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Towards implementation of reverse electrodialysis for power generation from salinity gradients

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ABSTRACT

Reverse electrodialysis is a conversion technique to obtain electricity from salinity gradients. Over the past few years, the performance of reverse electrodialysis on laboratory scale has improved considerably. In this paper, we discuss the challenges we are still facing concerning the economic and technological feasibility and the developing path of reverse electrodialysis. We focus on the following issues: (i) the development of low-cost membranes, (ii) pre-treatment in relation to stack design and operation, and (iii) the economics of reverse electrodialysis. For membranes, the challenge is to increase availability (>km^2/year) at reduced cost (<2 €/m^2). The membranes should be manufactured at high speed to meet this challenge. For pre-treatment, a capital-extensive micro-screen filter with 50 μm pores was selected and tested. Such a straightforward pre-treatment is only sufficient given the fact that the reverse electrodialysis stack was redesigned towards a more robust spacer-free system. For the economic feasibility, a 200 kW repetitive unit was designed. The cost price is estimated to be less than 0.08 €/kWh (excluding any subsidy or compensation), comparable with that of wind energy. The feasibility of the technology should be proved with a scaled-up system under practical conditions. The intended pilot facility at the Afsluitdijk (The Netherlands) will be an essential step towards implementation of reverse electrodialysis for power generation.

Keywords: Salinity-gradient energy; Reverse electrodialysis; Blue energy; Renewable energy; Fouling; Biofouling; Ion-exchange membranes

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1. Introduction

1.1. From scientific research to technical development

Salinity-gradient energy is the energy that can be gained by mixing two flows of water with different salinity, see Table 1. The idea was formulated for the first time in 1954 by R. Pattle [1]. The potential of salinity power has been estimated in the 1970s on the basis of average ocean salinity and annual global river discharges to be between 1.4 and 2.6 TW [2,3]. In The Netherlands, river water discharge and sea water are abundantly available. On average the river Rhine discharges 2,200 m^3/s.

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Assuming an energy potential of 1.5 MJ per m^3 of river water [4,5], this means an electricity potential of over 6 million households (>80% of all households). Even if this river discharge can be used only to a certain extent, it is an enormous source of renewable energy. Further, it is inherently clean and sustainable. There is no emission of CO_2 and no thermal pollution. Moreover, in principle, energy can be generated continuously 24 hr per day and 365 days a year, unlike wind or solar energy. In theory, there are different techniques to obtain this energy. The most promising are reverse electrodialysis (RED) and partially retarded osmosis (PRO). Post et al. [4] have pointed out that in the case of sea water and river water, the reverse electrodialysis technique would be the best choice (see process scheme in Figure 1, for explanation see [4]).

Wetsus—centre for sustainable water technology in the Netherlands—started in 2005 with the project 'Blue Energy' with a focus on reverse electrodialysis. At that time only a few scientific papers were published over a period of 50 years [1,3,6,7] concerning experimental reverse electrodialysis systems. In the past few years (2007–present), the performance of reverse electrodialysis on laboratory scale has improved considerably (Tables 1, 2). The specific power or power density is probably the most important measure for performance. Although it was recognized for a long time that the power density was mainly determined by the intermembrane distance [8], no real attempts were made to minimize the spacer thickness. The first attempt by Turek and Bandura [9] was not quite successful as only a power density of 0.4 W/m^2 was obtained. However, this low power density could be caused by ionic short-circuits in the system [10] due to the small current-passing area of their setup as can be seen from the low obtained open-circuit voltages. Veerman et al. were the first to report a much higher power density of 0.95 W/m^2 [11] and more recently [12] an even higher power density of >1.2 W/m^2. Furthermore, Post et al. [5] showed that from mixing sea water and river water using reverse electrodialysis, in principle, a high energy recovery of more than 80% can be obtained, which means an energy yield of >1.2 MJ per m^3 of river water.

Thus, reverse electrodialysis experiments have typically been performed on a laboratory scale, varying from current-passing areas of just a few square centimeters [9] to hundreds of square centimeters [11] and from four cell-pairs [5] to fifty cell-pairs [12]. State-of-the-art is a stack with an active membrane area of 25 × 75 cm^2 and 50 cell-pairs with a power output of about 16 Watt (Figure 1; manufactured by REDstack B.V., The Netherlands). To achieve practical implementation, reverse electrodialysis still needs to be scaled-up by several orders of magnitude. This scaling-up and practical implementation are beyond the academic expertise and need to be done by specialized companies. For this reason REDstack B.V. was founded by Magneto and Harlingen Holding Industries (owner of Landustrie/Hubert), two companies participating within the Blue Energy research project of Wetsus.

1.2. Development challenges

Before starting the scale-up, the following hurdles should be overcome by the companies: (i) there are no specially developed low-cost membranes available for reverse electrodialysis, (ii) there is no vision on the requirements for stack design in relation to pre-treatment and friction losses and (iii) there is no project to be evaluated to get the economic figures.

Ion-exchange membranes are the key components in a reverse electrodialysis system. In the 70s, Weinstein and Leitz [3] concluded that large-scale energy conversion by reverse electrodialysis may become feasible, but only with major advances in the manufacturing of ion-exchange

Table 1
Definition of salinity-gradient energy.

