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An alternative hybrid concept combining seawater desalination, solar energy and reverse electrodialysis for a sustainable production of sweet water and electrical energy

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ABSTRACT

Fresh water and oil/gas based energy will become scarce since their actual (increase in) consumption rate is definitely unsustainable, when considering their restricted world reserves. Moreover, the large scale burning of such fuels for the production of electrical energy or in industry/transport results in a significant rising of the carbon dioxide concentration in the atmosphere and therefore a rising of global temperatures. Research and development regarding alternative energy sources such as e.g. nuclear fusion is proceeding but mankind also becomes more aware of the sun as being a giant fusion reactor, already at their free disposition and able to act as a lasting and sustainable energy source. The sun in fact delivers continuously about 89,000 TW of usable insolation (photons) power to our planet while the actual global power consumption is about 15 TW. From this point of view, the sun is thus able to provide about 6000 times the world's energy demand, thus highlighting the enormous potential of solar energy from such numbers in a very obvious way. A major disadvantage of insolation energy of course is its discontinuous and fluctuating availability during daytime. To circumvent such, a solution could eventually be found in the storage of solar power as osmotic energy in highly concentrated salt solutions. The development of salinity gradient power (SGP) based on reverse electrodialysis (SGP-RED) could therefore possibly become an important alternative approach. When combined with classic or solar power based seawater desalination technologies, the resulting hybrid system could well be a candidate for the simultaneous production of potable water and electrical energy. The concentration of the brine from the seawater desalination unit (SWDU) could be substantially increased by using solar energy while also producing additional sweet water (condensate). Electricity could then be produced from the mixing energy of the highly concentrated brine and seawater, by using the principle of reverse electrodialysis (RED). In this way the disadvantageous brine waste situation in seawater desalination could eventually be converted into an opportunity regarding the production of a large amount of additional fresh water, a significant amount of electrical energy and an answer to the brine disposal environmental problem. The theoretical simulation results from SGP-RED stack modeling using highly concentrated brine and seawater (brackish water) point to the absolute need of the development of a battery oriented SGP-RED stack configuration, requiring thin ion conductive membranes and thin spacers as to minimize the internal battery resistance and maximize the electrical power output.

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Keywords: Salinity gradient power; Reverse electrodialysis; Brine; Solar; Desalination; Evaporation; Potable; Fresh; Sweet; Energy; Sustainable

1. Introduction

The negative effects from specific human activities on the earth's environment, such as global warming, are now considered to be fully proven by scientists. Natural fossil energy resources such as oil and gas are consumed at a very high pace and large amounts of carbon dioxide are thus generated. Moreover, oil or gas reserves are limited and will indeed be depleted within only a few generations if there will be no drastic shift in the low added value oriented thermal consumption pattern of these valuable resources. Alternative ''green'' sustainable/renewable energy resources are thus evaluated as being very important for future generations. One potential candidate could be salinity gradient power (SGP) which is based on the electrochemical energy difference (also indicated by ''osmotic'' energy) between a concentrated and a diluted salt solution. Reverse electrodialysis (RED) can be used to directly produce SGP as electricity. RED was already suggested in 1954 by Pattle [1], Weinstein et al. [2] while Lacey [3] elaborated further on the RED concept. Wick and Isaacs [4] also pointed towards the potential of osmotic energy. Loeb [5,6] e.g. considered the principle of pressure-retarded osmosis (PRO). The functioning of PRO was demonstrated by Skilhagen [7] while a large PRO demo installation is actually activated (from November 2009) and tested by Statkraft (Norway). Post [8] calculated the limits of SGP potential for PRO and RED since, when combining river/lake water and sea water, there is no alternative as to extract as much as possible of the mixing energy in one go. The hybrid system suggested in this publication however uses solar energy and allows in principle to ''re-charge'' the SGP-RED battery as explained further and thus shows, in theory for now, a larger SGP extraction control flexibility. Additional information on SGP can be found in Chapter 5 ''Salinity Gradient Energy'' within [9].

