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A Reverse Osmosis and Electrodialysis System Simultaneously Powered by Gravitational Potential Energy

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Abstract

This chapter proposes an alternative system for conventional reverse osmosis (RO) and electrodialysis (ED) desalination plants by incorporating the use of gravitational potential energy (GPE). The proposed system is devised with two subsystems, the RO module followed by the ED module, both simultaneously powered by GPE. This kind of energy is obtained by storing the brackish water to be desalinated. The system's primary source of energy is wind. Windmills harness the wind energy to pump water to a reservoir located at a certain height (<20 m). The stored water has the GPE that will make a special plunger pump work. The piston of this special plunger pump is designed so that high pressure (about 15 bar) can be achieved in a different way from conventional RO plants. In the alternative system, here proposed, to pump water to the RO membranes, the special pistons go downward due to their own weight and are lifted, through a system of pulleys, with a counterweight filled with water obtained from the reservoir. The technical viability of the alternatives was theoretically proven by deductions based on physics and mathematics and with a special plunger pump prototype that worked successfully.

Keywords: wind energy, gravitational potential energy, reverse osmosis, electrodialysis, water desalination

1. Introduction

Desalination is a process through which pure water is obtained from water with a high concentration of dissolved salt (seawater or brackish water). In general, in a desalination plant, there is an inlet flux of salted water and two outlet fluxes (**Figure 1**).

One of the outlet fluxes (the brine) has a concentration higher than the inlet flux, and the other has a much lower concentration than the inlet flux (drinking water). To achieve that high reduction of solute concentration, it is necessary to deliver a certain amount of energy. The consumption of energy of a desalination plant is generally evaluated in terms of the quantity of energy used for each cubic meter of drinking water obtained. This parameter is called the specific energy consumption expressed

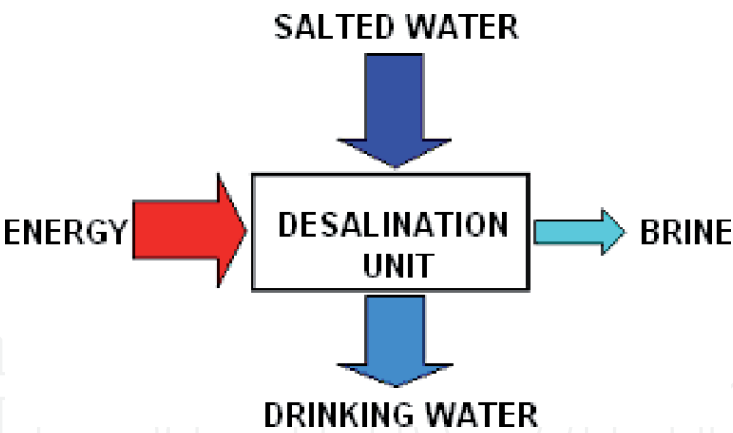


Figure 1.
Simplified scheme of a desalination unit.

in kWh/m³. Among all desalination processes, we will briefly describe the reverse osmosis process for it is the one used with the system proposed in this chapter.

2. Reverse osmosis (RO)

Reverse osmosis is the reversal of a process that occurs naturally named osmosis. Osmosis occurs when two solutions with different concentrations are separated by a semipermeable membrane (**Figure 2**).

In such circumstances, there is a natural tendency to achieve the chemical equilibrium. Thus, the solvent crosses the membrane from the side of less concentration to the other side until the concentrations on both sides are the same. To reverse this natural tendency, a pressure (higher than the osmotic pressure) must be exerted on the side originally with higher concentration. This is what is done to achieve

