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Photovoltaic system for brackish water desalination by electrodialysis and electricity generation

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ABSTRACT

Desalination typically requires significant amounts of energy. Although renewable energy (RE) sources can be indirectly connected to a desalination plant through the electrical grid, the direct connection of RE to low or medium capacity desalination plants is more convenient, especially in remote regions. Photovoltaic (PV) energy can be used to power a desalination system by electrodialysis (ED) in a reliable and autonomous way. In this paper, a new configuration for dual desalination and electricity production is presented. Photovoltaic modules are connected in series (strings), and a number of strings are connected in parallel according to the electrical power of the system. The ED reactor is directly connected in parallel with a small number of the photovoltaic modules. The PV arrays can be connected to batteries (stand-alone system) or to the grid (grid connected system). The ED system is modelled as a time-varying resistance that draws a time-dependent intensity of current from the solar modules. The surplus of energy generated in the solar panel (a function of the incident solar irradiance) is injected into the electrical system (batteries or inverter) in a very efficient way, without changes in the configuration.

Keywords: Photovoltaics; Desalination; Distributed generation; Dual systems

1. Introduction

Energy and water are two resources of outmost importance. The lack of potable water poses a big problem in arid regions of the world where freshwater is becoming very scarce and expensive.

Current desalination technologies (either membrane or thermal) require large amounts of energy. Desalination based on fossil fuels is neither sustainable nor economically feasible in a long-term perspective, as fuels are increasingly becoming expensive and scarce and contribute to the generation of green house gases in addition to various pollutants and particulate matter. Environmental protection through the use of renewable energy must become a part of the present and future desalination industry [1].

Solar power offers a sustainable alternative to fossil fuels for electricity production and desalination. Solar energy potential alone has been found to exceed the total world energy demand by several orders of magnitude (the theoretical solar potential is 3,900,000 exajoules per year, some 7.000 times greater than the global primary energy demand). The decentralized characteristics of solar energies may play a significant role for power supply in rural areas, were grid electricity is not available. Distributed solar generation technologies provide flexibility because of their small sizes and their short construction

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times compared to most types of central power plants. Solar energy generation uses local resources and may promote local business opportunities and local employment. In particular, photovoltaics provides a viable means for decentralized energy and water production in areas with abundant solar resource.

Photovoltaics (PV) is the direct conversion of radiation into electricity. Non-concentrating photovoltaic systems use the direct and diffuse (global) irradiance for electricity generation, but the electricity production of solar cells can be increased by concentrating solar radiation with reflective surfaces and by using sun-tracking devices. Photovoltaic technology is modular (i.e., existing systems are expandable), has a long lifetime (manufactures give guarantees of up to 25 years), is silent and emission-free during use. The use of PV presents several advantages such as high reliability, low maintenance requirements, simple structure, low transportation cost and short construction time. Due to the high cost of PV their use is reasonable for small-scale plants and at remote areas where electricity from conventional sources is not available or the electricity production cost is high. Costs have declined by 20% for each doubling of installed capacity, and there is a considerable potential for cost reduction due to new materials and more efficient and cheaper developing mass production techniques. PV systems can be installed anywhere and at any size, from small stand alone systems to large grid connected plants of several MW of capacity. The currently world capacity is of more than 2200 MW (growing ratio of 40% in 2007), and previsions indicate the possibility to achieve 1 million MW for 2030. PV is specially suited for distributed power supply and should play an important role in the field of renewable energies.

Photovoltaic systems can be connected to the electrical network (grid-connected systems) or can be used in autonomous mode (off-grid systems). A number of PV modules can be connected in series (arrays) and/or parallel and the solar radiation incident on the surface of the PV modules is transformed into electric energy (direct current). In an off-grid PV system, the generated electricity is sent to batteries that are protected by a regulator for overcharging or excessive discharge. The energy stored in the batteries can be used as electrical back-up when the energetic (electrical) demand and the availability of solar hours are not simultaneous. If the electrical loads need an alternating (ac) voltage, an electronic dc/ac converter (inverter) who transforms the direct current into alternating current. These systems can be used in remote sites for the self-sufficiency of electrical power in a reliable and autonomous way. A maximum power point tracking (MPPT) which controls the current drawn from the PV field in order to obtain the maximum power output under varying conditions, particularly irradiance and module temperature is very convenient. In a grid-connected PV system, batteries and charge controller are no needed.

2. PV for combined power and desalination

As some other renewable energy sources (RES), solar plants can be indirectly connected to a desalination plant through the electrical grid, but the integration of low or medium capacity desalination plants with solar technologies is more convenient and efficient. Membrane technologies (reverse osmosis, RO, and electrodialysis, ED) are considered to be promising for future applications [2].

A high correlation between solar energy and water demand (water needs increased in summer where the solar energy potential is increased) makes the use of solar energy very attractive. Direct connection of photovoltaics to low or medium capacity desalination plants is efficient, and in most remote regions economically viable.

For instance, in Mauritania a big percentage of the population does not have access to fresh water and electricity. The growth of population is supposed to be of 3%. Electricity demand is growing at an annual rate of 12.5%, and water demand grows even with higher rates. Mauritania is a country with deficiencies in basic infrastructures (only 45% of the people have access to electricity), and it has neither the economy nor the indigenous fossil fuel resources for this development, but it has one of the highest levels of solar irradiation of the world (more than 2500 h/y), in a land of 1.025.520 km^2. Its current electricity demand could be satisfied with only 2 km^2 of PV solar panels. In coastal areas, concentrating solar power could be a solution both for water and electricity supply. In inner areas, the brackish water quality varies from one location to another and PV connected to reverse osmosis (PV–RO) or electrodialysis (PV–ED) systems would cover all the demands. For instance, in the village of Nebaghuiya (3600 inhabitants in 2008), 45% of homes is planned to be electrified with solar kits (one module of 100 Wp, a 12 V 70 A battery, a charge regulator and 150 W inverter). The energy requirements for the ED-desalination of the water of a brackish well could be supplied by only 80 kWp [3].

PV–RO is a good combination for small stand-alone systems [4]. Since both technologies are highly mature and reliable, these systems require minimum maintenance and are especially recommendable for remote areas.