In principle, a highly concentrated salt solution effluent can be recovered from a seawater desalination unit (SWDU) and its concentration can be further increased by using solar heat during an evaporation process. Moreover, additional potable water can then be produced through condensation of the water vapor. When thus combining a SWDU, solar energy and a SGP-RED unit, a hybrid system [10] can be considered involving the highly concentrated salt solution as the SGP-RED unit ''concentrate'' feed while seawater (/brackish water) is the low concentrated salt solution SGP-RED unit ''dilute'' feed. The hybrid system thus could store solar energy as osmotic energy in a concentrated salt solution. When buffering the concentrate, the stored osmotic energy then could be continuously converted in electricity by a SGP-RED based electrical battery unit and thus used during the night. A very important aspect in this hybrid concept is the possibility to even re-concentrate the (controlled) diluted concentrate effluent from the SGP-RED unit. In that way, the SGP extraction is not restricted any longer by an ever fading salinity gradient over the path-length of the SGP-RED stack when trying to collect as much as SGP energy from the mixing process (as in the case of river water versus sea water). By the re-concentration option through solar energy to re-evaporate the diluted SGP-RED stack effluent, the dilution in the SGP-RED stack can thus be controlled. As a result, from the use of solar power to re-evaporate and reuse the SGP-RED effluent brine, the salinity gradient could be kept at a much higher level in the SGP-RED stack and therefore the process would not be limited any longer by the theoretical mixing energy as described in [8]. In such an approach there is no need any longer to squeeze out the complete mixing energy in one go and the input of solar energy therefore can be considered as a continuous ''recharge'' of the SGP-RED battery (by keeping the salinity gradient in the SGP-RED stack to a high level). Moreover and importantly, the salinity gradient is much larger when using the highly concentrated brine versus seawater (/brackish water) when compared with the combination of seawater and fresh water.

Key to the success of the theoretical hybrid concept is evidently the adequate design of a high-performance SGP-RED stack. A SGP-RED process model was already published by Lacey [3]. This model was implemented in a solver software to further investigate the effect of specific parameters [11] (membrane thickness, temperature, compartment width) while implementing in the model two distinct dilute and concentrate compartment widths. From these simulations, important first recommendations resulted with respect to the design of the SGP-RED unit. The effect of these specific parameters on the SGP-RED power output were simulated and the results were reported in [11]. In practice however, the final specifications regarding an optimal SGP-RED unit can only be obtained through a broad and dedicated research/development program (including the modeling of the SGP-RED stack at a higher level such as e.g. a finite element approach) Such research program would also enable the techno-economical evaluation with respect to the design/production of an adequate SGP-RED stack (including the development of thin ion-conductive membranes and the experimental verification of the model data). In addition, an adequate solar energy based evaporation technology (including condensation with energy reclamation) should be evaluated and selected by experts, also on techno-economical grounds. Such complex information is evidently not yet available with respect to the suggested hybrid configuration and this publication therefore only highlights main research issues which should be given attention, regarding the hybrid concept involving solar energy, a SWDU and a SGP-RED unit.

2. Description of a hybrid system

2.1. Osmotic energy

In order to apply SGP on e.g. seawater as the high concentration salt solution, one obviously has to mix it with e.g. fresh (river, lake) water as the low concentration solution, either through the PRO or the SGP-RED principle. SGP indeed always requires two salt solutions, showing an important difference in salt concentration, as in the case of sea water and fresh water. However, the approach is not limited to the combination of sea water as the salt solution with the high salt concentration and fresh water as the salt solution with a low salt concentration, in order to obtain a sufficient salinity gradient. It is of course also possible to use brackish water or seawater as the solution with a ''low'' salt concentration and a highly concentrated salt solution (e.g. 250 kg/m^3) as the solution with the ''high'' concentration in order to enable SGP, while even substantially increasing the osmotic energy content when compared to the mixing of seawater and fresh water.

Having therefore a location at e.g. a sea shore

- where sea water (or brackish water) is abundantly available as the ''low'' concentration salt solution
- where a seawater desalination factory (SWDU) is producing potable water and a concentrated salt solution SWDU effluent
- where solar energy is also abundant in order to significantly increase the concentration of the SWDU concentrate further (e.g. 250 kg/m^3) by evaporation

the possibility exists of extracting the osmotic energy from the highly concentrated brine in a SGP-RED stack.

The principle of SGP could be illustrated through the free energy of mixing (enthalpy and entropy part). However, an indicative calculation method is straightforward. Sea water has a salt concentration of about 35 kg per m^3, corresponding to an osmotic pressure of about 2,700,000 Pa (27 bar). This value corresponds to the pressure exerted by a water column of 270 m high. In energy terms: if a volume V of 1 m^3 of fresh water would be produced from an infinite amount of sea water having an osmotic pressure P of 2,700,000 Pa, the theoretical energy E needed to force the volume V of 1 m^3 of water (through a semi-permeable membrane surface area S of 1 m^2 over a distance d of 1 m behind the membrane) then would be $E = P \times V = P \times S \times d = 2{,}700{,}000\ \text{Pa} \times 1\ \text{m}^2 \times 1\ \text{m} = 2.7\ \text{MJ}$ (0.75 kWh). Therefore the theoretical amount of osmotic energy in 1 m^3 is 2.7 MJ/m^3. An amount of 2.7 MJ/m^3 of energy corresponds in lifting 1 m^3 of water (1,000 kg) to a height of about 270 m.