Salinity-gradient energy

Salinity-gradient energy is thermodynamically defined as the free energy change resulting from mixing a concentrated and a diluted salt solution:

$$\begin{aligned}\Delta G &= \sum_i \left(G_{i,c} + G_{i,d} - G_{i,b}\right)\\ &= \sum_i \left(c_{i,c} V_c RT \ln\left(x_{i,c}\right) + c_{i,d} V_d RT \ln\left(x_{i,d}\right) - c_{i,b} V_b RT \ln\left(x_{i,b}\right)\right)\end{aligned}$$

where G is the free energy (J), c the molarity (mol/m^3) and x the mole fraction (-) of component i (i = Na^+, Cl^-, H_2O), V the volume (m^3), R the universal gas constant (J/mol.K), and T the temperature; subscript c refers to the concentrated salt solution, subscript d to the diluted salt solution, subscript b to the brackish salt solution which remains after mixing. The theoretically available amount of energy from mixing 1 m^3 sea water (comparable to 0.5 mol/L NaCl) and 1 m^3 river water (comparable to 0.01 mol/L NaCl) both at a temperature of 293 K is 1.4 MJ.

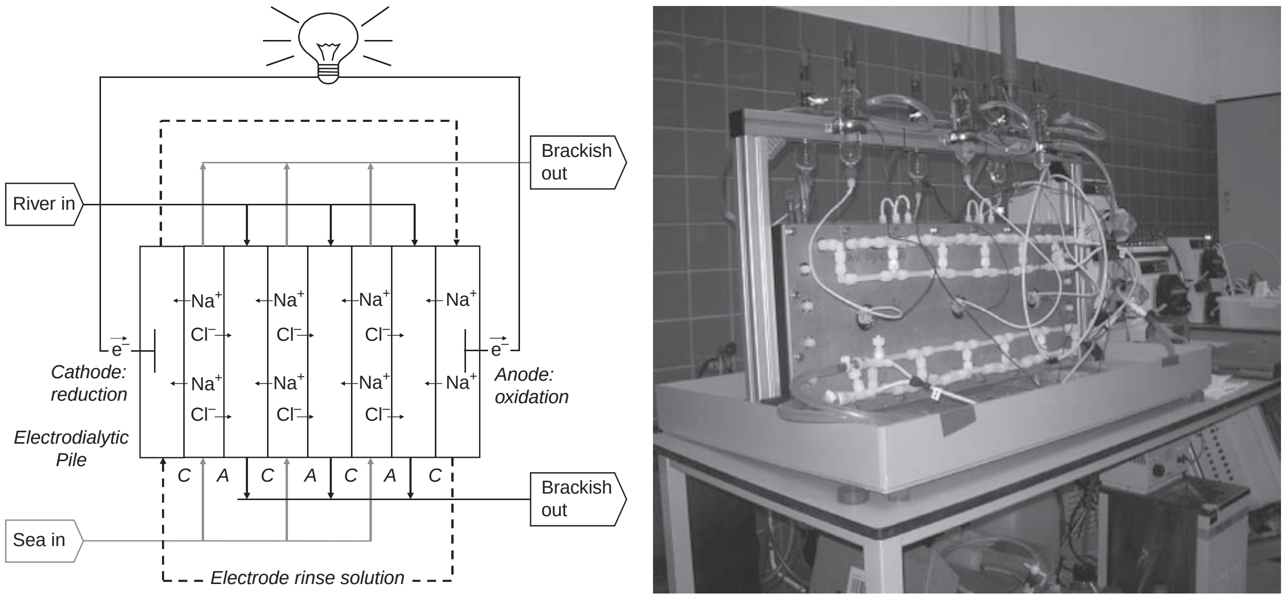

Fig. 1. Process scheme and picture of a reverse electrodialysis stack (membrane area of 25x75 cm^2 and 50 cell-pairs as manufactured for research purposes by REDstack B.V., the Netherlands).

Table 2
Obtained power density (W/m^2) and spacer thickness (mm); experiments with sodium chloride solutions, typical concentrations 0-1 g/L and 30-35 g/L NaCl [12].

Author	Year	Power density (W/m^2)	Spacer thickness (mm)
Pattle	1954	0.05	0.7
Weinstein and Leitz	1976	0.17	1.0
Jagur-Grodzinski and Kramer	1986	0.41	0.55
Turek	2007	0.46	0.19
Suda	2007	0.26	1.0
Veerman et al.	2008	0.95	0.2
Veerman et al.	2009	1.18	0.2

membranes and with careful optimization of the operating conditions. Given a proper stack design, the membrane characteristics directly influence the power output [13] and energetic efficiency [5]. Moreover, the membrane price is a key issue for successful market introduction of the reverse electrodialysis technology [9].

Although mentioned in scientific papers, challenges such as the pre-treatment of river water and sea water [5], and the hydrodynamic aspects of reverse electrodialysis [14] are often ignored or underestimated. Regarding the pre-treatment, Lacey [8] assumed activated-carbon filtration as pre-treatment, just to perform economic calculations. However, until now there is neither experimental basis nor a clear vision on the feed water quality requirements. This lack is probably mainly due to the fact that the pre-treatment requirements can not be seen separately from the hydrodynamic design of the reverse electrodialysis stacks. Regarding the hydrodynamics, Lacey [8] modeled the friction losses. Jagur-Grodzinski and Kramer [6] and Turek and Bandura [9] measured these friction losses and reported both the gross power output and net power output. These studies showed considerable energy losses for pumping, even under laboratory conditions without membrane fouling.

At this moment, electricity of salinity-gradient energy is still costly compared to electricity of other renewable energy sources due to high membrane prices of commercially available membranes. Reverse electrodialysis has never been applied before at commercial scale. An economic evaluation can, therefore, be only done on realistic assumptions and expectations.