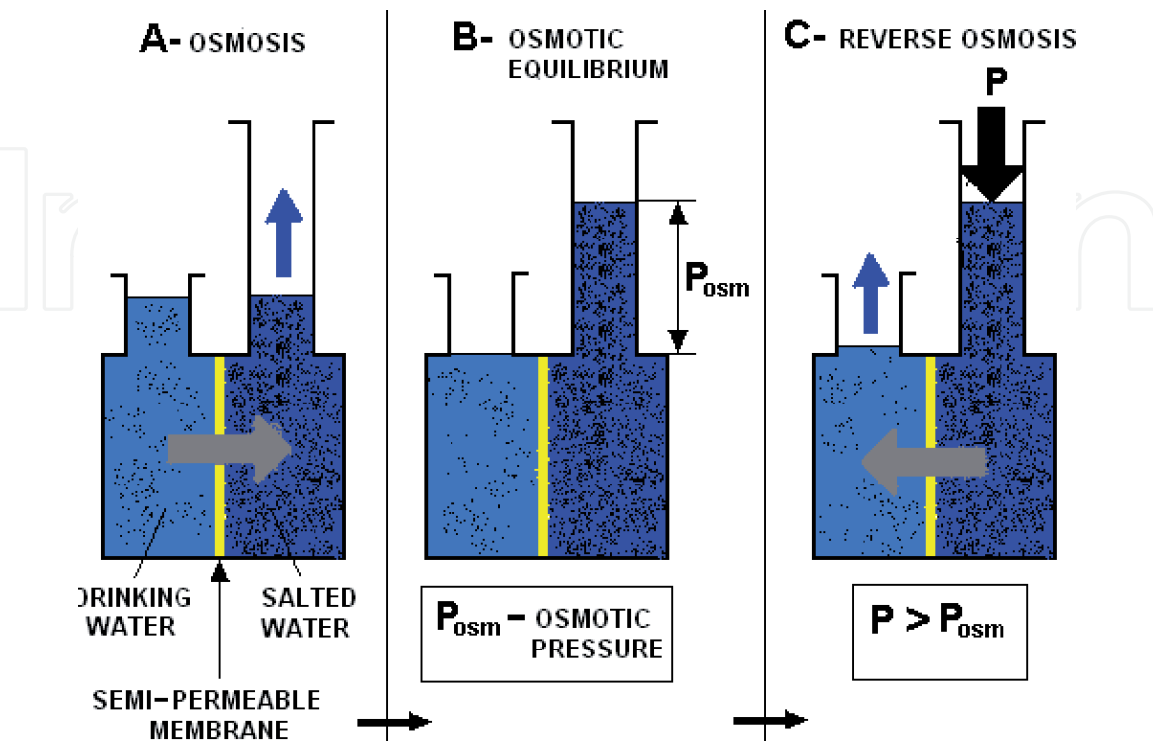


Figure 2.
Fluxes by osmosis and by reverse osmosis.

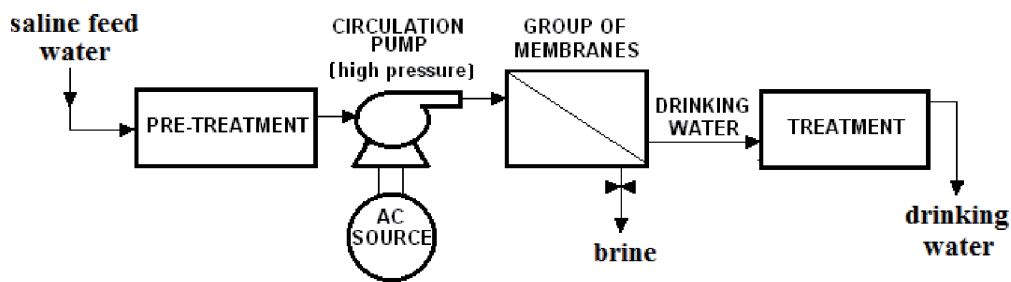


Figure 3.
Scheme of a reverse osmosis desalination plant.

desalination by reverse osmosis and why, generally, there is a high specific energy consumption. **Figure 3** shows a schematic of a RO desalination plant.

In this chapter, an alternative RO system powered by wind and gravitational potential energy (GPE) is proposed. The proposed system would basically replace the high-pressure circulation pump shown in the configuration of **Figure 3**.

3. Electrodialysis

The scientific principle that sustains electrodialysis (ED) is the electrical attractions between ions and electrodes of opposite electric charge. This phenomenon suits desalination since the dissolved particles in salted water are electrically charged (positive and negative ions). In ED desalination selective membranes are used to “sift” the ions. Some retain the positive ions and allow the negative ones to pass through, while others perform with the inverse characteristic. Membranes with inverse characteristic are placed alternately between the positive and negative electrodes. This configuration yields two separate outlet fluxes, drinking water, and brine. **Figure 4** depicts a conventional ED desalination module. ED is mostly used to desalinate brackish water.

