRO is seawater reverse osmosis with high-pressure membranes, NF is nanofiltration with low-pressure membranes, BWRO is brackish water reverse osmosis with low-pressure membranes, and ED is electrodialysis with electro-membranes; pre-treatment options are explained in the text.

Table 1
Characteristics of current SWRO compared to innovative scheme involving ED

	SWRO desalination	ED (pre-)desalination
1. Water recovery	*Is limited to 35–50% due to limitation in driving force (applied pressure)* The hydrostatic pressure that membranes can stand is typically 7.0 MPa [3]. Consequently, the recovery is at best 50%, the osmotic pressure of the concentrate is then close to the maximum applied pressure. This means that for each produced m^3 of permeate at least 2 m^3 seawater need to be pressurized and pre-treated.	*Is not limited by driving force* ED runs under atmospheric conditions. Of course, there exists a transport limitation ('limiting current density') which is mainly defined by the salt concentration of the diluate. If this concentration will become too low, water-splitting could occur with associated irreversible losses (i.e., this is one of the reasons to introduce ED primarily as a pre-desalination step).
2. Specific energy use	*Is determined by conversion and water permeation* The irreversible system losses are mainly determined by the conversion of electrical energy to mechanical energy by the high-pressure pump and by the water-permeation resistance of the dense membranes. SWRO has a specific energy consumption of 3–5 kWh/m^3 [1,9]. Even with recent model calculations simulating very efficient energy recovery devices, the ultimate promise for SWRO is ~2.4 kWh/m^3 [10][a].	*Is directly proportional to the amount of salt removed* ED needs no conversion from electrical energy to mechanical energy (only an efficient AC/DC conversion). The irreversible system losses are mainly determined by the ion-permeation resistance of the ED cell-pairs. The main contributor to this resistance is the diluate between the membranes when it becomes too diluted (i.e., another reason to use ED primarily as pre-desalination step). The coulombic efficiency can become close to 100% [11].
3. Economy	*Does not allow low water fluxes (and thus low irreversible losses)* Irreversible losses due to the permeation resistance could be minimized by decreasing the water-flux through the membranes. However, the process cost will become unacceptably high as more costly high-pressure membrane elements and vessels are needed.	*Does allow low ionic fluxes (and thus low irreversible losses)* Irreversible losses due to the permeation resistance could be minimized by decreasing the current density. Several hundreds of low-cost membranes can be piled between two electrodes in relatively low-cost housings (no pressure-vessels needed) [12].
4. Gradual process	*Cannot be operated with infinitesimal changes in salinity* The salinity-gradient over the SWRO membrane is not built-up gradually[b], i.e., it is not possible to obtain intermediate states of desalination degrees. Thus, it is less likely that the system is near thermodynamic equilibrium throughout the entire process.	*Can be operated with infinitesimal changes in salinity* At the desalinated water side ('diluate'), the salinity can be built-up gradually. This makes ED suitable as pre-desalination step too each desired degree of desalination. This also holds the promise to approach a reversible thermodynamic process.
5. Pre-treatment	*Needs an intensive pre-treatment of feed water* The pre-treatment prior to SWRO is both capital and energy intensive. State-of-the-art pre-treatment includes double sand filtration. A more recent trend is to use an ultra filtration (UF) prior to SWRO [2].	*Does not need an intensive pre-treatment of feed water* The pre-treatment requirements of ED could be limited to a simple microstrainer [12] to prevent clogging of the ED stack (this is important for extra seawater that is needed for concentrate make-up).

[a] For a 50% water recovery, the calculated reversible limit is 1.0 kWh/m^3 of permeate.

[b] At the desalinated water side ('permeate'), the salinity is a few percent of the salinity at the feed side, depending on the salt rejection of the applied membrane.

- A hybrid scheme with nanofiltration (NF) as a pre-desalination step;
- A hybrid with electrodialysis (ED) as a pre-desalination step.

In Fig. 1 three options are given for the pre-treatment: (i) conventional pre-treatment, (ii) advanced pre-treatment, and (iii) minimum pre-treatment. These options are explained separately.