1.3. Objective

In this paper, we discuss the economic and technological challenges we are facing in the scale-up of reverse electrodialysis. We take the achievements of the academic research as presented in this introduction as starting point. We focus on the following issues: (i) the development of low-cost membranes (section 2), (ii) the pre-treatment in relation to stack design and operation (section 3), and (iii) an economic evaluation (section 4). Further steps towards application in practice are presented in section 5.

It should be noted that these issues are closely related. The economic evaluation in section 4 is the result of an iterative design process. On forehand, we did an educated guess to quantify the cost criteria for membranes and pre-treatment to values that may make the process affordable. After the aimed cost prices were set, we started the discussion if it is realistic to aim for membranes at this low cost price, and we selected a pre-treatment which could meet the cost price criterion. After this, we were able to make a more detailed process design in order to evaluate the economic feasibility of the entire system. If the system was found to be not feasible, we would have to proceed with stricter cost-price criteria for membranes and pre-treatment. It appeared, however, that the chosen values were sufficient to meet the economic feasibility.

2. Development of low-cost membranes

2.1. Membrane requirements

Audinos [7] already mentioned explicitly the importance of membranes specially developed for reverse electrodialysis. Nevertheless, most research was done with standard electrodialysis membranes (e.g., [3,6,11]). As a result, nowadays available homogeneous ion-specific membranes may be used (e.g. from Asahi Glass, Tokuyama or Fumatech [13]) as a benchmark for the development of tailor-made membranes. The requirements for the ion-exchange membranes for reverse electrodialysis are summarized in Table 3.

During the development process, it may be sufficient to use a straightforward model to evaluate the performance of the membranes with respect to the maximum power density [13]. However, we are aware that this evaluation is just a guideline to give direction to the development of membranes for reverse electrodialysis. Absolute values as calculated by a simple model are likely to overestimate the specific power since numerous assumptions (e.g. total effective membrane area available for ion transport, ideality of solutions, no depletion of feed streams) and simplifications are made. The most important uncertainty is the translation of membrane characteristics as measured by the standard characterization methods to apparent characteristics of the same membranes when applied in a reverse electrodialysis stack.

As can be seen from the desired characteristics in Table 3, our focus is on the development of membranes with high perm-selectivity and low electrical resistance. It is difficult to optimize these characteristics of ion-exchange membranes for reverse electrodialysis since

Table 3
Membrane requirements for reverse electrodialysis.

Criterion	Requirement	Comments
Perm-selectivity	>95% (this can be measured as in [13])	The perm-selectivity determines the membrane potential which is available as a driving force for the process, and the transport of co-ions which is in fact energy dissipation [5]
Electrical resistance	$<3\ \Omega\ \mathrm{cm}^2$ (this can be measured as in [13])	The internal resistance of the stack should be as low as possible, and the lower the electrical resistance of the membranes, the lower the electrolytic shortcircuits are through the manifolds [11])
Mechanical stability	Enables construction of a stack	The membranes should have enough strength to be used for stack construction. This measure is hard to be quantified, but should be part of the evaluation.
Chemical stability	Lifetime >5years	Mild membrane environment, no special requirements (neutral pH's, no free chlorine), although certain resistivity for cleaning agents is preferred, etc.
Cost price	<2 €/m^2	Explained in section 4

the different properties (thickness, swelling degree, ion-exchange capacity) often have a counteracting effect on these characteristics. For instance, thin membranes have a relatively low area resistance (desired) but also a low perm-selectivity (not desired).

2.2. Challenges are cost-price and production scale

Although the technical requirements are already met by currently available membranes, the cost-prices are out-of-range to make reverse electrodialysis affordable. According to Turek and Bandura [9], it is hard to believe that the price of low-resistance ion-exchange membranes may be reduced a hundred times, which seems to be the desired cost level [9].

Nevertheless, after a look at related markets, we are more optimistic that membrane prices for (reverse) electrodialysis can be reduced tremendously [4]. One should be aware of the fact that electrodialysis membranes have never had a considerable market share. Even then, on the global market, heterogeneous ion-exchange membranes can be found with very low cost-prices (<5 US\$/m^2). Of course, low-resistance ion-exchange membranes have higher prices of 100 US\$/m^2 or more [9], but even these prices can be expected to fall, as manufacturing techniques improve, and the range of applications expands. Market research for related membrane applications show unit prices of installed membranes falling by an order of magnitude in 10 years, and this made Sutherland [15] to predict that the 1 US\$/m^2 of installed membrane is not far off.

It should be noted that, even when the total current membrane manufacturing capacity is considered (neglecting the differences in technical specifications of membranes), this global production capacity would never be able to match the demand of membranes for power production. The global turnover in 2003 for sales and after-sales of desalination membrane modules was 1,814 million US\$ [15]. Assuming a cost price of <10 US\$/m^2 installed membrane, this means a market of >180 km^2 of membrane per year, i.e., equivalent to the demand of one medium-sized salinity-gradient power plant. For the development of low-cost manufacturing of ion-exchange membranes and stacks, this means that besides the expertise in manufacturing of membranes an expertise of mass production is needed.

Therefore, a comparison with the market of ionites—or more specifically of synthetic ion-exchange resins—would be more appropriate than a comparison with the membrane market. The chemistry of ion-exchange polymers in bead-shaped materials is comparable to that of ion-exchange membranes. Besides, ion-exchange resins can be directly used for preparation of heterogeneous membranes when they are mixed in a basically uncharged polymer membrane matrix [16,17]. Regarding the market, ion exchangers for deionization and water softening applications can be considered commodity chemicals (excess of production capacity, limited market growth, and intense competition) with a global market volume that exceeds 0.15 million m^3 per year [18]. To get an idea, this would be comparable to a market volume of >1,500 km^2 of ion-exchange membrane per year (i.e., equivalent to several medium-sized salinity-gradient power plants), if we assume 100 μm thick membranes. Current prices for commodity ion-exchange resins are in the order of 3,000-6,000 US\$/m^3 [18], indicating that a membrane price in the order of 1 US\$/m^2 is indeed within reach [15].