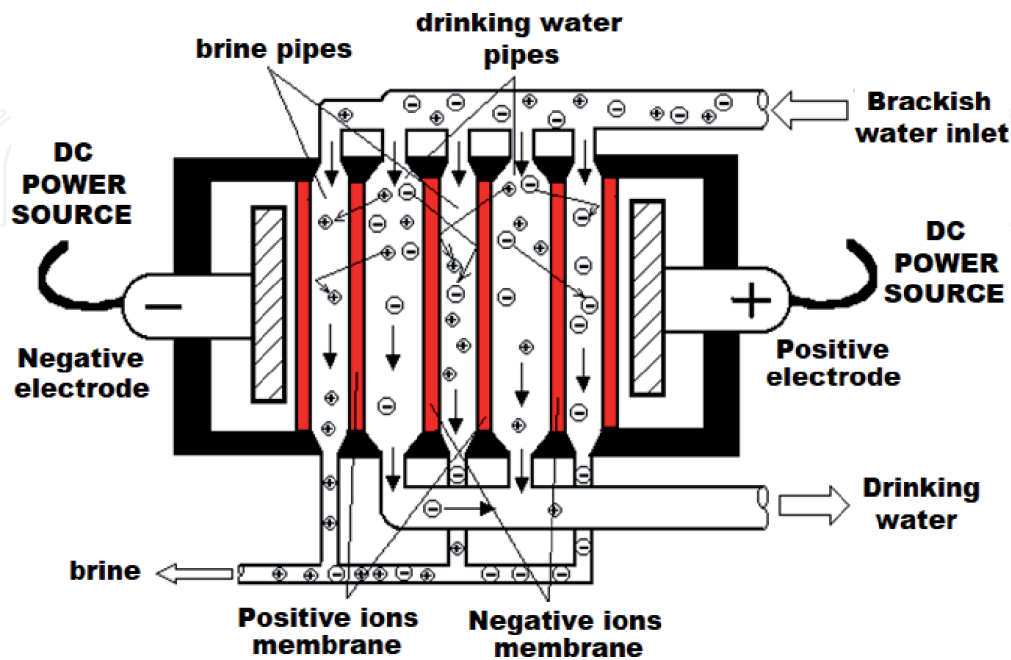


Figure 4.
Electrodialysis membrane configuration. Source [1].

4. The proposed system

Figure 5 shows the general configuration of the proposed system which simultaneously desalinates brackish water by RO and ED. The system’s primary source of energy is wind power which is harnessed by windmills that pump brackish water to a reservoir at a certain height (less than 20 m). A subsystem (the hydraulic power column (HPC)) uses the gravitational potential energy of the stored water to achieve the necessary pressure (about 15 bar for brackish water) to feed the RO module. Notice that the flux of brine (still at high pressure) exiting the RO module is used to activate the Pelton wheel which, in turn, produces electricity to run the ED module.

Figure 6 shows the block diagram of the model outlining the hydraulic power column (HPC) where the increase in pressure occurs (from less than 2 bar to over 15 bar). As is technically required for RO and ED, before saline water reaches the membrane modules, it should undergo a pretreatment process to avoid premature malfunction. Cautiously, this feature should be integrated in the system both for the RO and the ED modules.

For seawater desalination, one needs to have an operation pressure of around 55 bar, while for brackish water it is around 20 bar. With the proposed system, this magnitude of pressure is given by a special piston working inside the HPC.

Figure 7 shows the proposed configuration for the HPC. The model is composed of two HPCs which, separately, can be seen as individual special piston pump. The two individual pumps are connected through a hydraulic automation system in