3.1.1. Option 1: Conventional pre-treatment for spiral wound membrane systems

The general recommendation for proper conventional pretreatment is the use of coagulation-flocculation, dissolved air flotation and filtration or the use of coagulation-flocculation, settling and filtration [13]. Many SWRO plants operate for many years with conventional pre-treatment, consisting of coagulation-flocculation and a double rapid sand filtration [14]. However, if this conventional pre-treatment is not designed and operated carefully, RO plants can have severe problems with membrane fouling. The costs of this conventional pre-treatment system are about 0.10 €/m^3 of pre-treated water, with about half of the costs being coagulants (Table 2). These numbers are in accordance with references [13,14].

3.1.2 .Option 2: Advanced pre-treatment for spiralwound membrane systems

A more advanced pre-treatment is the use of ultrafiltration (UF), optionally combined with an inline flocculation. Compared to conventional technology, the investment costs for UF are higher and thus the capital expenditures associated with pretreatment will increase. Concerning the operational expenditures, the costs for chemicals (mainly coagulant) will decrease with about 50% [13], but in turn costs for UF membrane replacement is added (Table 2). The costs of UF are about 0.15 €/m^3 of pre-treated water. Until recently, the general perception is that UF as pretreatment to SWRO is technically favorable but economically unviable [14]. Following the recent experience in pilot units and the continuously cost reduction, however, this option is now seriously considered for application in seawater systems [14] (e.g., the Seaguard system of Norit).

3.1.3. Option 3: Minimum pre-treatment for spacer free membrane systems

A minimum pretreatment consisting of mechanical filtration (e.g., drum filters) could only be applied in case of spacer free membrane configurations, like in spacer free ED [12]. The costs of this minimum pre-treatment is only 0.01 €/m^3, excluding the dose of coagulants (coagulants are not applicable in an ED stack, as the coagulant has not been removed by a filtration step).

3.2. Assumptions on membrane performances

3.2.1. SWRO with high-pressure membranes

For the purpose of this study, we assume the SWRO membranes being perfect selective (i.e., no permeate polishing is needed). State-of-the-art membranes can withstand a hydrostatic pressure of maximum 70–80 bar [2,3]. The recovery is limited by this maximum applicable hydrostatic pressure to 50%. With a recovery of 50% and very low concentration of the permeate (0 g/L NaCl), the required pressure to overcome the osmotic pressure difference over the membrane together with the hydraulic resistance of the membrane approaches the maximum applicable pressure.

The permeability of a typical SWRO membrane is 3.9×10^{-12} m/s.Pa [15]. We assume therefore the following irreversible losses associated with water transport through the membranes:

- For a typical flux of 15 L/m^2.h, the associated pressure loss over the membrane is 10 bar (~0.3 kWh/m^3 permeate).
- Friction losses over feed and permeate spacers are about 2 bar over one stage with 6–7 membrane elements in series [16] (~0.05 kWh/m^3 permeate).
- With an efficiency of 70% for the high pressure pump and an efficiency close to 100% for the pressure exchanger, the additional efficiency losses can be calculated.

The annual costs of SWRO are assumed to be about 24 €/m^2.y (Table 3) (50% for capital expenditures, 50% for operational expenditures including membrane replace-

Table 2
Cost estimations of different pre-treatment schemes

	Option 1 Conventional 8 m^3/m^2.h	Option 2 Advanced 0.1 m^3/m^2.h	Option 3 Minimum 30 m^3/m^2.h
Capex[a]			
Microsieves	0.010	0.010	0.010
Settler + sand filter[b]	0.030		
Ultrafiltration[c]		0.090	
Opex			
Membrane replacement[d]		0.050	
Chemicals	0.060	0.030	
Energy	0.002	0.005	0.001
Operation and maintenance[e]	0.011	0.018	0.002
€/m^3 pre-treated	0.11	0.20	0.01

[a] Annuity 6%, [b] Based on cost breakdown by Mekorot of 90,000 m^3/d desalination plant [14] and numbers from [13], [c] idem, [d] Annuity 25% and membrane price 90 €/m^2, [e] 3% of construction costs

ment once per 5 years, but excluding energy costs). With the typical flux of 15 $L/m^2.h$ and 8,000 production hours per year, the cost price can be calculated as 0.20 €/m^3 of desalted water (excluding energy costs).