In the reverse osmosis process, the application of pressure higher than the osmotic pressure makes water to pass from more concentrated solution to less concentrated one, which is the reverse of the principle of osmosis. If a saline solution in contact with a semi-permeable membrane is placed under pressure, which is in excess of its osmotic pressure, water from the solution will flow through the membrane. Water flow will continue till the pressure created by the osmotic head equals the osmotic pressure of the salt solution. The salt content in the water produced can be controlled by reducing the pressure or increasing the number of filtrations. The main attraction of this process is its low energy consumption. The energy required

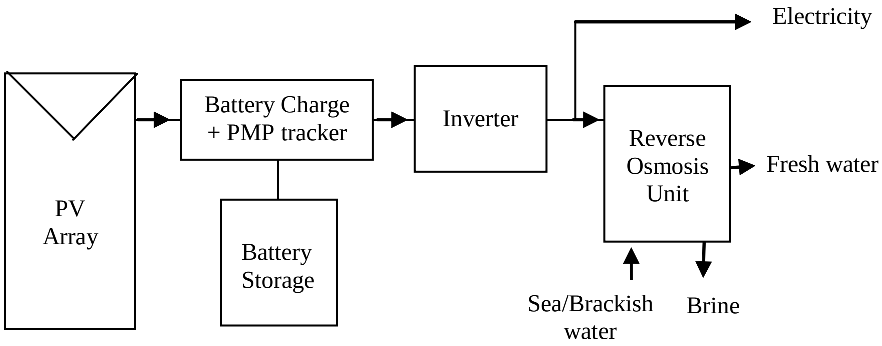

Fig. 1. PV–RO scheme.

to operate the process increases with the salinity of the feed water. Higher water salinity requires more energy to overcome the osmotic pressure, where the RO system needs only mechanical power to raise the pressure of feed water. The rate at which fresh water crosses the membrane is proportional to the pressure differential across the membrane that exceeds the natural osmotic pressure differential. No heating or phase change takes place. The major energy requirement is for the initial pressurization of the feed water. Seawater RO plants have recoveries from 25% to 45%, while brackish water RO plants have recovery rates as high as 90%.

The batteries in Fig. 1 allow operation at constant flow and pressure, which is the norm for RO systems. They are sized to stabilize the power supply to the RO unit on a daily basis, as well as to account for fluctuations in solar energy and water demand. However, batteries are problematic, especially in hot climates where they have a short life expectancy. The expected lifetime of the PV generator is estimated to be over 35 years, while that of the batteries and membranes of the RO unit are expected to be 5 years. Replacement of batteries and RO membranes when they become fouled and can no longer be effectively cleaned (the rate of membrane fouling is very dependent upon feed-water quality) constitutes the main operation costs. Battery efficiency must also be considered. Thompson and Infield [5] showed the possibility of operation without batteries.

Advantages of RO systems include low investment costs at low capacities, simplicity of operation, flexibility in capacity expansion (modularity), operation at ambient temperature, short construction periods, their compact sizes and lower environmental impacts.

Another excellent possibility is the combination of photovoltaics and electrodialysis (PV–ED). Electrodialysis is a technique based on the transport of ions through selective membranes under the influence of an electrical field. In the electrodialysis process salt is removed from the saline water [6]. This is done by transporting ions through membranes by means of an electric current. Saline water enters into the cell compartments, which are separated by permselective membranes that are alternatively permeable to cations and to anions. When a potential difference is applied to the electrodes, a dc electric field is created. Cations are attracted towards the negative pole and anions towards the positive pole. Depending on the nature of the membranes, ions pass through them or are rejected. The energy consumed is a function of salinity of the raw water. A large number of alternating cation and anion membranes are stacked together, separated by flow spacers which are plastic sheets that allow the passage of water. The streams in alternating flow spacers are a sequence of diluted and concentrated water which flow in parallel to each other. To prevent scaling, the modern processes utilize inverters which reverse the polarity of the electric field about every 20 min (electrodialysis reversal, EDR).

A wide range of trace contaminants, including fluoride and nitrate, can usually be found in surface waters, groundwater and brackish water. For waters with relatively low salt concentrations (less than 5 g/L), electrodialysis is generally the most economic process in comparison to reverse osmosis (RO). However, the desalination of waters with higher concentrations of dissolved solids (30 g/L) can successfully be performed through ED. This technique has proved its feasibility and high performance in the desalination of brackish water, when the required salinity of the produced water is of the order of 500 ppm, the desalting of amino acids and other organic solutions, effluent treatments, recycling of industrial process streams and salt production

The combination of PV and ED shown in Fig. 2 is attractive because ED requires a direct current (dc) power supply as the driving force for removing the salt ions [7]. The ED reactor and the pumping system can be powered directly with dc current, and thus an inverter DC/AC is not necessary. This fact represents an energy saving because of the elimination of energetic losses in the transformation.

These systems are appropriate for small applications in isolated locations with lack of electric grid where continuous fresh water production is not needed and the volume of daily treated required water is small (about 1–10 m^3). Several pilot plants of ED systems connected to photovoltaic cells by means of batteries have been implemented. Most of these studies use batteries for the

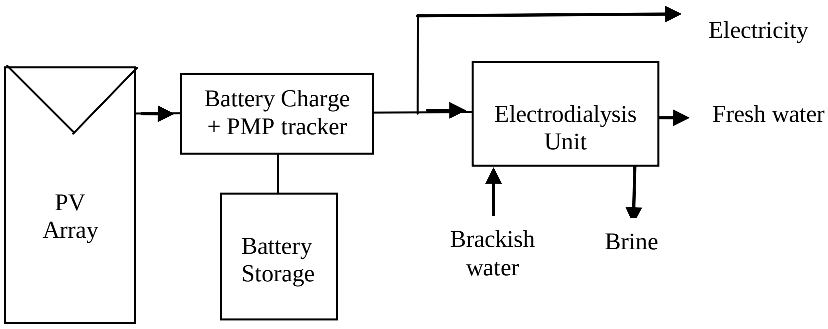

Fig. 2. PV–ED scheme.

storage of the photovoltaic electric energy that is on its turn transformed in ac electric energy for powering the pumping system and the rectifier for the electrodialyzer.