The analogy of the osmotic energy in sea water with the hydraulic energy stored in a water dam, both capable of producing electricity, is then obvious. It is indeed possible to use PRO to drive a water turbine and a generator, as explained in [7] or to convert the osmotic energy directly in electrical energy by RED [1–3]. It is interesting to note that, as reported in practice, the production of potable water from seawater reverse osmosis (SWRO), requires in practice about 8...9 MJ/m^3 (2.2 ... 2.5 kWh/m^3) (when assuming hydraulic energy recovery from the pressurized concentrate). When compared with the theoretical osmotic energy value of 2.7 MJ/m^3 for seawater, the SWRO energy consumption is three times this value. However, SWRO is performed at a specific recovery, e.g. 50%. At such recovery, 2 m^3 of seawater is converted into 1 m^3 of potable water and 1 m^3 of concentrate. As an approximation, the salt concentration of the 1 m^3 of concentrate can be considered as being doubled with respect to seawater, thus about 70 kg/m^3. The osmotic pressure of the concentrate is then also about twice the one of seawater, thus about 5,400,000 Pa. The osmotic energy content of the concentrate therefore is about 5.4 MJ (1.5 kWh/m^3) per m^3. It is thus important to realize at this point that a substantial amount of energy, as being used during SWRO, is converted into osmotic energy, thus being stored within the concentrate. When disposed of in the sea, this osmotic energy is regrettably wasted, next to the environmental hazardous effect of such disposal of brine at a high salinity on local marine life.

2.2. The hybrid system

In [10] a, for now still theoretical concept of a, hybrid combination of a SWDU, solar energy and a

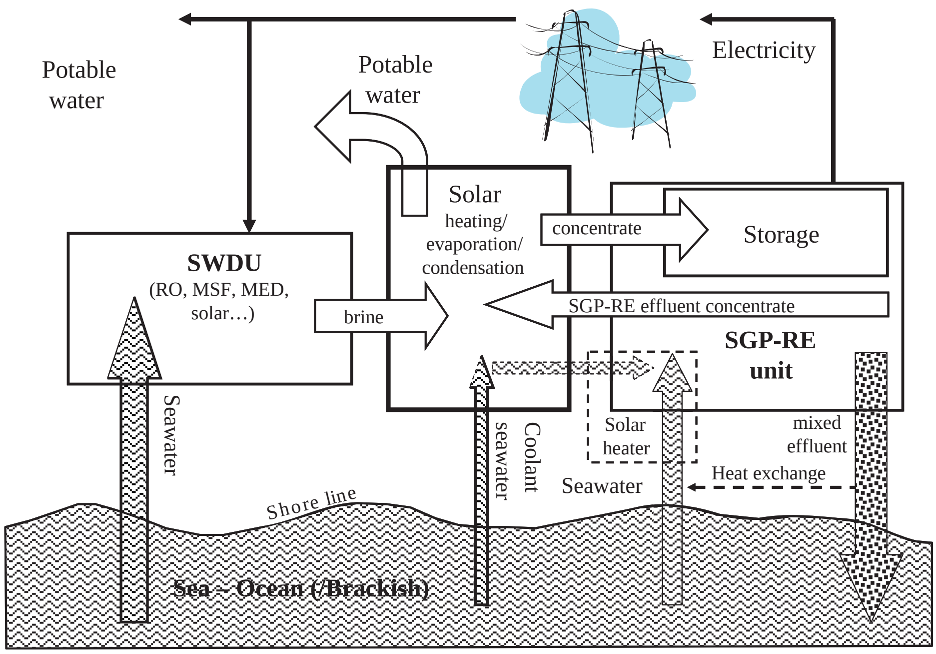

Fig. 1. Hybrid combination of solar energy, SWDU and SGP-RED unit.

SGP-RED unit was suggested, as illustrated schematically in Fig. 1. In the SWDU, potable water is produced through an adequate desalination method: eventually reverse osmosis, eventually evaporation (multi stage flash [MSF], multi effect distillation [MED], thermal vapor compression [TVC], mechanical vapor compression [MVC], solar energy based, . . .), eventually electrodialysis (brackish water) or a combination of those. It can be noted that at the SWDU, it would even be possible to increase the temperature of the incoming seawater through solar energy in order to improve the desalination process; as an example: for SWRO it is indicated in [12] that when the feed temperature is increased from 18 °C to 45 °C, an important pressure saving of between 7% and 26% can be obtained. The heat within the SWDU effluents should of course be reclaimed for re-use within the hybrid system.

The brine from the SWDU is then directed to the SGP-RED unit after first being concentrated further by solar energy through evaporation. As a result, additional potable water can also be produced by condensing the water vapor. During the condensation step, not only the precious additional potable water is produced but also the very important latent heat of evaporation is reclaimed as heat of condensation. The production of additional potable water is even considered in this publication as a primary goal of the hybrid set-up, thus being in fact at least as important or even much more important than the SGP production by itself.