3.2.2. BWRO with low-pressure membranes

For the purpose of this study, we assume the BWRO membranes being perfect selective (i.e., no permeate polishing is needed). The membranes can withstand a hydrostatic pressure of maximum 40 bar.

The permeability of a typical BWRO membrane is 13×10^{-12} m/s.Pa [17]. We assume therefore the following irreversible losses associated with water transport through the membranes:

- For a typical flux of 20 $L/m^2.h$, the associated pressure loss over the membrane is 4 bar (~0.1 kWh/m^3 permeate).
- Friction losses over feed and permeate spacers are about 2 bar over two stages with 6 membrane elements in series [16] (~0.05 kWh/m^3 permeate).
- With an efficiency of 70% for the high pressure pump and an efficiency close to 100% for the pressure exchanger, the additional efficiency losses can be calculated.

These membranes cannot be used for desalination of seawater without a pre-desalination step. The osmotic pressure difference over the membrane together with the irreversible pressure losses will become close to the maximum applicable pressure, even when an excessive amount of seawater is used for desalination (i.e., at a very low water recovery). Operated at the maximum pressure of 40 bar and with 6 bar for irreversible losses, the osmostic pressure difference over the membrane is 34 bar. Seawater (3.2 wt% NaCl) has an osmotic pressure of 27 bar, indicating that the recovery should be kept limited to only 20% (i.e., about 5 m^3 of seawater is needed for the production of 1 m^3 desalted water)

The annual costs of BWRO are assumed to be about 16 €/m^2.y (Table 3) (50% for capital expenditures, 50% for operational expenditures including membrane replacement once per 5 years, but excluding energy costs). With the typical flux of 20 $L/m^2.h$ and 8,000 production hours per year, the cost price can be calculated as 0.10 €/m^3 of desalted water (excluding energy costs).

3.2.3. NF with low-pressure membranes

For the pressure limitations and irreversible losses associated with water transport, we assume the same characteristics and costs for NF membranes as for BWRO membranes. For the purpose of this study, we assume the NF membranes being perfectly selective for multivalent ions (but we assume the mole fraction of multivalent ions to be negligible with respect to the contribution to the osmotic pressure). The retention for sodium chloride is very much depending on the operations [18].

There is a trade-off between the permeate salinity and the obtainable water recovery. The effective pressure difference over the membrane that can be used to overcome the osmotic pressure difference $\Delta\pi_{\max}$ is 34 bar ~ 3.4×10^6 Pa (see previous calculation for BWRO). The obtainable water recovery γ is dependent on the permeate salinity, according to the mass balance [Eq. (1)] and the limiting pressure [Eq. (2)]:

$$\begin{aligned} c_p\cdot\gamma\cdot V \quad + \quad c_c\cdot(1-\gamma)\cdot V &= c_f\cdot V \\ \gamma\cdot\left(c_p-c_c\right) &= \left(c_f-c_c\right) \end{aligned} \tag{1}$$

and

$$\begin{aligned} -\pi_p \quad + \quad \pi_c &\le \Delta\pi_{\max} \\ -2RT\cdot\left(c_p-c_c\right) &\le \Delta\pi_{\max} \end{aligned} \tag{2}$$

with c the molarity (mol/m^3), V the volume (m^3), R the universal gas constant (J/mol.K), and T the temperature; subscript c refers to the concentrate, subscript p to the permeate, subscript f to the feed solution. It was calculated that with a permeate salinity of 0 g/L NaCl, the maximum concentrate salinity is 40 g/L [700 mol/m^3; Eq. (2)] and the maximum recovery is thus only 20% [Eq. (1)]. More open NF membranes with lower retentions could yield higher recoveries. For example, with a diluate salinity of 16 g/L NaCl (half seawater), the recovery could become about 60%.