While at the start of the membrane development for reverse electrodialysis, we paid much attention to the technical requirements and cost prices of base materials, nowadays we are focusing on high-volume manufacturing. Given the enormous amount of membrane area needed for large-scale energy conversion by reverse electrodialysis, the scale-up of the production processes becomes more and more important. In our vision, the membranes should be manufactured on labour-extensive reel-to-reel production lines operating at high speeds. The post-processing such as alternating piling of the cation-exchange membranes and anion-exchange membranes in the required stack configuration should be automated as well.

3. Stack design related to friction loss and pre-treatment

3.1. Process design

The required water quality parameters are still unknown. As in the previous section, it is tempting to look at experiences with desalination membranes. However, the usually applied pre-treatment steps [19] are probably excessive and certainly too capital-intensive to be viable for reverse electrodialysis. Besides the quality and cost aspects, the footprint, energy consumption, and use of chemicals, would be important factors regarding the feasibility of reverse electrodialysis. We defined these requirements in Table 4.

On forehand, it should be mentioned that these requirements are based on the assumption that the reverse electrodialysis stacks are redesigned toward a system *without* spacers between the membranes. If spacers were used, the question remained whether these requirements would be sufficient. Reverse electrodialysis stacks *with* spacers would require an even more extensive pre-treament than conventional flat-sheet membrane systems as the distance between the membranes is less than 0.5 mm. The design of experimental reverse electrodialysis stacks were still based on the common stack

Table 4
Pre-treatment requirements for reverse electrodialysis.

Criterion	Requirement	Comments
Separation cut-off	<50 μm	Sufficient to prevent fouling with Common or Blue Mussel (*Mytilus edulis*). Fertilized eggs are 60–90 μm in diameter [26].
Costs	<1 €ct/m^3	Each 1 m^3 pre-treated water (i.e., 0.5 m^3 seawater and 0.5 m^3 river water) could yield 130 Wh ~ 1 €ct [5].
Energy consumption	<6–7 Wh/m^3 (<2–3 m water column)	Our arbitrary aim to limit parasitic losses to <10% of yielded energy, with a maximum of 50% for pre-treatment.
Footprint	> 15 m^3/h of capacity per m^3 reactor	Our arbitrary aim to limit the footprint. Obtained flux (m^3/m^2.h) times packing density of the reactor (m^2/m^3) could be used for indication.
Chemical use	No dosage	May be incidentally used for cleaning

design of electrodialysis with the use of screen spacers. These screen spacers, however, were identified not only as undesired insulators [5] and cause of relatively high friction losses [12], but moreover as a place for biofilm accumulation causing pressure drop increases [20] and a decline of the electrical performances. Therefore, the reverse electrodialysis stack was redesigned towards a more robust spacer-free system, using a developed computational fluid dynamics model for flat sheet membrane configurations [14]. Instead of spacers, now flow paths are formed in the membranes providing a more open design with fewer crevices for physical entrapment of solids. With a cross-flow velocity of 3 cm/s it was confirmed using model calculations and experiments with an non-fouled system, that the friction loss is less than 2–3 m water column (~6-7 Wh/m^3). Assuming that each 1 m^3 water (i.e., 0.5 m^3 seawater and 0.5 m^3 river water) yields 130 Wh [5], the related pumping energy loss accounts only for 5%.

For the selection of a suitable pre-treatment technology, our aim was to find commercially available operational units that meet the self-defined criteria in Table 4. We assumed that floating coarse debris such as weed, reed, and plastics were removed from the surface water at the intake by using weirs and bar-screens. For further pre-treatment all kind of separation processes were reviewed—settling, decanting, centrifugation, filtration, hydro-cyclone, flotation, elutration, flocculation and biological treatment. Based on the criteria as given in Table 4 it was concluded that two types of filtration technologies would be suitable as pre-treatment: (i) river/sea-bank filtration or (ii) mechanical filtration. Most technologies were expelled as they are too expensive and have too low fluxes or too high residence times, leading to a huge footprint and building volume.

River/sea-bank filtration also has low fluxes (0.1–1 m^3/m^2.h), but this open-field extraction process requires no big building volumes and could well be combined with other functions (e.g. recreation, landscape development). Sea-bank filtration is used for desalination systems with reverse osmosis membranes. The use of (vertical) beach-wells has the benefit that bank-filtrated seawater needs minimal additional pre-treatment prior to the reverse osmosis. We did not further design this pre-treatment as the applicability of beach wells is very site-specific, e.g. depending on the soil morphology. For desalination plants with a high capacity, an open seawater intake is in many cases the only feasible option [21,22]. Nowadays, new techniques are available to increase the capacity of beach wells by using drainage pipes installed in horizontally drilled holes [23].