The concentrate influent of the SGP-RED unit has thus a much higher concentration than the brine effluent of the SWDU. With respect to the further evaporation of the brine from the SWDU before entering the SGP-RED unit, solar energy could be applied in multiple ways. Either as heat through e.g. a similar set-up as in the SEGS configuration but by using the oil, being heated by parabolic mirror through type collectors to 400 °C, to evaporate the effluent brine from the SWDU. Since simulation calculations will require a full research program, it is not possible in this paper to consider all possible combinations of technologies in the suggested hybrid configuration of solar energy/SWDU/SGP-RED in order to select an optimal combination on the basis of techno-economical considerations/requirements.

In the SGP-RE unit, electricity is to be produced which can be delivered to the electricity distribution network. The electricity thus could be used in the SWDU, to drive e.g. the electrical motors of the SWRO pumps. As already indicated, an advantage of the solar based hybrid system is the possibility to recycle SGP-RED concentrate effluent to the solar based evaporation configuration between the SWDU and the SGP-RED. In this way the salinity gradient in the SGP-RED unit can be kept at a high level as a result of the implementation of solar power in the hybrid system. This should strongly increase the power potential of the SGP-RED approach (while simultaneously needing much less membrane surface area). When storing an adequate volume of evaporated concentrate (large salt pond), the continuous production of electrical power by a SGP-RED stack, thus also during the night, should be feasible. It could be noted here that the Dead Sea in that respect is a giant reservoir of brine, even at the saturation level.

2.3. The use of solar energy

In general, different approaches to use solar energy, directly (e.g. photovoltaic panels) and indirectly (e.g. wind energy), exist. With respect to a direct conversion of the energy of the solar photons, multiple approaches do exist, or are under research and development [13–22]. The references indicated represent only a very small number of the publications on solar energy and this paper does not intend to give a review on such complex matter. This paper only intends to point to an, at the moment mainly theoretical, hybrid concept combining desalination, solar energy and RED.

Desalination is performed in processes either:

– without a phase change, e.g. reverse osmosis or electrodialysis (ED). In both cases the energy applied to drive the process is (mostly) electrical. In SWRO the pumps are thus driven mostly by electrical motors. In ED, an electrical field across the electrodes of the ED stack drives the transport of ions from the diluate to the concentrate compartments. The electrical energy can be acquired from classic thermal or nuclear power plants. However, electricity can also be produced by photovoltaics (PV) or by solar heat. A well known plant is SEGS (Solar Energy Generating Systems) in the Mojave Dessert in California. SEGS operates 9 solar power plants with a total capacity of 354 MW. The photon collectors are of the parabolic mirror through type. There are about 1,000,000 collectors and the total occupied surface is about 6.5 km^2. The parabolic mirrors collect the sun rays and focus these at a central pipe in which oil is heated to 400 °C. The oil then heats water in order to produce steam which drives Rankine cycle based steam turbines and the electrical generators. It is interesting to remark that in desert regions, such as e.g. the Middle East regions, the solar power can peak over 1,000 W/m^2 at midday. When considering a Direct Normal Radiation (DNR) value of 200 W/m^2 over a period of 24 h, the available power for a completely covered surface area of 6.5 km^2 is then in theory 1,300 MW. This puts somewhat in perspective the 354 MW as obtained by SEGS on the occupied surface area of 6.5 km^2. At the SEGS Kramer Junction location the DNR value is even 7.44 kWh/m^2.day which equals to (7440 Wh divided by 24 hm^2) a DNR value of 310 W/m^2. The total insolation power at the full surface area of 6.5 km^2 at a DNR of 310 W/m^2 is then even 2,000 MW. This again puts in perspective the massive power available from the incoming solar radiation at a relatively small surface area.
– with a phase change from heating, evaporation and condensation (e.g. multi stage flash (MSF); multi effect distillation (MED); thermal (TVC) or mechanical (MVC) vapor compression based systems); membrane distillation (MD)). In principle it is of no importance what kind of heat energy is going into these processes. Therefore, conventional desalination installations based on heat could, in principle, also be driven by solar energy or waste energy. As explained with respect to the SEGS where the oil at 400 °C is used to produce the steam to drive the turbine and electricity generator, it is possible to advantageously use such heat directly (or even the waste heat from the electricity plant) in a conventional evaporation desalination process.

3. The importance of SGP-RED process parameters

In [11], the effect of primary SGP-RED process parameters were revealed by model simulations. The model simulations were based on the approach in [3] but with an additional emphasis on a different diluate and concentrate compartment thickness, membrane thickness and temperature. The object of the simulation was a theoretical minimization of the internal resistance of the SGP-RE battery in order to theoretically maximize the electrical power output. The basic SGP-RE cell pair in the model is represented in Fig. 2.