The photovoltaic array can also be directly connected to the electrodialyzer without batteries. In a PV–ED system without battery, due to the fact that the electrodyalizer is directly connected to the PV panels, the electrodialysis process system is sensitive to variations on solar irradiation. From experimental results [8], it can be established that the desalination of brackish water using a system of electrodialysis powered by photovoltaic energy can be successfully carried out at different meteorological conditions. The process has an easy start-up and shut-down of the process for intermittent operation. But the applied cell voltage is a critical operating condition in electrodialysis processes as the voltage determines the current in the cell and hence the desalination efficiency as well as energy consumption. Besides, with the direct connection of the electrodialysis unit to the panels, the operating point of the PV generator can be located far from the maximum power point, with a low efficiency in the conversion solar/electricity. In [8], several changes in the configuration of PV modules are proposed to use during the desalination process (all the PV modules in parallel in the first stages, all the modules in series at the end, and other configurations in the intermediate stages) in order to obtain a better drinking water production per m^2 of solar panel.

3. Combined PV–ED system proposed

In this section, a new combined PV–ED system is presented. The system provides with ac voltage and fresh water, without batteries no changes of configuration in the stages of the desalination process, and with high efficiency. The PV–ED scheme proposed is shown in Fig. 3.

In this configuration, the electrodialysis unit is directly connected to one or several PV modules in a bigger PV generator which is connected to an electronic converter which incorporates a new strategy of control that optimizes the efficiency in the conversion of the solar energy (optimum power point tracker). The electronic converter provides with electrical energy, at the more convenient level of voltage. In grid-connected applications, the output must be an alternating current, and an ac/dc converter (inverter) must be used. In autonomous (off-grid) applications a dc/dc converter or a battery charge controller (regulator) are used.

The system has been modelled in Pspice, and different cases and configurations have been simulated in order to test their performance and refine the design before touching a piece of hardware. In this paper, some results of the simulations of this PV–ED system are shown. PSpice is a simulation program that models the behaviour of a circuit containing analog and digital devices. PSpice can perform permanent and transient analyses, so the response of a circuit to different inputs can be tested [9].

In particular a solar cell can be modelled as a sub-circuit, and then, several solar cells can be connected in series and parallel to model a PV module, or, in general, a PV generation field. It is also possible to model other

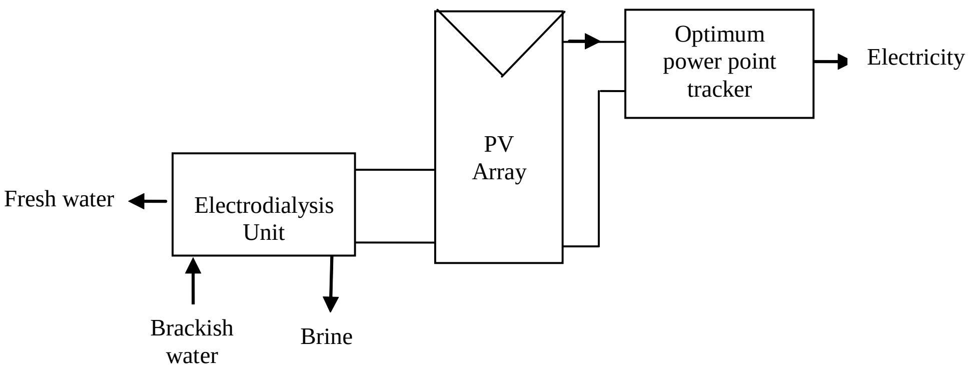

Fig. 3. PV–ED system proposed.

electronic or passive components (regulator, inverter, batteries, resistances, etc) and compute the output current and voltage of a PV module or combination or modules, including effects as temperature, irradiance or spectrum, among other parameters.

The electrodialyzer unit has been modelled as a time-variant resistance. The electrodialysis stack resistance is dependent on the concentration of ions in the feed and permeate solution and also on the intrinsic properties of the membranes [10,11]. The resistance of the cation and anion exchange membranes are inherent characteristics of the membrane and they may be assumed to be constant. The resistance of the concentrate solution is generally ignored because electrodialysis starts with a reasonably high concentration of solution in the concentrate compartment. The resistance of the feed solution is inversely proportional to the feed water concentration. The resistance of the diluate cell is the main contributor to the overall voltage drop in an electrodialysis stack. With more reduction of salt content, the resistance in diluate compartments increases which predominates the ultimate resistance of the stack. With the progress of the desalination process the concentration of feed water decreases and hence the resistance increases.

The value of the resistance has been approximated by Eq. (1) (Fig. 4):

$$R(t) = 0.0034\, t^3 - 0.0794\, t^2 + 0.6742\, t + 20.643 \qquad (1)$$

This expression gives values for $R(t)$ very close to those obtained in the experiments [8].

Photovoltaic modules are connected in series (strings), and a number of strings are connected in parallel according to the electrical power of the system. The ED reactor is directly connected in parallel with a small number of the photovoltaic modules. The general configuration of the PV field is shown in Fig. 5.

The commercial modules used in the simulations are the s-Si Sanyo 200. They consist of 72 monocrystaline silicon cells connected in series. Their maximum power (in standard test conditions, STC: 1000 W/m², spectrum AM 1.5 G, temperature of the cell 25ºC) is 200 W. Other electrical characteristics of the module are the open circuit voltage, V_{oc} = 49.6 V, and the short-circuit current, I_{sc} = 5.5 A. The voltage of the maximum power point (MPP) is V_{MPP} = 40 V and the current of the maximum power point is I_{MPP} = 5A. Due to the voltage of these modules, the ED-unit can be connected in parallel to only one of them, as indicated in Fig. 5.

For the sake of simplicity, the case of having only two PV modules connected in series is shown in this paper, as it is shown in Fig. 6.