3.2.4. ED with electromembranes

For the purpose of this study, we assume the profiled ED membranes to be perfect ion-selective (i.e., no transport of co-ions and water). The membranes have a typical areal resistance of 3 Ωcm^2, and the inner membrane channels have a height of 0.2 mm. The conductance of the solutions is assumed to be linear with the salinity of the feed and concentrate (a constant equivalent conductance factor). The irreversible losses are very much depending on the extent of desalination and the chosen current density. As an example, without accounting for depletion, the irreversible loss at a current density of 100 A/m^2 is 70 mV per cell pair.

Based on currently available ED(R) cost references from Ionics, the annual costs of ED are assumed to be about 17 €/m^2.y (Table 3) (55% for capital expenditures, 45% for operational expenditures including membrane replacement once per 7 years, but excluding energy costs). The cost price of desalted water is very much depending on the chosen diluate salinity and current density.

For this project, however, where ED membranes are considered in application on seawater instead of brackish water, we want to incorporate recent developments in ED, such as: low-cost membranes (5 €/m^2, already available in

Table 3
Cost estimations of different membrane types

	SWRO HP-mem	BWRO LP-mem	NF LP-mem	EDR Ionics	ED Profiled
Capex[a]					
SWRO[c]	12				
NF/LP-RO[b]		8.2	8.2		
ED[d]				9.6	4.8
Opex					
Membrane replacement[e]	7.5	5.0	5.0	3.7	0.9
Chemicals					
Energy		pm	pm	pm	Pm
Operation and maintenance[f]	4.5	3.0	3.0	3.5	1.8
€/m^2.y	24	16	16	17	7.5
€/m^3 desalted (excl energy)	0.20	0.10	0.10		

[a] Annuity 6%, [b] Based on NF installations in The Netherlands, [c] b times factor 1.5 for HP-equipment, [d] Based on Ionics function [ref. WaTER or "Water Treatment Estimation Routine"], [e] Annuity 25% for SWRO, BWRO and NF; 18.5% for EDR and ED membranes; and membrane prices of 30, 20, 20, 20, 5 €/m^2, respectively, [f] 3% of construction costs

China), thin membranes (< 0.2 mm, instead of thick membranes of ~1 mm as applied in EDR), and profiling of the membranes (excluding spacer materials, i.e., requiring a minimal pre-treatment with only micro sieves). The capitalization of these new developments is of course quite speculative, although it should be noted that respected membrane suppliers and developers agreed on much more ambitious numbers for their membranes for the application of power generation from salinity-gradients ('Blue Energy') [12]. In Table 3 the assumed numbers for recently developed profiled membrane system can be compared with the conventional EDR system.

4. Evaluation of schemes

4.1. Reversible desalination

The minimum energy consumption required for separating a saline solution into a dilute solution and concentrated brine under ideal conditions is dependent only on the salt content of the saline solution and the extent of desalination, regardless of the technology and configuration of the desalination scheme in question. In other words, all desalination schemes, which may be based on different technologies and may have different configurations, share a common minimum energy requirement for driving the separation process, regardless the system characteristics. The minimum energy consumption required for desalination under ideal conditions is thermodynamically defined as the free energy change resulting from separating a saline feed solution (subscript *f*) into a dilute solution (subscript *d*) and concentrated brine (subscript *c*):

$$\begin{aligned}\Delta G &= \sum_i \left(G_{i,f} - G_{i,d} - G_{i,c}\right) \\ &= \sum_i \Big(c_{i,f} V_f RT \ln\left(x_{i,f}\right) - c_{i,d} V_d RT \ln\left(x_{i,d}\right) \\ &\qquad - c_{i,c} V_c RT \ln\left(x_{i,c}\right)\Big)\end{aligned} \tag{3}$$

where G is the free energy (J), x the mole fraction of component i (i = Na$^+$, Cl$^-$, H$_2$O), V the volume (m^3). In Fig. 2 the reversible work is given for the production of a cubic