It is possible to define:

- 8 resistive voltages: $E_{12\text{Res}}$, $E_{23\text{Res}}$, $E_{34\text{Res}}$, $E_{45\text{Res}}$, $E_{56\text{Res}}$, $E_{67\text{Res}}$, $E_{78\text{Res}}$, $E_{81\text{Res}}$
- 6 diffusion voltages: $E_{12\text{Diff}}$, $E_{34\text{Diff}}$, $E_{45\text{Diff}}$, $E_{56\text{Diff}}$, $E_{78\text{Diff}}$, $E_{81\text{Diff}}$

The total voltage E_0 is obtained by summing the 14 voltage components [11]. The sum of the resistive components determines the internal resistance of the SGP-RED stack and this resistance is therefore highly counter-productive with respect to the power output. In order to minimize the effect of these resistive components, key parameters are the membrane thickness, the width of the low concentration salt solution compartment (in particular), the temperature of the salt solutions and also importantly the concentration (conductivity) of the salt solutions. Details of the simulations can be found in [11]. The results of the simulations are shown in Fig. 3 and Table 1 (the first column

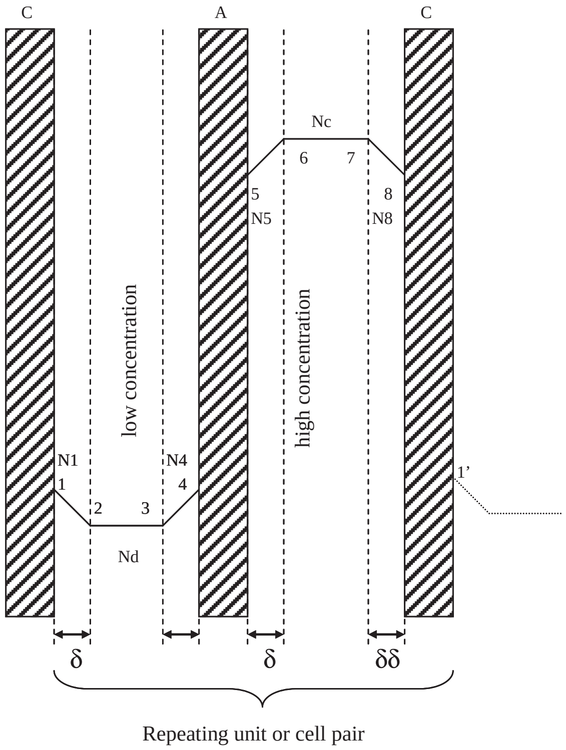

Fig. 2. Basic SGP-RED cell pair as presented in [3].

in Table 1 explains the labels of the Fig. 3 curves). The curve #2 as a reference represents the original power output graph as published by Lacey [3]. The concentration of the salt solution with the low concentration was assumed to be seawater at 35 kg/m^3. The concentration of the salt solution with the high concentration was assumed to be 263 kg/m^3.

The theoretical simulation results should not be perceived as a claim towards the practical feasibility of SGP-RED to obtain such high power output values. However, it gives at least an indication of the improvement that could eventually be obtained by fine tuning the SGP-RED stack. Up to now, much lower practical values of power output (W/m^2) have been reported in the literature but these are based on experiments with e.g. non-ideal membrane thicknesses (and moreover based on seawater versus fresh water, thus at a high initial compartment resistance in the fresh water compartment). In such experiments, regular industrial electrodialysis ''thick'' membranes are tested. From the simulations however, it is very obvious that one has to e.g. discard notions of using such thick existing classic ED membranes or current ED stack designs within a SGP-RED configuration. As in the case with the early development of reverse osmosis membranes, it was also realized that the thickness of the RO membrane was of crucial importance in order to have a substantial permeate flux when targeting a commercial application. Further developments then gave rise towards low energy membranes (TFC or thin film composite RO membranes). It is very clear that in the case of SGP-RED, ion-conductive membranes (AM and CM) need to be developed with a small thickness and that also a stack configuration needs to be engineered which would allow the use of such membranes. E.g. a specific spacer having a supporting function could be considered [11]. A SGP-RED unit should in fact be looked upon as a battery and the engineering approach involved therefore should be likewise. The internal resistance should be as small as possible with respect to power density. The fact that in the suggested concept seawater is used as the SGP-RED influent with the ''low'' concentration is also very beneficial in that respect since the high conductivity of seawater (when compared to fresh water) also dramatically lowers the internal resistance of the SGP-RED battery. This conductivity situation is obviously much more disadvantageous regarding the internal resistance in the case of the SGP-RED combination seawater (as the high concentration salt solution) and fresh water (as the low concentration salt solution).