Mechanical filtration is a more generic pre-treatment step than bank filtration. Filter media are used to remove or separate particles by steric rejection. The configuration of the micro-screen filter may have different configurations and screen fabrics. Hubert Stavoren B.V., one of the companies in our consortium, has an extensive track record on micro-screen rotating drum filters for pre-treatment of cooling water. In their configuration, the micro-screen consists of a drum, fitted along the circumference with screen panels. The drum is placed in a concrete pit or tank and rotates on a stationary hollow shaft which is provided with one or more funnel-shaped debris collectors. The feed water enters the drum axially and flows radially through the panels by gravitation (typically a level difference in the order of 10–20 cm), the dirt particles being trapped in the mesh. In order to prevent clogging of the fabric by particles, the drum rotates and the rows of screen panels subsequently pass a set of high-pressure water nozzles at the top of the drum. The dirt particles are washed from the screen and discharged through the funnel-shaped debris collector(s) and the hollow shaft.

Looking at the criteria in Table 4, the most critical factors for these drum filters are energy consumption and footprint. The high-pressure pump needed to supply the water to the high pressure nozzles (e.g., 8 bar overpressure) is the most energy consuming part of this system although the amount of pressurized backwash water is only a few percent of the filtrated water. Assuming 2% of pressurized backwash water, the net head loss is 1.6 m water column (and thus the criterion is met). In order to minimize energy consumption, the high-pressure pump is controlled by a level differential meter over the filter. Regarding the footprint, obtainable net fluxes are reasonable high even with a fabric with 50 μm pores, e.g. in the order of 20–40 m^3/m^2.h. The packing density of the reactor, however, is quite low (~0.5–1 m^2/m^3). The cylindrical drums with a filter area $A = \pi DL$ (diameter D <5 m, length L <6 m) are placed in a rectangular tank with a volume $V > D^2L$, resulting in a packing density $<\pi/D$. Consequently, the treated flow rate is 10-40 m^3/h per m^3 reactor. Depending on obtainable flux and design of drum and tank, the footprint criterion can be met.

3.2. Experimental validation

In the harbour of Stavoren (Lake IJssel, The Netherlands), we tested the effectiveness of pre-treatment. The experimental setup consisted of a rotating drum with a filter area of 1.1 m^2. The filtrate is fed to a flow-cell that represents the hydrodynamic design of a single membrane in a full-scale reverse electrodialysis stack with membrane-integrated flow patterns (Figure 2). During successive experimental runs, the screen panels were covered with different types of fabrics to test the flux and energy consumption of the pre-treatment. Also the pressure-drop over a flow cell was measured to test the effectiveness of the pre-treatment.

The capacity of the filter was depending strongly on the chosen fabric and the pore size. We took comparable synthetic fiber materials with pore sizes of 20 μm and 50 μm and tested the maximum flux to be 22 m^3/m^2.h and 50 m^3/m^2.h, respectively. These filter fabrics, however, were not reliable enough as pre-treatment in cases of failures with the backwash. When a support layer is added to the 50 μm fabric to gain mechanical strength and robustness, the maximum flux decreased to 21 m^3/m^2.h. This is worse when compared to a stainless steel fabric with 40 μm pores with a maximum flux of 43 m^3/m^2.h.

With the latter two fabrics (i.e., the reinforced synthetic fabric with 50 μm pores and the stainless steel fabric with 40 μm pores), we were able to measure the energy consumption and the effectiveness of the filter over longer periods without interruptions (Table 5). The energy consumption of the filter drum was very much dependent on the seasonal water quality. During summer season with elevated water temperature (17–19°C) the high-pressure pump was switched on more frequently than during the winter season wit low water temperatures (5–7°C), causing a monthly average net head loss of 1.87±0.17 and 0.36±0.34 meter of water column, respectively. Even in summer period, the criterion for the energy consumption is met (Table 4), not only with the monthly average, but even with a once measured maximum of a net head loss of 2.92 meter water column.

During the test periods, the pressure drop over the flow cell (membrane) did not increase, indicating that the filter drum was effective as pre-treatment. The pressure drop appeared to be dependent on seasonal temperature fluctuations, the lower the water temperature, higher the head loss across the flow paths in the membrane. The total energy consumption in all cases met the objectives for pumping power losses.

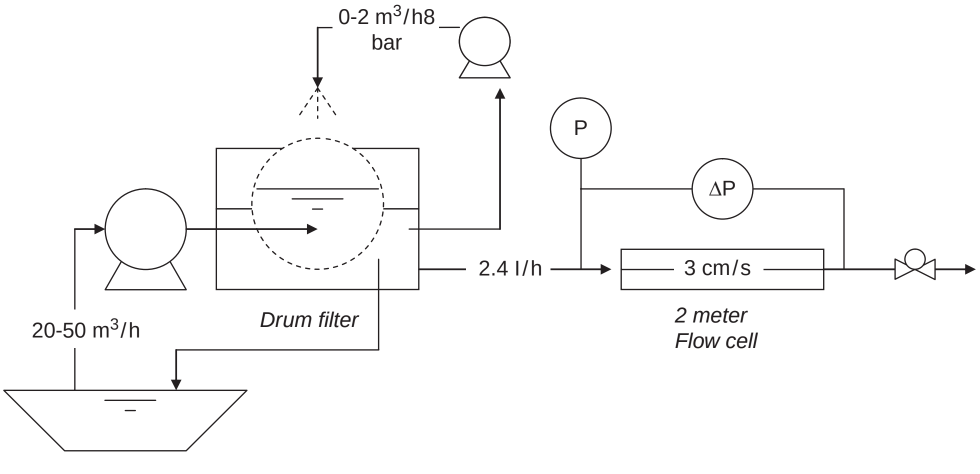

Fig. 2. Experimental setup to test the capacity and energy consumption of a drum filter and the effectiveness of this pre-filtration on a flow cell which represents the hydrodynamic design of a single membrane in a full-scale reverse electrodialysis stack.