A photovoltaic generator has a characteristic I–V curve where the possible values of current and voltage at the terminals are represented. The I–V curve depends on the solar irradiation and the temperature of the panel. The I–V curve presents two clearly differentiated zones. Firstly, a plateau is observed where the values of current are approximately equal to *Isc* in a wide range of voltages. The second region is characterized by a sudden decrease of the current being the values of the voltage approximately equal to *Voc*. But the fact of adding the variable resistance to the PV field modifies the V–I curve seen by the electronic converter connected in AB. In particular, a reduction in the value of maximum power is observed. In Fig. 7, the V–I curves of the system in STC conditions for several values of the electrolyzer resistance are shown. Although in the final stages of the desalination process (high values of *R*), the V–I curves are very similar to the ideal curve, with the initial values of the *R* of the electrolyzer (*R* = 20 Ω) the curve is different, with an important deformation in the central part of it.

The power delivered by a PV generator is the product

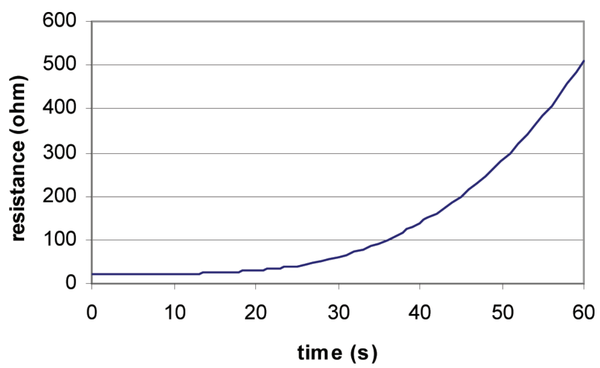

Fig. 4. ED resistance vs. time.

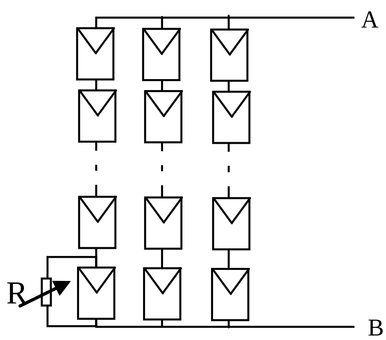

Fig. 5. PV–ED scheme.

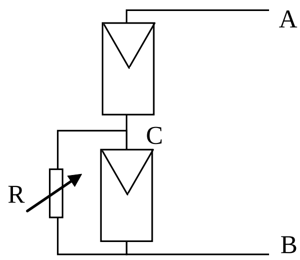

Fig. 6. Two PV modules case.

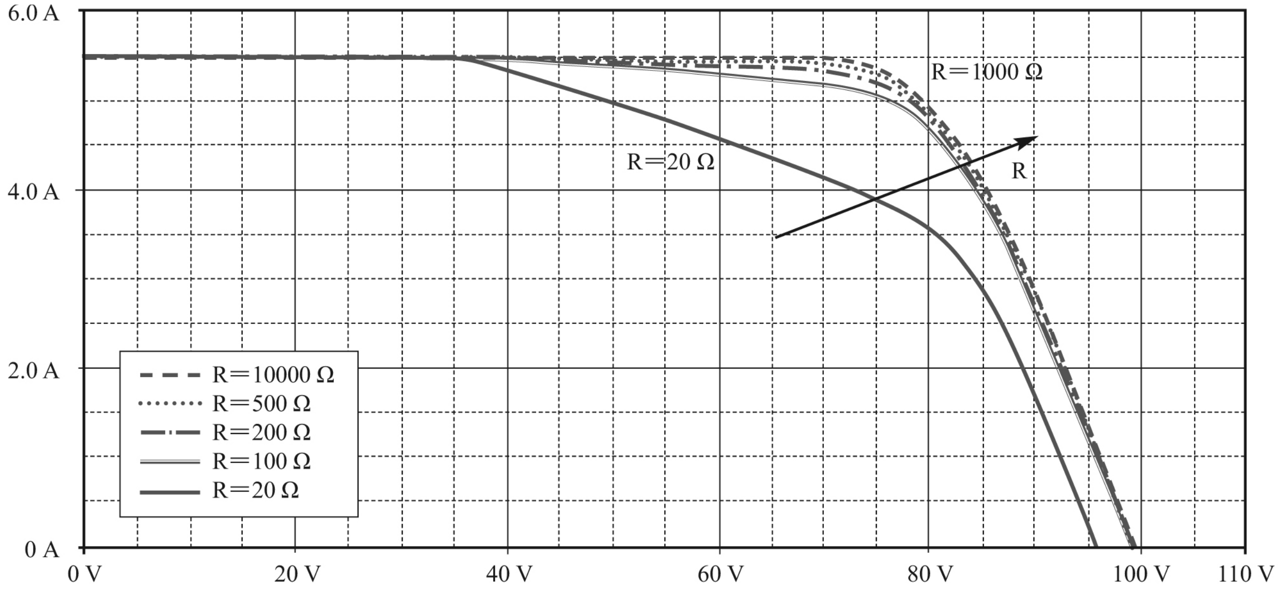

Fig. 7. V–I curve in STC conditions for different values of resistance, from $R = 20\ \Omega$ to $R = 1000\ \Omega$.

