Design of an autonomous photovoltaic system for desalination of groundwater by electrodialysis

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Abstract. Ultrafiltration-electrodialysis (UF-ED) systems for water desalination at different scales require electrical energy. The objective of this work is to size and select the components of an autonomous photovoltaic system (APVS) to supply energy to the UF-ED system at laboratory scale in a continuous process and to determine the percentage of salinity removal (PSR) and the specific energy consumption (SEC) at different conditions of the ED system. Two PV modules and a battery were selected. A maximum power of 150 Wp was chosen for each PV module and a capacity of 200 Ah and 12 V for the battery. A charge controller was selected with a power greater than 300 Wp and a nominal charge current greater than 18.52 A and an input voltage greater than 21.6 V. An inverter with an output power greater than 112 W was selected. The PSR and SEC were determined for different operating conditions (6 V and 25 mL/min, 12 V and 25 mL/min, 6 V and 50 mL/min, 12 V and 50 mL/min). The UF-ED system reduced the salinity of the groundwater, obtaining 64% removal at 12V and 25 mL/min in a continuous process.

1. Introduction
Solar power offers a sustainable alternative to fossil fuels for electricity production and desalination. The decentralized characteristics of solar energies may play a significant role for power supply in rural areas, where grid electricity is not available [1]. A PV system can be used in remote sites for the self-sufficiency of electrical power in a reliable and autonomous way [2].

An APVS consists of a set of PV modules (PV panels), a battery, a charge regulator or controller, a direct current (DC) to alternating current (AC) inverter and loads. The PV modules can be connected in series and/or in parallel and are in turn made up of a set of PV cells that are also connected in series and parallel [3]. The PV cell directly converts solar energy (solar radiation) into DC electrical energy [4].
Currently around 768 million people lack access to drinking water, 83% of them live in rural areas of developing countries, where sometimes the lack of drinking water is exacerbated by the lack of electricity and many of these areas have access to brackish groundwater, sources that can be treated to obtain potable water through desalination. In addition, these areas may have high potential for the use of renewable energy such as PV solar energy [5]. The use of solar energy for the implementation of desalination technologies is a possible sustainable solution to the problem of the shortage of drinking water in the world [5-6]. About 30% of freshwater is groundwater [7] and if it is overexploited it can become brackish groundwater.

Many studies of brackish groundwater treatment by ED are carried out to know the significance of this technology [8-10]. ED is an electrochemical process based on the selective separation of cations and anions from a solution by the effect of an electric field through a series of ion exchange membranes (IEMs) [11]. In a real process, an ED module is composed of a stack of membranes [12-13] placed between the electrodes of the cathode and the anode. The stack consists of cation exchange membranes (CEMs) and anion exchange membranes (AEMs), placed alternately and separated by spacers to form compartments [13]. The ED process requires DC and AC, therefore the use of an APVS becomes attractive when solar energy is used [12,14].

The objective of this work is to size and select the components of an APVS to supply energy to the UF-ED system at laboratory scale in a continuous process and to determine the PSR and the SEC at different conditions of the ED system.

2. Methodology

2.1 Autonomous photovoltaic system

In the design of the APVS, four main components were taken into account, as can be seen in figure 1. The purpose of sizing the APVS is to calculate the number of modules and batteries required to reliably supply the energy consumption of the UF-ED system. Figure 2 shows a flowchart the steps to follow for this calculation and the selection of the charge controller and inverter. In our calculation, the NASA database [15] was used to obtain the solar peak hours for the most unfavorable month.

![Figure 1. Scheme of the autonomous photovoltaic system.](image)

2.2 Ultrafiltration – electrodialysis system

A UF system, model KUF-3 from the Water Quality Association brand was used, as shown in the figure 3. The system has three stages: the first stage consists of a microfiltration membrane to remove suspended solids; the second stage is made of granulated activated carbon to remove organic
compounds, chlorine, smell; and the third stage is made of an UF membrane to remove suspended solids, turbidity, bacteria and other harmful substances present in the groundwater, in addition to preventing the pollution of IEMs of ED cell.

An ED cell of 21 IEMs was used, as shown in Figure 3, of which 11 were MK-40 CEMs and 10 were MA-41 AEMs, both of the Shchekinoazot brand. The work area of the IEM was 62.5 cm². An aqueous solution of sodium sulphate (Na₂SO₄) of 13 g.L⁻¹ was prepared to flow through the electrode compartments in order to conduct the current and evacuate the gaseous products obtained from the oxidation and reduction reactions in the ED cell electrodes during the desalination process. Two 66 W (AC) and 36 W (CC) pumps were used to drive the washing solution and groundwater, respectively, and three vessels were used to hold the dilute, the concentrate and the electrode wash solution.

Figure 2. Flowchart for sizing the autonomous photovoltaic system.

2.3 Groundwater
The source of origin of the groundwater is located in the district of Rimac, province of Lima, department of Lima, Peru.

2.4 Ultrafiltration - electrodialysis system powered by an autonomous photovoltaic system
An APVS was used as a DC and AC power supply for the ED cell and pumps. Between the load controller of the APVS and cell ED was placed a voltage regulator. A multimeter was connected in series to measure the current and another multimeter was connected in parallel to measure the working voltage.