Table 5
Pre-treatment experimental results.

Season		Filter drum		Head losses (meter water column)					
				Filter drum		Membrane		Total	
24–31 Days	Water temp °C	Pores µm	Flux m/h	avg	max	avg	max	avg	max
Summer	17–19	50	21	1.87 ± 0.17	2.92	1.23 ± 0.05	1.30	3.10 ± 0.70	4.12
Winter	5–7	50	18	0.36 ± 0.34	1.18	2.06 ± 0.27	2.70	2.41 ± 0.45	3.30
Spring	12–14	40	27	0.96 ± 0.46	1.69	1.80 ± 0.19	2.09	2.75 ± 0.58	3.55

4. Economic feasibility

4.1. Designing a 200 kW module

To get a view on construction costs, we designed a module of 200 kW (net) in 40 ft sea-container frames. A full-scale plant can contain multiple of these modules. A modular design has the advantage that a localized breakdown can be fixed very soon, and only a small part (200 kW) of the total plant capacity has to be stopped in case of maintenance. One frame contains six reverse electrodialysis stacks (Figure 3) with a total effective membrane area of 100,000 m^2.

The calculated power density is 2 W/m^2, according to the model presented by Post et al. [4,5], with an energy recovery of 70%. The gross power output is 220 kW, but about 10% of this is subtracted for pumping power losses and DC/AC conversion. Most piping and fittings are located outside the frame. These are sufficiently dimensioned for the supply and distribution of 0.2 m^3/s fresh water and 0.2 m^3/s salt water, and for the discharge of 0.4 m^3/s brackish water. The interconnecting pipes between the feed headers and included valves enable a reversal of feed flows (salt water side becomes fresh water side, and vice versa) and a reversal of feed direction (supply header becomes collection header, and vice versa). This provides the possibility to clean the systems by applying osmotic shocks and to wash out the remnants of detached biofilms, respectively. Furthermore, each unit has its own electrical connection.

Another frame contains two rotating drum filters for the pre-treatment of both feed flows. Assuming a diameter D = 1.7 m and a length of L = 4.5 m per filter, the area per filter is 31 m^2. Assuming a flux of 30 m^3/m^2.h, the filter can easily supply the required 0.2 m^3/s. Since the filtrate comes out at atmospheric pressure, it is logical to locate the filter drums on a little higher level than the stacks (e.g., filter drums on the first floor and stacks on the ground floor), enabling a gravitational flow from

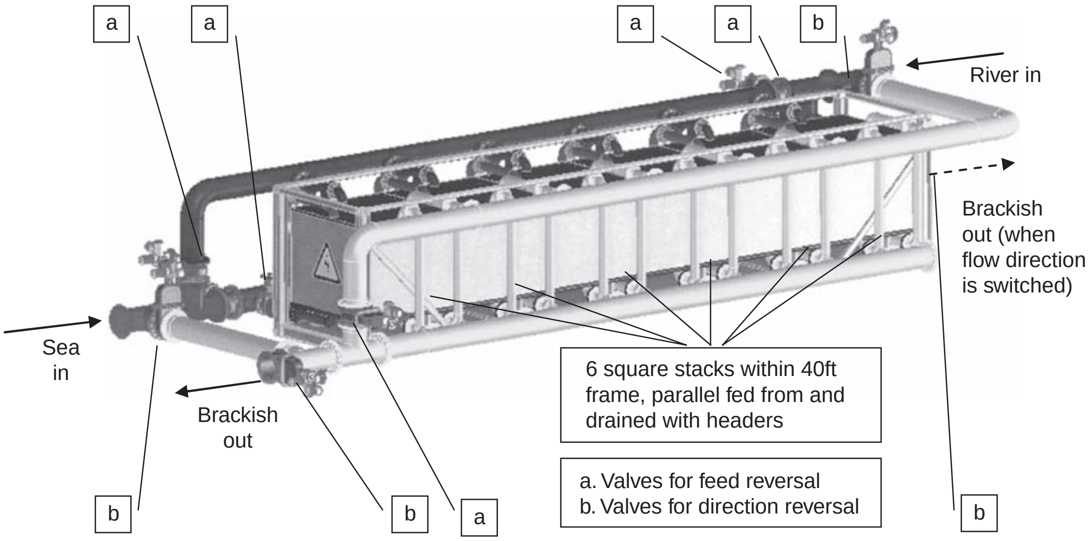

Fig. 3. A 200 kW (net) unit with six reverse electrodialysis stacks in a 40 ft sea container frame.

drum filter through the stacks to the outlet. With this hydraulic line, the feed pumps raise the level of the water from the inlet water surface to the water level within the filter drums, i.e., to a level of 5 m above the water level of the brackish water outlet. The actual head which has to be delivered by the pumps depends on the water level differences between intake and outlet.

A cost break-down was made (Table 6) by using detailed cost calculations from the supplying companies. Hubert made a cost calculation for drum filters with a concrete pit, according to Hubert's standardized specifications. Landustrie made a cost calculation for piping, fittings and pumps, based on a bill of quantities and standardized overhead for construction. For the reverse electrodialysis stacks, the assumption was made of an installed membrane price of 2 €/m^2 (i.e., including end plates and electrodes). The mechanical and electrical construction for components of a 200 kW unit is less than 900,000 €. The cost price is less than 0.08 €/kWh.