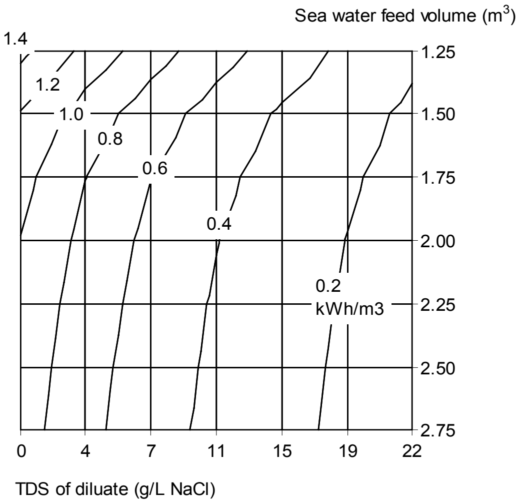

Fig. 2. Theoretical desalination work to produce 1 m^3 of diluate from seawater (in kWh), at different diluate salinity (x-axis; TDS = total dissolved solids) and different amount of seawater feed volumes (y-axis); Seawater was assumed to consist of an ideal 3.2 wt% NaCl solution at 293 K.

meter of diluate with different diluate salinities and from different feed amounts of seawater.

Furthermore, Fig. 2 shows that the first extent of mixing takes relatively less work per removed amount of salt: e.g., when 1 m^3 of diluate is produced from 2 m^3 of seawater, the desalination from 32 g/L to 16 g/L takes only 0.25 kWh whereas the further desalination from 16 g/L to 0 g/L takes 4 times more.

It should be noted that in the reversible desalination scheme, the water recovery (needed amount of seawater) and the extent of desalination (diluate salinity) can be chosen independently. Furthermore, it might be true that a reversible desalination has no limitations with respect to operational aspects (applicable pressure, limiting current density), but the calculated desalination work does not account for state changes (e.g., precipitation of sparingly soluble salts at a recovery higher than 80%, or liquid to gas by evaporation, etc.). It can be seen that the reversible desalination work for desalination of seawater is 1.4 kWh/m^3 of fresh water produced (dialute salinity → 0) at a water recovery of 80% (i.e., produced from 1.25 m^3 of seawater).

4.2. State-of-the-art desalination scheme with UF-SWRO

For state-of-the-art seawater desalination, the maximum water recovery is 50%. Thus, for each m^3 SWRO permeate, at least 2 m^3 seawater should be pre-treated with a conventional pre-treatment (option 1) or an advanced pre-treatment (option 2). The specific energy consumption for this scheme is calculated to be 2.0 kWh/m^3 (of which 1.0 kWh defined by thermodynamics according to Fig. 2, the other 1.0 kWh is calculated from the assumptions on irreversible losses as introduced in section 3.2. The costs of this scheme is about 0.81 €/m^3 (for pre-treatment option 2). For the cost breakdown, see Table 4.

4.3. Hybrid scheme: UF-NF-SWRO

The recovery of NF is limited by the maximum applicable hydrostatic pressure, but also to the extent of desalination (the salt concentration of the NF permeate). With a recovery of 60%, a concentration of the NF permeate could be obtained of 16 g/L NaCl (half seawater). The following SWRO can be operated at a high recovery of about 80% (another option would be to use a BWRO instead of SWRO, but in that case the recovery of the BWRO will only 60%, due to pressure limitations). The overall recovery of this system is 60%·80% = 50%. Thus, for each m^3 SWRO permeate, at least 2 m^3 seawater should be pre-treated with a conventional pre-treatment (option 1) or an advanced pre-treatment (option 2).

The energy consumption of this scheme is calculated to be 2.1 kWh/m^3 (of which 0.6 kWh for the predesalination with NF and 1.5 kWh for SWRO; the reversible part is 0.3 kWh for the pre-desalination and 0.7 for the SWRO).

The costs of this scheme is about 0.95 €/m^3 (for pre-treatment option 2). For the cost breakdown, see Table 4. With comparable water recovery and energy consumption, the costs are higher than for state-of-the-art SWRO due to the addition of an extra NF step. This scheme seems to be not an attractive direction for further development.

4.4. Hybrid scheme UF/ED-SWRO

The water recovery of ED can be chosen independently from the extent of desalination. For practical reasons we choose a water recovery of 50%, which means that both sides of each membrane (the diluate side and the concentrate side) are fed with equal amounts of seawater. The diluate side is fed with seawater which is pre-treated according to option 1 or 2. The diluate needs to be pre-treated extensively as it is fed to the subsequent spiral-wound membrane installation either with SWRO (this paragraph) or BWRO (paragraph 4.5). The brine-make-up water at the concentrate side consists of seawater which is pre-treated according to option 3 (the concentrate is discharged to the sea).