Four experimental tests were carried out in which the potential difference was set at 6 V and 12 V, and the volumetric flow of both the dilute and the concentrate was set at 25 mL.min⁻¹ and 50 mL.min⁻¹.
2.5 Measuring instruments
To measure the potential difference and current in the ED cell, two digital multimeters model CD 771, Sanwa brand, were used; and to measure the salinity of the dilute and concentrate, a salinity sensor and a LabQuest 2 data collector were used, both from the Vernier brand.

![Diagram of the ultrafiltration-electrodialysis system](image)

**Figure 3.** Scheme of the ultrafiltration-electrodialysis system.

3. Results and discussion
3.1 Autonomous photovoltaic system
Considering the location of the National Engineering University with UTM coordinates 277071.8 m East and 8670125.9 m North, zone 18, southern hemisphere, the total daily energy consumption equal to 560 Wh (two pumps and the ED cell) and the calculations according to the flowchart, two PV modules and a battery were determined. A maximum power of 150 Wp was chosen for each PV module and a capacity of 200 Ah and 12 V for the battery, ensuring the power supply to the UF-ED system.

A charge controller was selected with a power greater than 300 Wp and a nominal charge current greater than 18.52 A and an input voltage greater than 21.6 V. An inverter with an output power greater than 112 W was selected. An appropriate use of the pumps requires the inverter power to be set three times higher than the total power consumption of the loads in order to avoid problems with power peaks when turning on the equipment.

3.2 Electrodialysis system
The salinity (dilute and concentrate) and current (through the ED cell) are shown with respect to time in Figures 4 to 7, which correspond to the four experimental tests.

The efficiency of groundwater treatment by ED is evaluated by calculating the percentage of salinity removal (PSR) was used, which is expressed by equation:

$$\text{PSR} = \frac{(C_i - C_o)}{C_i} \times 100$$  \hspace{1cm} (1)

where $C_i$ and $C_o$ are inlet and outlet values for salinity of the groundwater, respectively. Salinity is expressed in mg.L$^{-1}$. 

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Figure 4. Salinity vs time and current vs time for test N° 1 ($P = 6 \text{ V} \text{ y } F = 25 \text{ mL.min}^{-1}$).

Figure 5. Salinity vs time and current vs time for test N° 2 ($P = 12 \text{ V} \text{ y } F = 25 \text{ mL.min}^{-1}$).

Figure 6. Salinity vs time and current vs time for test N° 3: ($P = 6 \text{ V} \text{ y } F = 50 \text{ mL.min}^{-1}$).
Figure 7. Salinity vs time and current vs time for test N° 4 ($P = 12 \text{ V}$ y $F = 50 \text{ mL.min}^{-1}$).

In Table 1, PSR results indicate that the potential difference is a factor that positively influences this desalination process, whereas the volumetric flow is the opposite. Another study [12] obtained similar results where the increase in volumetric flow led to a lower quality of the desalinated product. The PSR equal to -4% in test N° 1 indicates that the conditions under which it was carried out did not favor the desalination process. Other study [16] considers that an increase of the ion concentration in the ED cell compartments up to a maximum level along with a low current flowing through the cell caused the apparition of a backscatter phenomenon, as the ions that cross the membranes compete with the ions that move through the electric field in the ED cell.

Specific energy consumption SEC is the energy consumption per volume of desalinated groundwater during a certain time and the unit in which it is expressed is kWh.m$^3$. SEC can be expressed by the following equation [17]:

$$SEC = \frac{P \int_0^t I \, dt}{V_d}$$  \hspace{1cm} (2)

where $P$ is the applied potential difference (V), $I$ is the current (A) that passes through the ED cell and $t$ is the duration of the desalination process (h), in this work the duration of each test was 16 minutes. The diluted volume ($V_d$) is calculated from equation:

$$V_d = F \, t$$  \hspace{1cm} (3)

where $F$ is the volumetric flow of desalinated groundwater (dilute).

Figures 4 to 7 show that the lower the current that passes through the ED cell, the lower the SEC, see table 1. This is corroborated by another study [18].

**Table 1.** Percentage of salinity removal and specific energy consumption for the desalination process of groundwater using electrodialysis.

| Test N° | Potential difference, $P$ (V) | Volumetric flow, $F$ (mL.min$^{-1}$) | Initial salinity (mg.L$^{-1}$) | Final salinity (mg.L$^{-1}$) | PSR (%) | SEC (kWh/m$^3$) |
|---------|-------------------------------|-------------------------------------|-------------------------------|-------------------------------|---------|-----------------|
| 1       | 6                             | 25                                  | 434                           | 451                           | -4      | 0.04            |
| 2       | 12                            | 25                                  | 434                           | 156                           | 64      | 0.25            |
| 3       | 6                             | 50                                  | 434                           | 288                           | 34      | 0.05            |
| 4       | 12                            | 50                                  | 434                           | 239                           | 45      | 0.15            |

4. Conclusions
The methodology for the sizing and selection of the components of the APVS allowed to guarantee the supply of electrical energy to carry out the groundwater desalination process on a laboratory scale.
The UF-ED system reduced the salinity of the groundwater, obtaining 64% removal at 12 V and 25 mL.min⁻¹ in a continuous process. A direct relationship was found between the PSR and the SEC.

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