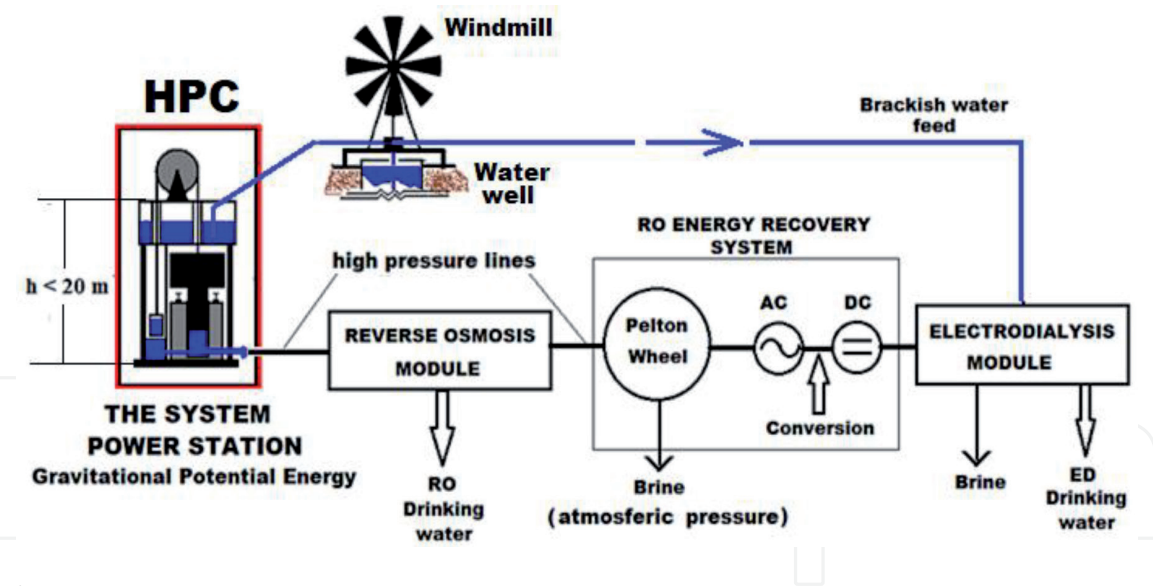


Figure 5.
The hydraulic power column renewable system.

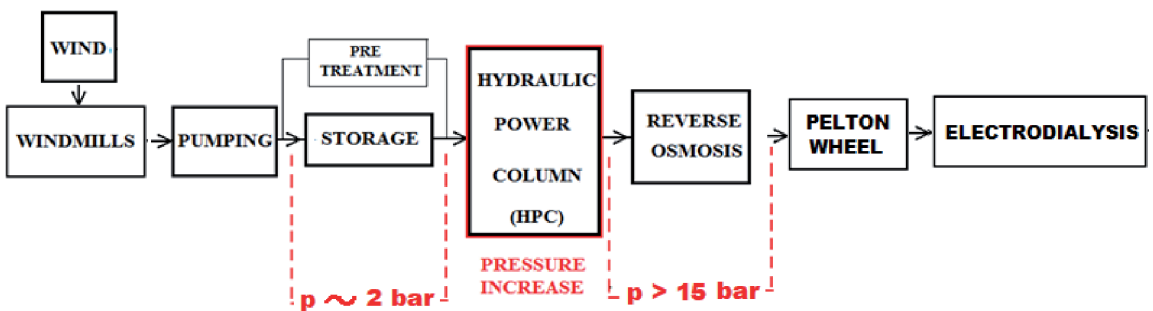


Figure 6.
The hydraulic power column renewable system.