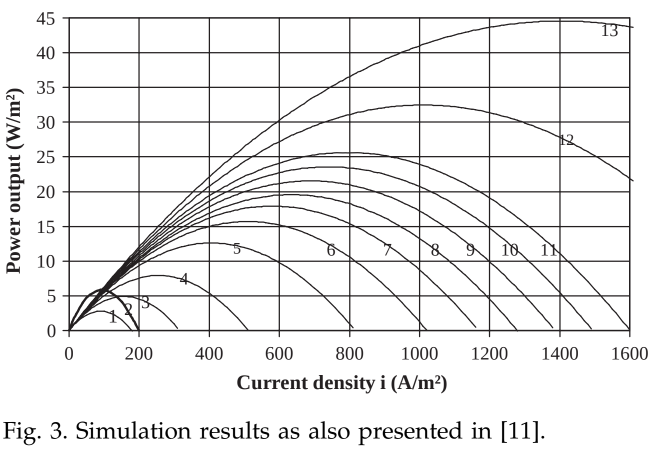

Fig. 3. Simulation results as also presented in [11].

4. The hybrid system's performance by arbitrary example

As a preliminary indication and by an arbitrary and theoretical example of the potential of the hybrid setup, a configuration is considered here having:

- an SWRO pressure driven membrane filtration unit as the SWDU producing 500 m^3/h of potable water from sea water at a recovery of 50%. The sea water has a salt concentration of 35 kg/m^3. There is thus also a stream of about 500 m^3/h of SWRO brine effluent at a concentration of 70 kg/m^3

Table 1
Simulation results

Curve no.	Membrane thickness (μm)	Low conc. compartment thickness (μm)	Temp. (°C)	Max. power output (W/m^2)	Stack power density (kW/m^3)
1	100	200	25	2.8	4.6
2 (Lacey)				6	
3	50	200	25	4.9	9.8
4	25	200	25	7.9	17.6
5	10	200	25	12.6	30.0
6	5	200	25	15.7	38.3
7	2.5	200	25	17.9	44.2
8	1	200	25	19.6	48.6
9	1	200	30	21.5	53.6
10	1	200	35	23.6	58.6
11	1	200	40	25.6	63.7
12	1	150	40	32.5	92.2
13	1	100	40	44.6	147

- a solar based evaporation which increases the SWDU brine effluent concentration to 263 kg/m^3 and delivers potable water through condensation (thus reclaiming the latent heat of evaporation)
- an SGP-RED unit which uses the 263 kg/m^3 brine as the high concentration influent and seawater as the low concentration influent

With respect to the SWRO installation it is assumed that the energy consumption is 9 MJ/m^3 (2.5 kWh/m^3). At a production rate of 500 m^3/h (12,000 m^3/day) of potable water, the electrical power needed at the SWRO is then 1.25 MW.

Regarding the estimates for an evaporation treatment of the brine, it is not intended in this paper to evaluate in detail any evaporation technology. A detailed techno-economical study is indeed needed but can only being done and reported about later after a broad, dedicated and substantial research project (in order to establish a selection by the experts of an optimal evaporation technology). Reference could be made here in that respect to e.g. the extensive modeling as described by El-Desouky & Ettouney in [20].

The salt concentration is assumed to be increased by a factor of about 3.75 from 70 kg/m^3 to 263 kg/m^3 (4,500 eq/m^3 NaCl as a reference). When evaporating 500 m^3/h of SWRO brine up to a concentrate having a salt concentration of 263 kg/m^3, the amount of water to be evaporated per hour is then about 370 m^3/h while the flow of remaining brine at a salt concentration of 263 kg/m^3 is about 130 m^3/h.

For now, it will be assumed in this publication, that a suitable solar energy based evaporation technology will be developed/available as to obtain a technically and economically feasible technology in the future. It is well known that the latent heat of evaporation is of prime importance in evaporation technology since the latent heat of evaporation of water is about 2,500 kJ/kg. Without reclaiming the latent heat of evaporation the brute force evaporation of 370 m^3/h of water therefore would need about 257 MW of power. At a DNR of

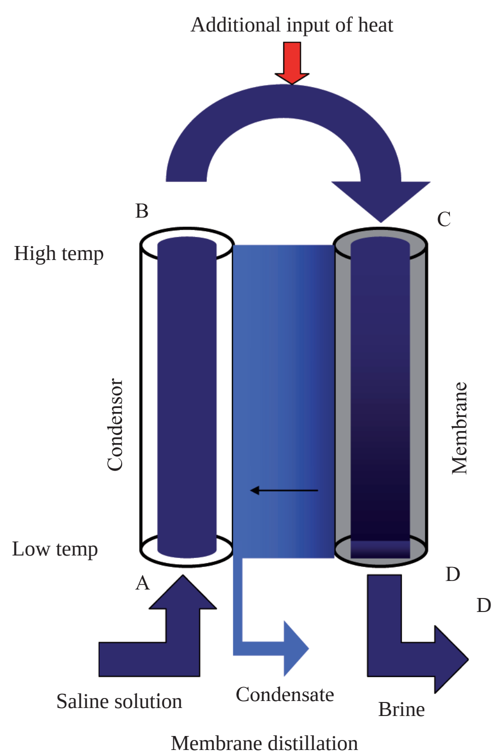

Fig. 4. Principle of membrane distillation (Memstill, TNO, The Netherlands; adapted).