The diluate can be produced with different salinity. In order to obtain a high recovery with a SWRO, a diluate concentration of 16 g/L (half seawater) is sufficient to obtain a recovery of 80% on the SWRO.

The energy consumption is very much dependent on the chosen current density, which can be in the range of 10 A/m^2 to few hundreds of A/m^2 (limiting current

Table 4
Cost breakdown of schemes with advanced pre-treatment (option 2: UF)

	4.2	4.3	4.4	4.5
	UF-SWRO	UF-NF-SWRO	UF/ED-SWRO	UF/ED-BWRO
Pre-treatment (Option 2: UF)	0.40	0.41	0.25	0.25
Pre-treatment (Option 3: mech. filtration)			0.02	0.02
Pre-desalination step (NF or ED)		0.13	0.14	0.14
Desalination step (SWRO or BWRO)	0.20	0.20	0.20	0.10
Energy (0.1 €/kWh)	0.20	0.21	0.21	0.19
€/m^3 desalted	0.81	0.95	0.82	0.70

density is estimated to be in the order of hundreds A/m^2). The needed m^2 of electromembranes is inversely proportional to the current density. With current relatively low energy prices and relatively high membrane prices, a current density of a 50–100 A/m^2 would be beneficial (Fig. 3). However, in future, with expected increase of energy prices and decrease of electromembrane prices an operation with low current density will become more and more attractive.

The energy consumption of UF/ED-SWRO is calculated to be 2.1 kWh/m^3 at a current density of 50 A/m^2 (of which 0.6 kWh for the pre-desalination with ED and 1.5 kWh for SWRO; the reversible part is 0.3 kWh for the pre-desalination and 0.7 for the SWRO). The costs of this scheme is about 0.82 €/m^3 (for pre-treatment option 2). For the cost breakdown, see Table 4. This is comparable with the cost price as calculated for state-of-the-art SWRO.

4.4. Hybrid scheme: UF/ED-BWRO

Another option which could be attractive is to obtain a lower diluate concentration of 6 g/L (~20% of seawater concentration) in order to feed it to a BWRO installation that is operated at a recovery of 80%.

The energy consumption of UF/ED-BWRO is calculated to be 1.9 kWh/m3 at a current density of 50 A/m2 (of which 1.3 kWh for the predesalination with ED and 0.6 kWh for BWRO; the reversible part is 0.7 kWh for the pre-desalination and 0.3 for the BWRO). The costs of this scheme is about 0.70 €/m3 (Fig. 3; for pre-treatment option 2). For the cost breakdown, see Table 4. This is considerably lower than the cost price as calculated for state-of-the-art SWRO.

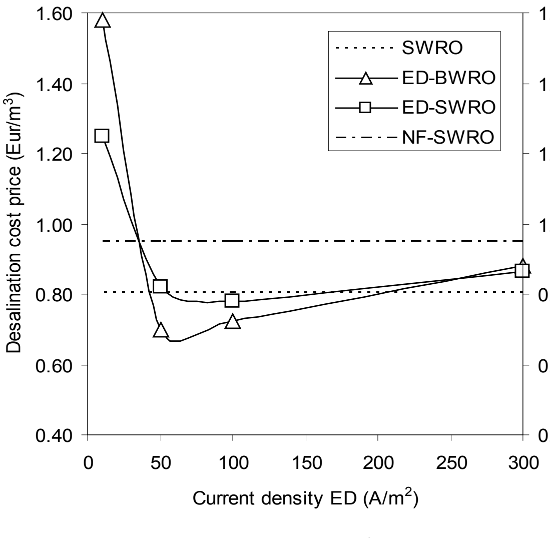

Fig. 3. Cost price for desalination (€/m^3) as function of current density (A/m^2) of ED. Showed figures were calculated with pre-treatment option 2 (UF).