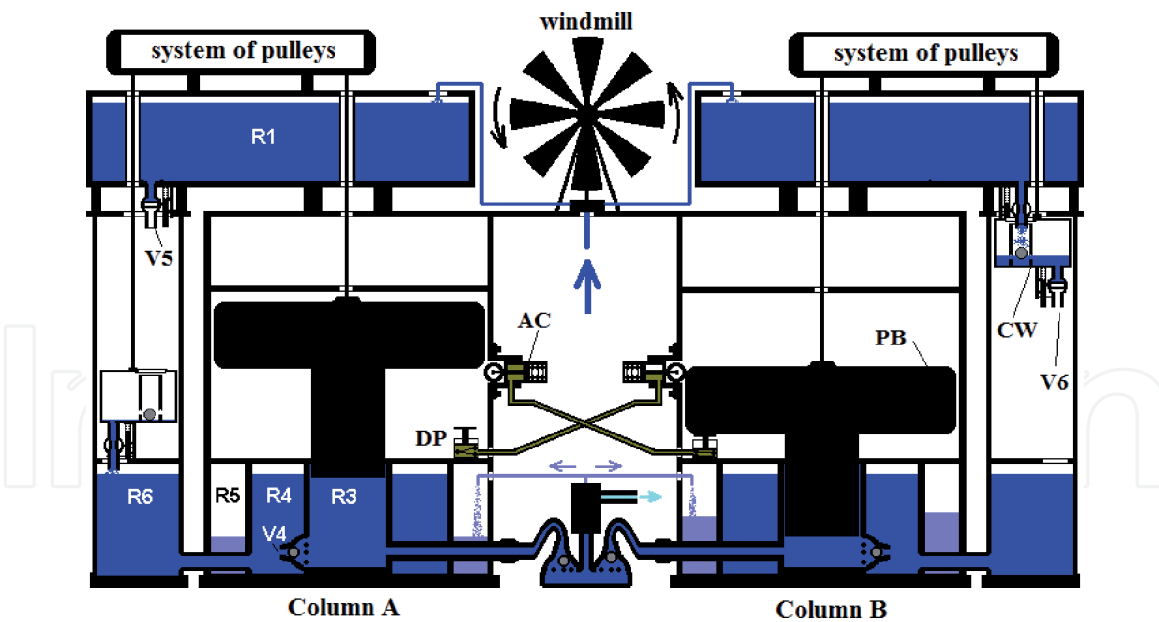


Figure 7.
 Parallel operation of two hydraulic pressure columns. R1 fed with a windmill.

order to send a continuous flux of salted water to the modules of membrane where the desalination occurs.

The pretreatment of seawater, namely, filtering, is designed to occur by gravity in reservoir R1. After the filtering process, chemicals may be added if necessary. Note that if a reverse osmosis desalination system works with a low recovery rate (e.g., 20%), chemicals may not be needed. Recovery rate is the percentage of drinking water obtained from a volume of sea water that passes the membrane module (the rest is brine at high pressure).

With the system here proposed, to recover the brine energy, a Clark pump is used. It is a kind of flow work device. Brine at high pressure enters the Clark pump, leaves it at atmospheric pressure, and delivers work through a double piston pump. The system uses this work to pump water to the top reservoir R1.

Calculations have shown [2, 3] that it is possible to reach high pressures with a special piston of moderate dimensions. The counterweight gets the necessary volume of water (GPE) from the reservoir R1 to make the special piston go upward. The system of pulleys is designed so that it yields a reasonable force reduction to lift the piston. When the CW empties, the special piston goes downward, exerting pressure on the water in chamber R3. Consequently water is pumped into the reverse osmosis module under the designed and desired pressure, making reverse osmosis happen.

Shortly, during the parallel operation of columns A and B, (see **Figure 7**) there are the following events:

1. When the piston PB of column B reaches its bottom course, two events occur:
 - The counterweight CW is filled up because valve V5 opens.
 - The bottom of the piston rests on the dampers DP, pressing the fluid inside them. Simultaneously the actuators AC of column A retract due to the signal (fluid under pressure) received from DP, and the piston of that column is released.

Reciprocally, when the piston of column A reaches its bottom course, two identical events occur:

2. When the piston of column B, raised by the counterweight, reaches the upper course, two other events occur:

- It is braked by the actuators and will remain in that position until, after filled up with water, it receives the signal sent by the actuators of column A.
- Its CW empties because valve V6 opens.

An identical process takes place when the piston of column A comes to its upper course.

The hydraulic automatism guarantees the continuous function of the system as long as there is enough water in the reservoirs R1. The continuous flux of salted water to the modules of membrane is guaranteed by the two-way valve V7 that connects the two columns.

So far, a small prototype has been constructed at the polytechnic school of the *Universidade de São Paulo-USP in Brazil*. The prototype has proven that the mechanism of the HPC works. Since osmosis reverse is already a solid technique, the focus of the prototype was not to obtain drinking water because it would not be reasonable to reach 55 bar because of the size of the special piston.

Therefore the objective of the prototype was to prove that the HPC pumps water using the gravitational potential energy obtained from the water in R1 and that the necessary increase of pressure is achieved due to the shape of the special piston. The flux under the pressure exerted by the piston was used to drive a small Pelton wheel supported with magnetic levitation. This was done so, also to prove that the system can be used for electricity generation which is to be used to power the ED module.

5. The special pistons and their high pressure

Figure 8 shows the shape of the special piston that works inside the HPC. The HPC may work either with a massive special piston (piston B) or with one (piston A) where the increase of pressure is achieved mainly with the weight of water obtained from R1.