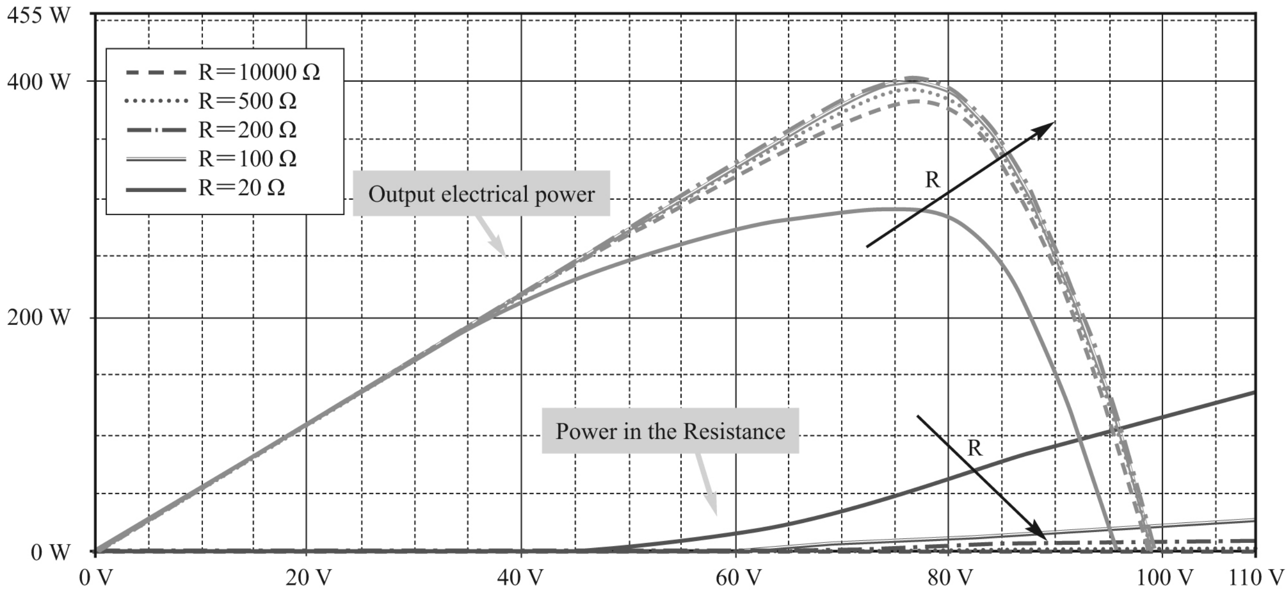

Fig. 8. Power in the ED unit and at the terminals AB for different values of resistance from $R = 20\ \Omega$ to $R = 1000\ \Omega$.

of current and voltage in the terminals. If the multiplication current times voltage is done point by point, for all the voltages from short-circuit to open-circuit conditions, a power curve is obtained, for a given radiation level and temperature.

Although the current has its maximum at the short circuit point, the voltage in this point is zero and therefore the power is also zero. The voltage is maximum at the open circuit point but again the output power is zero. There is one particular combination of current and voltage for which the power reaches a maximum. In the traditional case (without resistance connected to the PV modules) this point is called the maximum power point (MPP).

The usual controllers (in inverter or battery-charger) try to obtain the maximum electrical power that the PV field can provide with the current conditions of solar irradiation (*G*) and PV panel temperature. They make the modules operate in a working point close to the point of the I–V curve where the product of the current and voltage is maximum, by measuring the voltage U_{AB} and the current *I*. Although different strategies exist in the market for this MPP tracking, all of them start with the measurement of voltage and current at the terminals of the electronic device (A and B). But in the configuration proposed this strategy is not correct, due to the fact that the resistance connected to the modules is variable in time.

If we look at the power curves associated to the curves of Figs. 7 and 8, two interesting characteristics are observed. Firstly, the value of maximum output power decreases for low values of *R*. And secondly, the voltage at which the maximum power is obtained varies for different values of *R*, and it is lower than the voltage of the maximum power point when *R* equals to infinity (electrodialyzer not connected). With the usual strategies cited before (MPP tracking), the inverter or regulator try to operate the PV generator at these voltage points, in order to maximize the output electrical power (p_{AB}). But in this new configuration, we must also consider the power absorbed by the ED system, and try to optimize the total power output (power absorbed by the resistance plus the output electrical power). The voltage at which the maximum (electrical output) power is obtained, is lower with low values of *R*. The maximum total power point does not coincide with the maximum electrical power output, as it is shown in Fig. 9.

If we want to obtain the maximum total power of the PV generator, measurements of voltage and intensity of current in the electrolyzer (resistance) terminals are also required. Considering the output electrical power plus the power absorbed by the electrolyzer, the optimum voltages rise with low values of *R*.

A configuration efficiency related with the losses in the conversion irradiance/electrical system due to the introduction of the resistance in the system can be defined. As Table 1 shows, the configuration efficiency is high in

Table 1
Efficiency, total power and optimum voltage for different values of the resistance

Resistance (Ω)	Optimum voltage (V)	Total power (W) (electrical + electrodialysis)	Configuration efficiency (%)
10000	76.301	400	100
500	76.84	399.13	99.78
200	76.84	397.33	99.33
100	77.123	393.35	98.33
20	79.452	349.18	87.295

all the stages of the desalination process (a bit worse in the first stages of the desalination process), with higher values than those obtained in a classical configuration (with batteries plus dc/dc converter in off-grid applications, or with rectifier plus dc/dc converter for connection to an ac grid). It is easy to find the maximum global power point (optimum power point, OPP), that is different from the maximum output power point. If instead of working at the OPP, we operate in the maximum power output, the efficiencies would be lower. Obviously, in a system connected to a battery without MPP, the efficiencies are much lower.

The differences are greater for other values of irradiance. Figs. 10 and 11 show the power curves for *R* = 20 Ω, with values of irradiance of 350 W/m², 500 W/m², 800 W/m² and 1000 W/m².

The value of the voltage of the MPP of the PV generator and the voltage that optimizes the total power (electrical output power plus power at the ED unit, optimum