It appears that each component has about an equal contribution to the cost-price. However, is should be noted that the cost price is most sensitive to changes in the assumed membrane price and lifetime expectancy (all other components contain proven technologies with less uncertainties and a typical deviation of less than 20%). A sensitivity analysis is worthwhile to perform, not only for assessing the feasibility but also for getting a view on the development path (see section 5). For a first generation, a higher membrane price would be acceptable. For instance, if on short term a membrane price can be achieved of 10 €/m^2 (5 times the aimed cost price), the contribution of the membranes to the kWh price would be 0.14 €/kWh, thus already resulting in a quite acceptable total cost price of 0.20 €/kWh.

4.2. Cost estimation for a 200 MW plant

With the 200 kW unit as a repetitive unit, a cost estimation could be made for a 200 MW plant consisting of 1,000 units. For the mechanical and electrical part, the investment costs of such a plant would benefit to a certain extent from the economy of scale. Instead of two small feed pumps per module, two pumping stations can be built for the total plant, for instance, each with 16 screw pumps of 12.5 m^3/s with an average lift of 5 m. The mechanical and electrical investments for a 200 MW plant would, therefore, not exceed 900 million € (i.e., 1,000 times the construction costs of a 200 kW module).

However, on the other hand, a site should be purchased and industrial building needs to be built. The total volume of buildings is in the order of 200,000 m^3. Taking into account a heavy construction and foundation due to the large amounts of water, the construction costs could be as high as 100 million € (i.e., a cost price of 500 €/m^3). Moreover, site-specific additional infrastructure could be a large investment. However, these costs for buildings and infrastructural works do not influence the overall cost price too much. This can be explained by the long lifetime expectancy of 40 years and relatively low expenditures for operation and maintenance. For a 200 MW power plant, each 100 million € of investment in civil engineering would add 0.005 € to the cost price of a kWh.

4.3. Comparison with wind energy

In order to valuate the impact of 200 MW salinity-gradient power plant, a comparison is made with wind energy. With a load factor of ~90% (8,000 hours per year base load), such a reverse electrodialysis plant delivers on annual basis 1.6 billion kWh to the public network, which is enough for over 0.5 million households. In 2007, all 1,800 existing wind turbines in The Netherlands produced on annual basis 3.7 billion kWh [24]. A salinity-gradient power plant of this size would have a significant contribution to the green electricity production of the country.

Meanwhile, also in wind energy a lot of technical progress has been made. In the near future, new wind turbines will be able to produce 3–5 MW at peak power [24,25]. These modern wind turbines have a diameter of

Table 6
Cost break-down for a 200 kW reverse electrodialysis unit on surface waters (in case of very clean industrial feed waters the costs for pre-treatment might be lower, resulting in a lower kWh-price).

Part	Construction	Annual costs (€/y)			Cost price
	Costs (€)	Capex[3]	Opex[4]	Total	(€/kWh)[5]
Frame with RED stacks[1]	200,000	37,000	6,000	43,000	0.027
Piping, fittings and pumps[2]	320,000	28,000	10,000	38,000	0.024
Frame with filter drums[2]	370,000	32,000	11,000	43,000	0.027
Total	890,000	97,000	27,000	124,000	0.079

[1]Membrane lifetime 7 years; [2]Depreciation in 20 year; [3]Annuity depreciation: discount rate 6%; [4]Operation and maintenance: 3% of construction costs; [5]Production of 8,000 hours per year (base load).

approximately 100 meters, and the height of the axis is found 80 meters above ground level. When calculating the number of new wind turbines that are necessary to produce the same amount of electricity as the salinity-gradient power plant of 200 MW, the differences in load factors should be taken into account (25–30% for wind turbines; 90% for salinity-gradient power). One can find that 140–240 wind turbines are needed. With a mutual distance of approximately 200 m this would imply a line of 30–50 kilometres. The impact on the landscape is obviously bigger than that of a salinity-gradient power plant. Assuming the investment costs for wind turbines to be 1–2 €/W [25], the investment costs are 700–1.400 million €. Investment costs and cost prices of both technologies are thus comparable.

5. Further steps

5.1. Aimed location for first power plant

In the Netherlands, five locations have been identified for salinity-gradient energy. Two of these locations provide the opportunity for a large-scale application—Afsluitdijk and the Dutch Delta. The Dutch Delta is interesting because of the enormous fresh water discharge, but requires more complicated infrastructural works. Despite of initial skepticism about applicability in the Dutch Delta [25], a recent model study showed that several alternative locations for salinity-gradient power plants of over 500 MW each are available [24]. On the shorter term, however, the ideal spot to realize reverse electrodialysis is the 30-km long Afsluitdijk in the North of The Netherlands (Figure 4).

This dike separates the 1,100-km^2 fresh Lake IJssel from the saline Wadden sea. In 1932 the lake was formed by closing of the Zuiderzee, the estuary of a couple of rivers with an average flow of 450 m^3/s. The dike provides a strict separation of salt and fresh water. Large outlet sluices discharge water from the lake onto the Wadden sea. Discharging the fresh water is not a continuous process but depends on tide levels on the Wadden sea.

The flow that can be used for salinity-gradient energy at this location is quite large, i.e. on average 450–m^3/s. Statistic model calculations should verify that this flow can be made available for power generation during the main part of the year (in summer time less fresh water is available than in winter time). This should, is however, not a big issue given the fact that upstream the discharge distribution can be regulated to guarantee this discharge. Moreover, given the fact that Lake IJssel already serves as fresh water storage, the lake can be used to absorb differences in the availability of fresh water.