The pressure P_A exerted by the special piston A on its circular bottom of diameter d_e is a function of the geometric parameters illustrated in **Figure 8**. According to results already obtained [2], it is possible to achieve pressures high enough (over

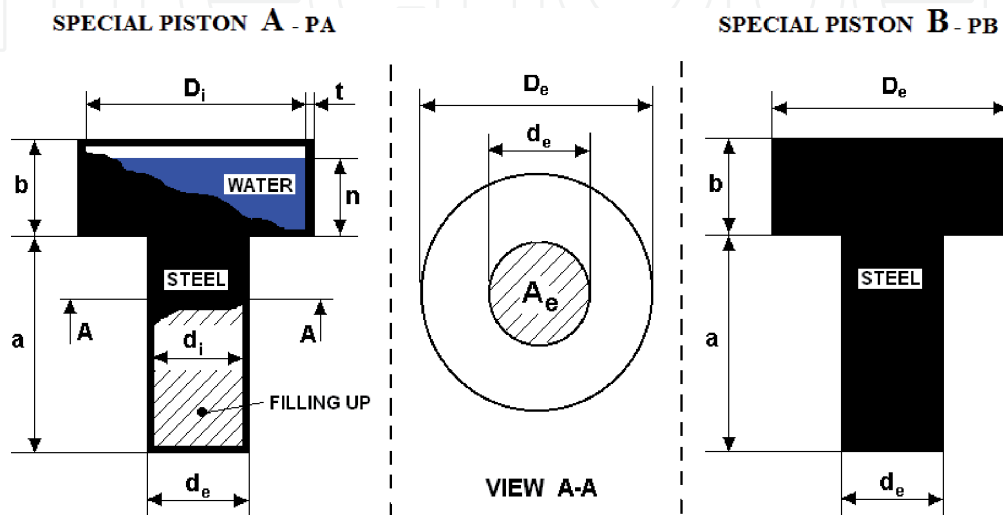


Figure 8.
Scheme of the special piston.

55 bar) to desalinate seawater with a special piston of moderate dimensions (fitting inside a 5-m-height HPC).

The expression for pressure P_A exerted by the special piston A on its bottom of diameter de is given by the total weight of the piston Pt , divided by the circular area Ae :

$$P_A = Pt / Ae \tag{1}$$

Starting with Eq. (1) and knowing that Pt is the sum of the weight of steel, $Psteel$ plus that of the water $Pwater$ in R2 and the filling up material $Pfill$, and that $Ae = \pi/4 de^2$, after some algebraic manipulation, one gets the following relation [2, 3]:

$$P_A = \frac{g}{de^2} [\rho_{stl} (De^2 b + de^2 a)] - Di^2 (b - 2 t) - di^2 a + \rho_{wat} Di^2 n + \rho_{fill} di^2 a \tag{2}$$

where g is the acceleration of gravity [m/s^2]; ρ_{stl} is the density of steel [kg/m^3]; ρ_{wat} is the density of seawater (or brackish water) [kg/m^3]; ρ_{fill} is the density of the of the filling up material [kg/m^3]; and $Di = De - 2 t$ [m], being t the thickness of the piston's wall.

A similar approach with special piston B leads to the following expression for P_B :

$$P_B = \frac{g}{de^2} \rho_{stl} (De^2 b + de^2 a) \tag{3}$$

A very interesting aspect of using special piston A is that the filling up material may be anything available where the system will operate such as stones, sand, or even recycled metals. This low-cost characteristic is useful for remote areas because it would not be necessary to transport a very heavy structure.

6. The system's specific energy consumption regarding the RO module

The analysis of a configuration for an underground HPC (Figure 9) led us to some conclusions about the specific consumption of energy [2, 3]. Notice that there is no need to pump water to R1, and the energy consumption is used only to lift the piston.