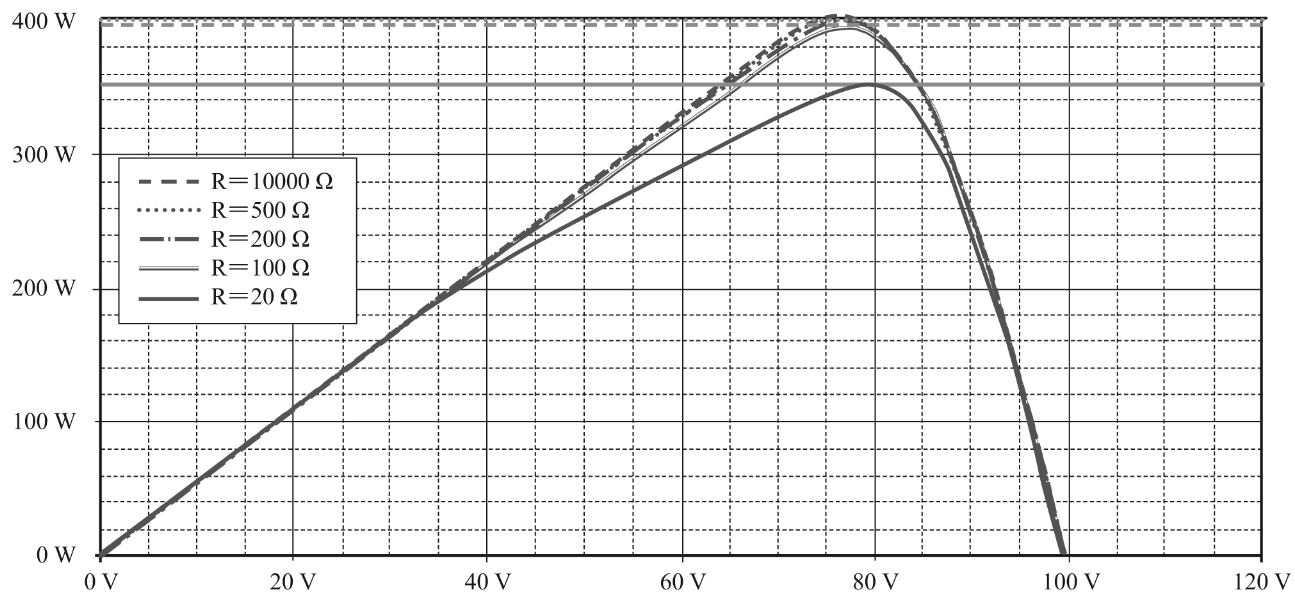

Fig. 9. Total power for different values of resistance from *R* = 20 Ω to *R* = 1000 Ω.

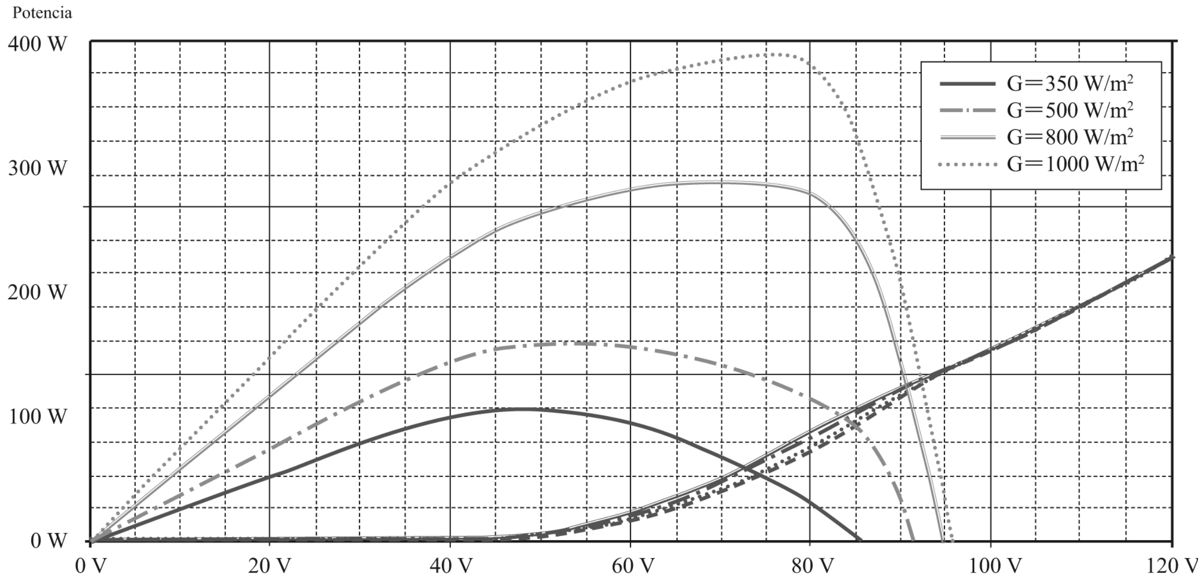

Fig. 10. Power in the ED unit and at the terminals AB for different values of irradiance, R = 20 Ω.

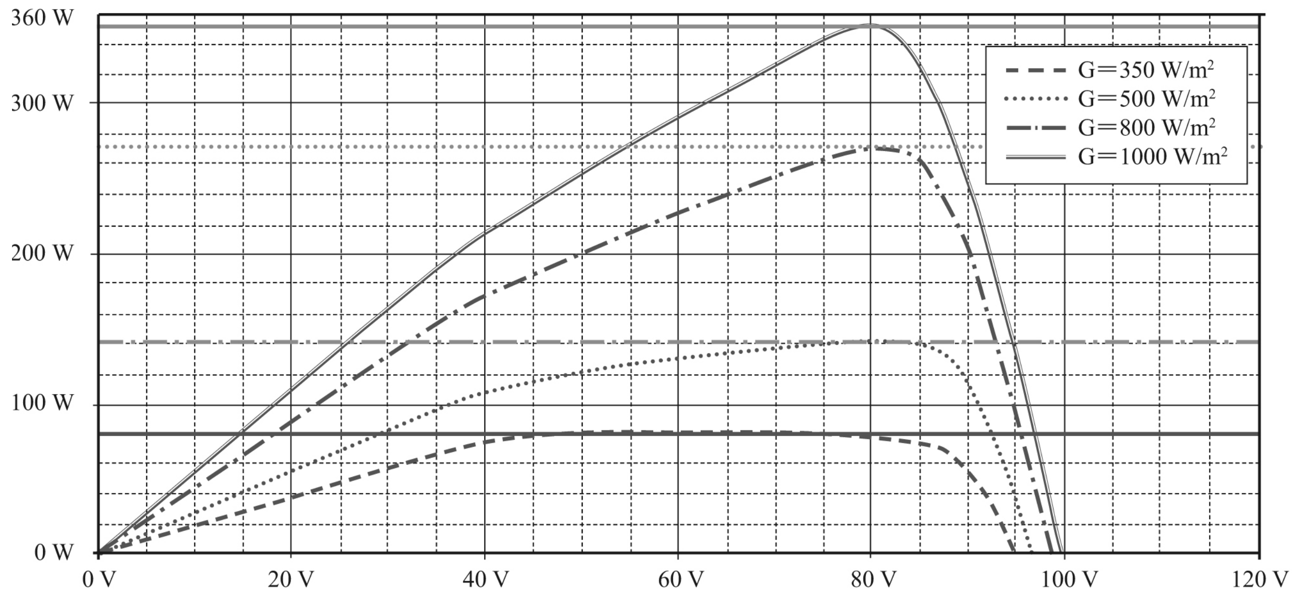

Fig. 11. Total power for different values of irradiance, R = 20 Ω.