The salinity of Lake IJssel is very low, around 0.2–0.5 g/L. The salinity of the Wadden sea is difficult to determine due the discontinuous discharging process of the outlet sluices. Every time the sluices open their gates, a large fresh water bubble builds up. This bubble influences salt concentrations in the sea. Hydraulic models should be used to verify that in case all water from the Lake IJssel is continuously mixed with water from the Wadden sea in a salinity-gradient-power plant, the salinity would be almost as high as that of the North Sea—around 28 g/L. This salinity could be reached due to a better mixed Wadden sea (continuous discharge of brackish water instead of fresh water bubbles) and due

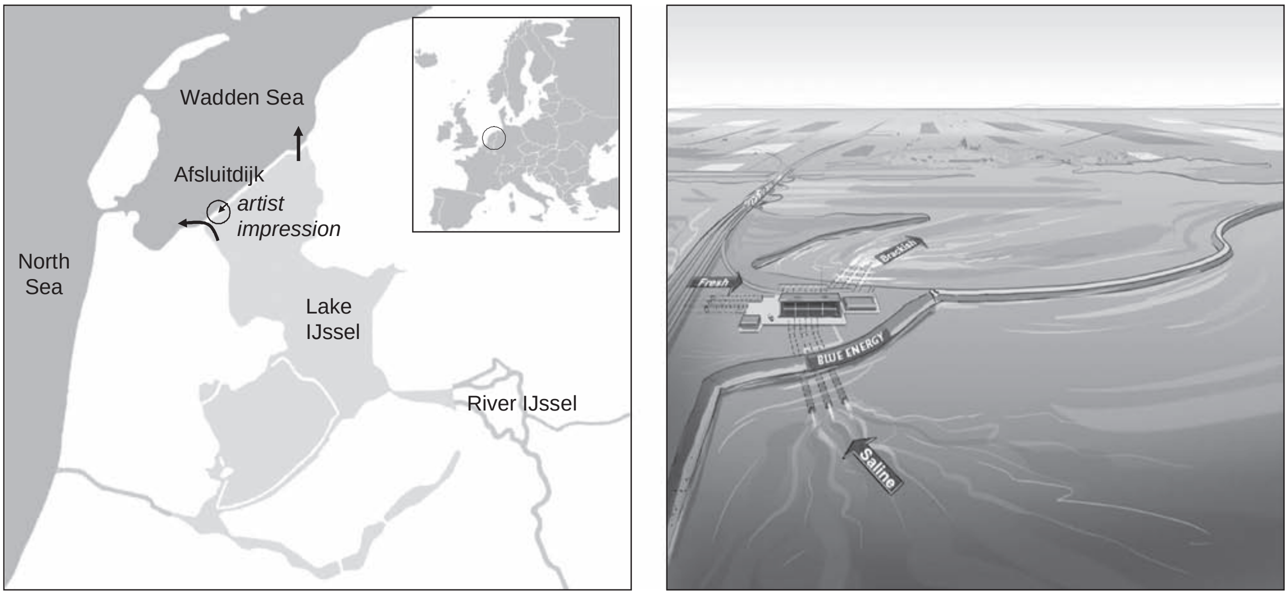

Fig. 4. Map and artist impression of a salinity-gradient power plant at the Afsluitdijk (source: Rijkswaterstaat).

Table 7
Development path of reverse electrodialysis scale-up.

Project	Scale	Aim
2008–2010 Pilot on industrial water flows	kW-scale	First step out of the laboratory. Pilot on saline flows in a salt factory of Frisia in Harlingen (Financially supported by SenterNovem, Innowator project)
2008 Engineering of pilot on surface waters	-	Feasibilty study and definition of requirements for a pilot on the Afsluitdijk (Private funding, 2008)
2010–2012 Pilot on surface waters	20–50 kW	Pilot on sea water and river water at the Afsluitdijk. Focus on 'design to work'
2013–2015 Demonstration plant on surface waters	1 MW	Demonstration on sea water and river water at the Afsluitdijk. Focus on 'design to cost'

to the use of dominant flows at the Wadden sea along the dike that provides the possibility of an upstream sea water intake and downstream brackish water release. Eventually, an additional embankment perpendicular to the Afsluitdijk is needed to enhance the separation of salt water and brackish water (Figure 4).

5.2. Scale-up: from pilot to full-scale

Before implementing reverse electrodialysis on a commercial scale, the feasibility of the technology should be proven in practice. The promising research and development of the technology raised interest of different industrial and energy companies and water authorities to invest in pilot facilities at the Afsluitdijk. Thus we are happy to find suppliers who are really prepared to take the opportunity to develop a prototype of a production line without an actual order for square km's of membranes. At this stage of the project, we focus on consortium building, with customers entering into technical development agreements with suppliers, joint design and test programs. The involved parties agreed on the following development path for scale-up of the system, see Table 7.

5.3. Other issues for study

Reverse electrodialysis is a clean and sustainable technology. The sustainability should be further analyzed and proven in the near future based on the experiences from these pilots and demonstration plants. Currently, expectations are based on the construction and production of a power plant and its components; however, attention should also be drawn to the processing of used materials (especially the membranes) at the end of their lifetime.

When applying salinity-gradient energy at a large scale, it might be necessary to change the hydraulic system and water management rules, because a lot of fresh and salt water is needed. These measures should fit within legislation and regulations. The impact on the environment and ecological system (e.g., flora and fauna, water quality, bank morphology) of changing nutrient flows, sediment transport, changing local salinities and gradients, building a power plant etc., should be entirely studied on short notice. Also other interests of the water system (shipping, recreation) and infrastructural works (protection, water management) should be taken into account. These aspects will be crucial for the decision making process. Therefore, we take care of partnering with knowledge institutes of different disciplines, like hydraulic engineering and water resources management.

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