200 W/m^2, as reported in Section 2, such would need an insolation surface area of at least 1.3 km^2.

This amount of energy could be reduced tremendously in a high-tech evaporation technology by reclaiming that latent heat of evaporation as heat of condensation. At the same time, the reclaimed condensate constitutes valuable additional potable water. The additional amount of potable water after condensation at a flow rate of 370 m^3/h increases the potable water from 500 m^3/h to 870 m^3/h, which corresponds to a potable water production increase of 75% when taking the SWDU potable water flow as a reference. On a yearly basis this represents an additional amount of 3.25 million m^3 of potable water which also represents a large economic value (at 1 \$/m^3 an added value of over 3 million \$).

Without claiming any techno-economical feasibility in this paper of an adequate evaporation technology based on solar energy, it is nevertheless assumed here for informative reasons that in the case of having a technology which only would consume 1% of the latent heat of evaporation, the heat input would be reduced to 2.57 MW. This thus implies a 100 fold reduced demand in insolation surface area to only 0.013 km^2 (which is about an area of 115 m × 115 m) when compared to the brute force evaporation value corresponding to 1.3 km^2.

Low energy consuming evaporation technologies are known since in e.g. MVC based evaporators the complete latent heat of evaporation is recycled during the condensation of the water vapor at the evaporator tubes/plates outer surface. An MVC system in fact could be considered as a heat pump system.

Also in MD [9, Chapter 4] the latent heat is recovered during condensation, as illustrated in Fig. 4. A saline solution is entering at position ''A'' into a condenser at a low temperature (e.g. 25 °C; data Memstill), thus condensing the water vapor arriving from the MD. Since the water vapor is condensing, each kg of condensate delivers 2,500 kJ of heat to the condenser surface. Since the heat capacity of the saline solution is very low when compared to the latent heat of evaporation, the heat of condensation then being absorbed in the condenser will heat the saline solution in such a way that the saline solution leaves the condenser at position ''B'' at a high temperature (e.g. 87 °C; data Memstill). In the example, the temperature of the saline solution is then further increased through the supply of some additional heat (e.g. solar or waste heat based) by a few degrees Celsius (e.g. up to 90 °C at position ''C''; data Memstill) as to further increase the water vapor pressure of the saline solution in the membrane pores. As a result, water is evaporating from inside the porous hydrophobic membrane and then diffuses through the membrane pores in the space between the condenser and the membrane. As indicated already, the water vapor then condenses at the colder condenser surface. Since the saline solution is evaporating, the temperature of the saline solution flowing through the inside of the membrane is dropping (e.g. down to 28 °C in position ''D''; data Memstill). The condensate can be collected as fresh water. From the fact that MD evaporation is based on partial vapor pressure effects it is known that MD allows to treat brines at very high salt concentration, even up to the saturation level. High recovery values are possible [23].

Vacuum membrane distillation (VMD) is also considered to be very heat efficient from the low internal heat loss. The option of further implementing additional heat pump technology to extract and upgrade low temperature waste heat from e.g. the condensate to reuse it in the MVD should be looked into. If techno-economically feasible, this would further increase the energy efficiency of MD. Since it is advantageous to have a MD process running 24 h/24 h it would be interesting to store (reclaimed/solar) thermal energy within the SGP-RED brine storage pond and extract the heat during the night in order to be used in the MD. MD is indeed a low temperature based process and can be solar powered (directly or indirectly). Even if the assumed level of 1% of latent heat consumption would not be feasible from techno-economical reasons, the insolation surface area being needed for the additional heat supply would evidently still be strongly reduced when compared to the brute force evaporation (such as in a salt pan or in the Dead Sea). It is stressed again that the additional production of fresh water (condensate) is of prime importance. Even in the case of large solar salt ponds, the eventual use of novel floating low cost covering-overs (being interconnected as modules) enabling the (ventilation forced) capturing and condensation of the water vapor in a condenser could be looked into. In this way the fresh water (condensate) and latent heat of evaporation could be recollected. The heat from the condenser could be reused by e.g. storage in the salt pond for evaporation enhancement (heat supply).