5. Concluding remarks

The proposed hybrid scheme with ED as pre-desalination seems very attractive due to savings in pre-treatment, especially when an advanced pre-treatment with UF is applied (option 2). Most attractive is a scheme in which the SWRO can be replaced by a BWRO due to the pre-desalination step. The ED should then be used for removal of 80% of the salinity. A cost reduction could be achieved of about 15% compared to the state-of-the-art SWRO.

Moreover, in future, when membranes are becoming cheaper, it will become possible to reduce the energy consumption of about 2 kWh/m^3 (all schemes) to about 1.4 kWh/m^3 by lowering the current density from 50 to 10 A/m^2. Therefore, our institutes will proceed with research and development of the electromembrane-based systems in application to seawater. First efforts could be to use profiled ED membranes, but other new configurations with electromembranes could also be investigated.

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References

[1] M.A. Shannon, P.W. Bohn, M. Elimelech, J.G. Georgiadis, B.J. Marinas and A.M. Mayes, Science and technology for water purification in the coming decades. Nature, 452 (2008) 301–310.

[2] I. Moch, The case for and feasibility of very high recovery seawater reverse osmosis plants. in ADA Conference. Lake Tahoe, 2000.

[3] M. Kurihara, H. Yamamura and T. Nakanishi, High recovery / high pressure membranes for brine conversion SWRO process development and its performance data. Desalination, 125 (1999) 9–15.

[4] M.G. Khedr, Development of reverse osmosis desalination membranes composition and configuration: Future prospects. Desalination, 153 (2002) 295–304.

[5] T. Seto, L. Ehara, R. Komori, A. Yamaguchi and T. Miwa, Seawater desalination by electrodialysis. Desalination, 25 (1978) 1–7.

[6] K.S. Spiegler and Y.M. El-Sayed, The energetics of desalination processes. Desalination, 134 (2001) 109–128.

[7] Y. Tanaka, A computer simulation of continuous ion exchange membrane electrodialysis for desalination of saline water. Desalination, 249 (2009) 809–821.

[8] M. Turek, Cost effective electrodialytic seawater desalination. Desalination, 153 (2002) 371–376.

[9] S.A. Avlonitis, K. Kouroumbas and N. Vlachakis, Energy consumption and membrane replacement cost for seawater RO desalination plants. Desalination, 157 (2003) 151–158.

[10] R.L. Stover, SWRO process simulator. Desalination, 221 (2008) 126–135.

[11] J.W. Post, H.V.M. Hamelers and C.J.N. Buisman, Energy recovery from controlled mixing salt and fresh water with a reverse electrodialysis system. Environ. Sci. Technol., 42 (2008) 5785–5790.

[12] J.W. Post, G.H. Goeting, J. Valk, S. Goinga, J. Veerman, H.V.M. Hamelers and P.J.F.M. Hack, Towards implementation of reverse electrodialysis for power generation from salinity gradients. Desal. Wat. Reuse, 16 (2010) 182–193.

[13] F. Knops, S. van Hoof, H. Futselaar and L. Broens, Economic evaluation of a new ultrafiltration membrane for pretreatment of seawater reverse osmosis. Desalination, 203 (2007) 300–306.

[14] P. Glueckstern and M. Priel, Comparative cost of UF vs. conventional pretreatment for SWRO systems. Desal. Wat. Reuse, 12(4) (2003) 34–39.

[15] W. Zhou and L. Song, Experimental study of water and salt fluxes through reverse osmosis membranes. Environ. Sci. Technol., 39 (2005) 3382–3387.

[16] J.A.M. van Paassen, W.G.J. van der Meer and J.W. Post, Optiflux: from innovation to realisation. Desalination, 178 (2005) 325–331.

[17] A. Sagiv and R. Semiat, Analysis of parameters affecting boron permeation through reverse osmosis membranes. J. Membr. Sci., 243 (2004) 79–87.

[18] A.M. Hassan, A.M. Farooque, A.T.M. Jamaluddin, A.S. Al-Amoudi, M.A.K. Al-Sofi, A.F. Al-Rubaian, N.M. Kither, I.A.R. Al-Tisan and A. Rowaili, A demonstration plant based on the new NF–SWRO process. Desalination, 131 (2000) 157–171.