Table 2
Efficiency, total power and optimum voltage for different values of irradiance, R= 20 Ω

Irradiance (W/m²)	MPP voltage (V)	Optimum voltage (V)	Total power (W) (electrical + electrodialysis)	Configuration efficiency (%)
1000	75.48	79	350	87.5
800	69.72	80–82.5	270	84.3
500	54.11	76–84.5	140	70
350	47.5	46.5–70.6	80.37	57.4

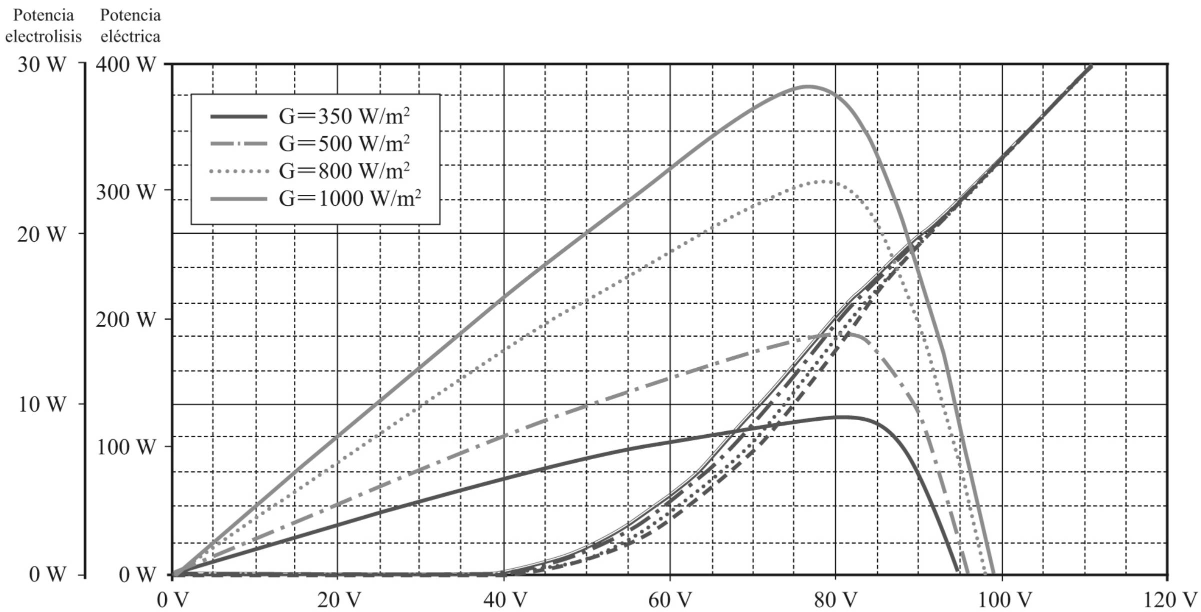

Fig. 12. Power in the ED unit and at the terminals AB for different values of irradiance, $R = 100\ \Omega$.

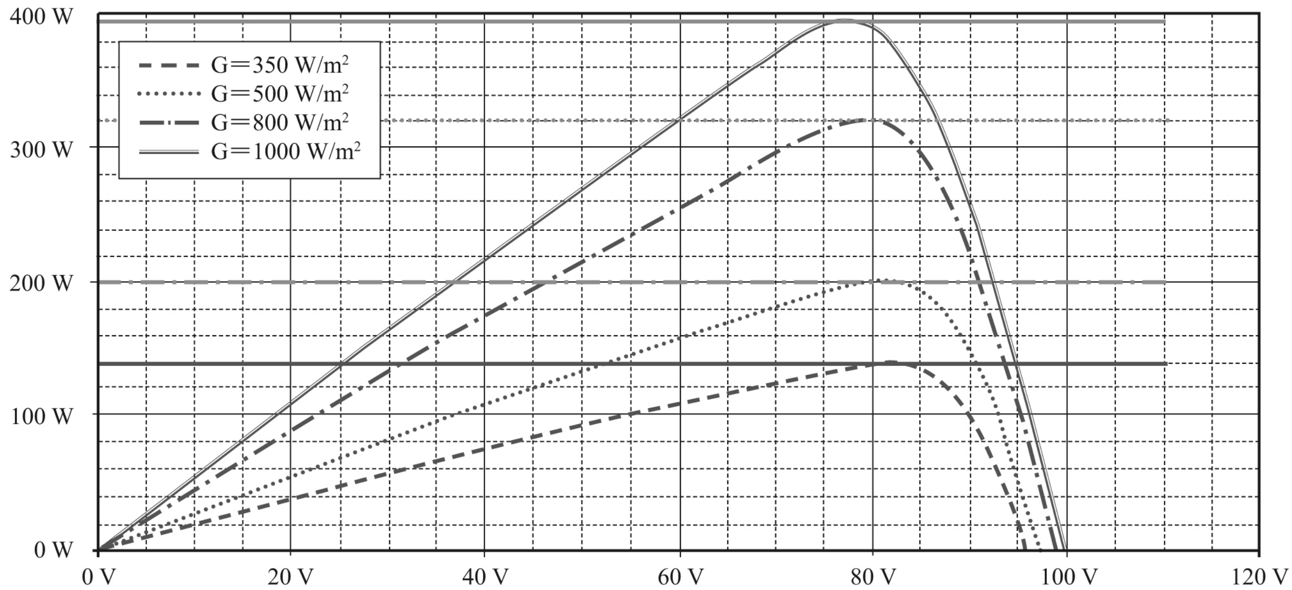

Fig. 13. Total power for different values of irradiance, $R = 100\ \Omega$.