Some further assumptions are made here regarding the functioning of the SGP-RED unit. These assumptions are also based on the simulation results as presented in Table 1. Case 9 is arbitrarily considered, showing a power output of 21.5 W/m^2 and a power density of 53.6 kW per m^3 of SGP-RED stack volume for a brine (263 kg/m^3) versus sea water (35 kg/m^3). In the near future, a more detailed SGP-RED stack model needs to be developed in order to simulate the stack power output and conversion potential of the osmotic energy from the salinity gradients in the stack (as a function of stack path length; e.g. through finite element analysis). A brine flow of 133 m^3/h is available. The osmotic energy of the concentrate at a salt concentration of 263 kg/m^3 is assumed to be 18.8 MJ/m^3 (showing here also the much higher SGP potential than the seawater – fresh water combination). It is already indicated that, in principle, it would be possible to reduce the concentration of the concentrate in the SGP-RED stack by only a small amount since the concentrate can be resend for re-evaporation. From such a point of view of recycling the SGP-RED brine effluent for re-evaporation and in the theoretical case of a full recycle, nearly all salt will be transferred to the dilute SGP-RED effluent and used during electricity production. Moreover, part of the 370 m^3/h condensate could be mixed with incoming SGP-RE seawater in order to lower the concentration of the SGP-RED influent, thereby increasing the salinity gradient (thus power). It is simplified/assumed here for now that 12.5 MJ/m^3 of brine could be extracted by the SGP-RED stack configuration. The SGP-RED battery is then able to produce 0.45 MW of electricity (24 h/24 h) when having a sufficient volume of brine storage in e.g. a large brine pond (to have a buffer for a significant time period) which is 36% of the electrical energy needed by the SWRO based SWDU in this example. This would reduce the annual electrical energy consumption by about 4,000 MWh. At an assumed electricity cost level of 100 $ per MWh this would be a substantial annual capital saving of 0.4 million $. In the case of the production of electricity in a classic thermal plant and when fueled by oil, the yearly saving of about 4,000 MWh corresponds to a yearly reduction in about 4,000 metric ton of CO_2 emissions.

In theory, the total volume and membrane surface area of the SGP-RED stack(s) in the case of .45 MW at a power density of 53.6 kW/m^3 and 21.5 W/m^2 would be respectively 8.4 m^3 and 21,000 m^2 AM/21000 m^2 CM. From a private communication, the material price for a specific homogeneous ion-conductive material is about 40 Euro per kg. For a membrane thickness of 5 μm and a membrane surface area of 21,000 m^2, the membrane basic material cost would thus be 0.2 Euro/m^2 of membrane, thus a total anion and cation membrane material cost of 2 $\times$ 4,200 Euro = 8,400 Euro. A basic material cost of 8,400 Euro is therefore not at all prohibitive from an economical point of view when compared with the annual energy cost saving. At this instant however, there is no further information with respect to all the other cost items, thus total investment cost of the considered SGP-RED stack. However, a yearly energy cost saving of about half a million Euro and the added value of the production of about 3.25 million m^3 of potable water is surely a considerable economical argument regarding the research into and the eventual building/exploitation of a SGP-RED unit and into an adequate SWDU concentrate evaporation/condensation technique. As stated earlier, a dedicated SGP-RED stack still needs to be developed. A research into a battery oriented stack design including the development of thin ion-conductive membranes is crucial in that respect.

It should also be remarked that in the example the (theoretical) conditions of curve #9 were used. If the theoretical conditions of curve #9 would be proven to exist in practice but also those of curve #13, evidently the SGP-RED could show an even higher performance (thus a still smaller footprint and lower membrane surface area). In addition it can be noted that in [11] the enhancing effect on the SGP-RED power output is also indicated when using:

- a concentrate, showing a Dead Sea type salt concentration
- brackish water (salt concentration of 10 kg/m^3) instead of seawater

A European FP7-FET type of research project was applied for at the end of 2009, involving multiple European partners. If the FP7-FET project eventually would be granted by the EU, it would take a start at the end of 2010.

As a result of the potential of the hybrid concept using solar power, the concept was also patented [24].

5. Conclusions

A hybrid concept of solar energy, an SWDU and an SGP by RED unit is discussed. Solar energy is abundantly available, allowing to be used directly in the SWDU for evaporation purposes or to be used in order to further increase the salt concentration of the SWDU concentrate. This would allow to produce at the same time large amounts of potable water and to store a significant amount of energy in the concentrate as osmotic energy. The osmotic energy can be reclaimed as electricity by using a SGP-RED battery, also at night. The concept is still highly theoretical at this moment and its techno-economical evaluation would require a major research project involving all aspects of solar energy conversion, evaporation and reverse electrodialysis. Specific thin ion-conductive membranes need to be developed and a specific SGP-RED stack design is crucial.

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