Table 3
Efficiency, total power, MPP voltage and optimum voltage for different values of the irradiance, $R = 100\ \Omega$

Irradiance (W/m^2)	MPP voltaje (V)	Optimum voltaje (V)	Total power (W) (electrical + electrodialysis)	Configuration efficiency (%)
1000	76	78	395	98.75
800	77.6	79	321	98.43
500	79.5	81	202	98.4
350	80.5	83	138	98.4

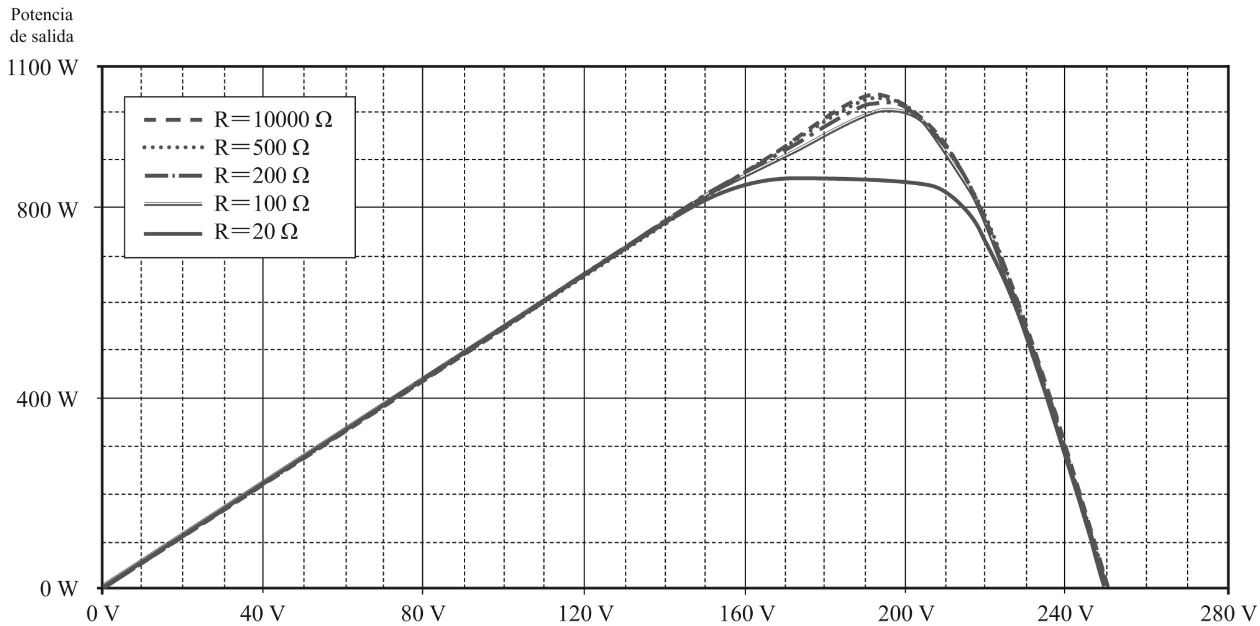

Fig. 14. Total power for different values of resistance, from $R = 20\ \Omega$ to $R = 1000\ \Omega$, $G = 1000\ W/m^2$, $T_c = 25°C$, five modules in series.

voltage) can be very different as it is shown in Table 2. Besides, the configuration efficiency for low values of irradiances is not very high.

With a resistance of 100 ohm, the efficiencies are better for any level of irradiance, and the difference between V_{MPP} and V_{OPP} are not significant , as it is shown in Figs. 12 and 13, and in Table 3.

In grid-connected systems is very usual to have arrays with voltages in the range of 350–600 V. For obtaining theses voltages, several PV modules are connected in series. In Fig. 14, the situation of having five PV modules in series is presented.

4. Conclusions

In this paper, the electrical characteristics of a new combined system for dual electric power generation and desalination with electrodialysis have been shown. Simulations with PSpice indicate that global efficiency of the proposed system is better than the efficiency obtained with other classical configurations. A different strategy needed for controlling the inverter (in grid connected installations) or the regulator (in autonomous systems) is pointed out. This new strategy relies on the operation of the system in the point that optimizes the power delivered by the PV field (optimum power point, OPP). This system is specially suited for local electricity and water supply in areas with high levels of irradiation and brackish water desalination needs.

References

[1] L. García-Rodríguez, Renewable energy applications in desalination: state of the art, Solar Energy, 75 (2003) 381–393.

[2] J. Martínez Beltrán and S. Koo-Oshima, eds., Water desalination for agricultural applications: Land and water, Proc. FAO Expert Consultation on Water Desalination for Agricultural Applications, Rome, 26–27 April 2004.

[3] A.A. Bayod-Rújula and A.M. Martínez-Gracia, Dual use of solar power for electricity and water supply, Proc. 6th Biennial International Workshop Advances in Energy Studies, Graz, Austria, 2008

[4] E. Tzen, K. Perrakis and P. Baltas, Design of a stand alone PV-desalination system for rural areas, Desalination, 119 (1998) 327–334.

[5] M. Thomson and D. Infield, A photovoltaic-powered seawater reverse-osmosis system without batteries, Desalination, 153 (2002) 1–8.

[6] J.M. Ortiz, J.A. Sotoca, E. Expósito, F. Gallud, V. García-García, V. Montiel and A. Aldaz, Brackish water desalination by electrodialysis: batch recirculation operation modelling, Desalination, 208 (2007) 89–100.

[7] H.M.N. AlMadani, Water desalination by solar powered electrodialysis process, Renewable Energy, 28 (2003) 1915–1924.

[8] J.M. Ortiz, E. Expósito, F. Gallud, V. García-García, V. Montiel and A. Aldaz Electrodialysis of brackish water powered by photovoltaic energy without batteries: direct connection behaviour, Desalination, 208 (2007) 89–100.

[9] L Castañer and S. Silvestre, Modelling Photovoltaic Systems Using PSpice, J. Wiley, 2002.

[10] S.K. Adhikary, J.M. Gohil and P. Ray, Studies on the resistance developed at different stages in an electrodialysis stack operated in parallel-cum-series flow pattern, J. Membr. Sci., 245 (2004) 131–136.

[11] L.J. Banasiak, T.W. Kruttschnitt and A.I. Schäfer, Desalination using electrodialysis as a function of voltage and salt concentration, Desalination, 205 (2007) 38–46.