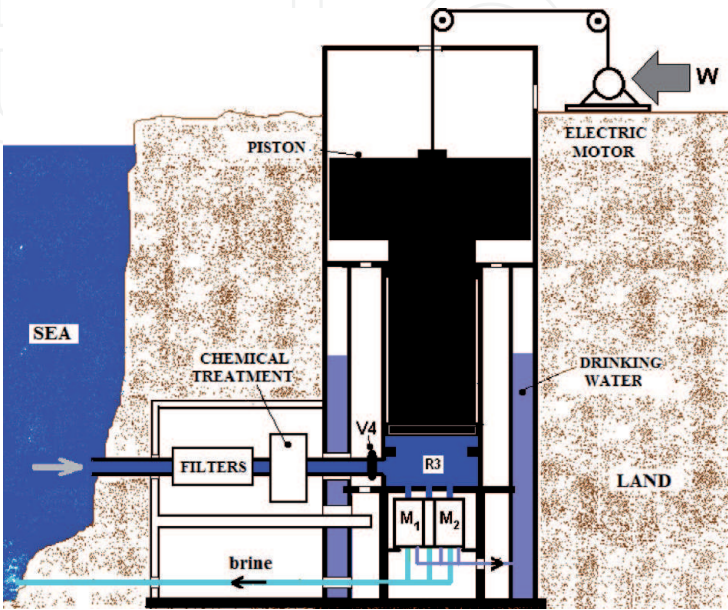


Figure 9.
Underground HPC.

- Considering a frictionless piston with an operating pressure of 20.3 bar, the system would consume around 0.563 kWh for each cubic meter of drinking water which is the minimum allowed by nature [4].
- Considering a frictionless piston with an operating pressure of 55 bar, the HPC would consume around 1528 kWh for each cubic meter of drinking water.
- For an operating pressure of 55 bar and taking into account acceptable efficiencies (“actual” values) for the components of the HPC, it has been shown that the predicted “actual” specific energy consumption is about 2811 kWh for each cubic meter of drinking water. This is a very good result compared to the conventional RO systems for which this parameter is generally above 4 kWh/m³. Taking into account the ED module, we can predict an overall energy consumption about 3 kWh/ m³ of drinking water.

7. Calculation of the systems’ pumping power

Figure 10 shows the chain of energy transformations that occur in the proposed system. Starting from wind energy until the storage of gravitational potential energy (GPE) in the reservoir R1 on top of the hydraulic power column.

In the block diagram of energy transformation, the conversion of wind power P_w into pumping power P_p that will be used to feed R1 with water to be pumped from a well is illustrated. Along those conversions, there are power losses due to the inefficiencies of the devices and mechanical connections (shafts, gears, etc.). Further in this chapter, it will be shown how the pumping power P_p is converted into a volume of water V_w stored in R1.

The power of wind flow P_w is given by [5]:

$$P_w = 1/2 \rho A V^3 \quad (4)$$

where ρ is the air density; A is the frontal area through which the air flows; and V is the wind speed.

A wind machine (windmill or wind turbine) can be used to harvest this wind power and convert it into its rotor power P_r . Betz has proven that 59% of P_w is the maximum P_r that an ideal rotor would be able to harvest from the wind [5]. Observing **Figures 10** and **11**, one concludes that for system 1 (windmill), P_r is used to drive a piston pump which will feed R1, while in system 2 (wind turbine), it will be converted into an electric power P_e that will power an electric pump which feeds R1.

Back to the rotor power, its magnitude is:

$$P_r = C_p 1/2 \rho A V^3 \quad (5)$$

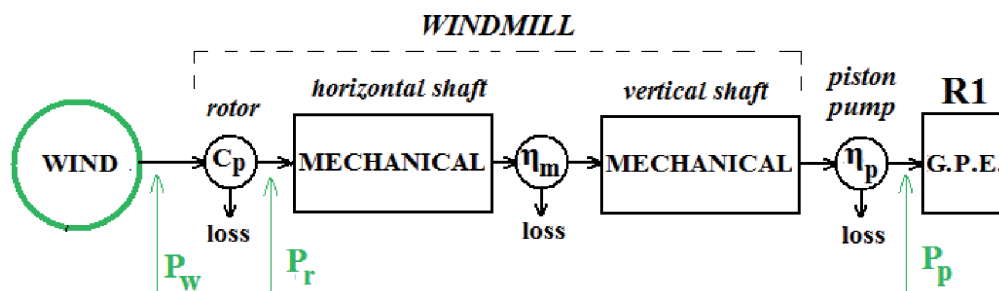


Figure 10.
Energy conversions of the system.

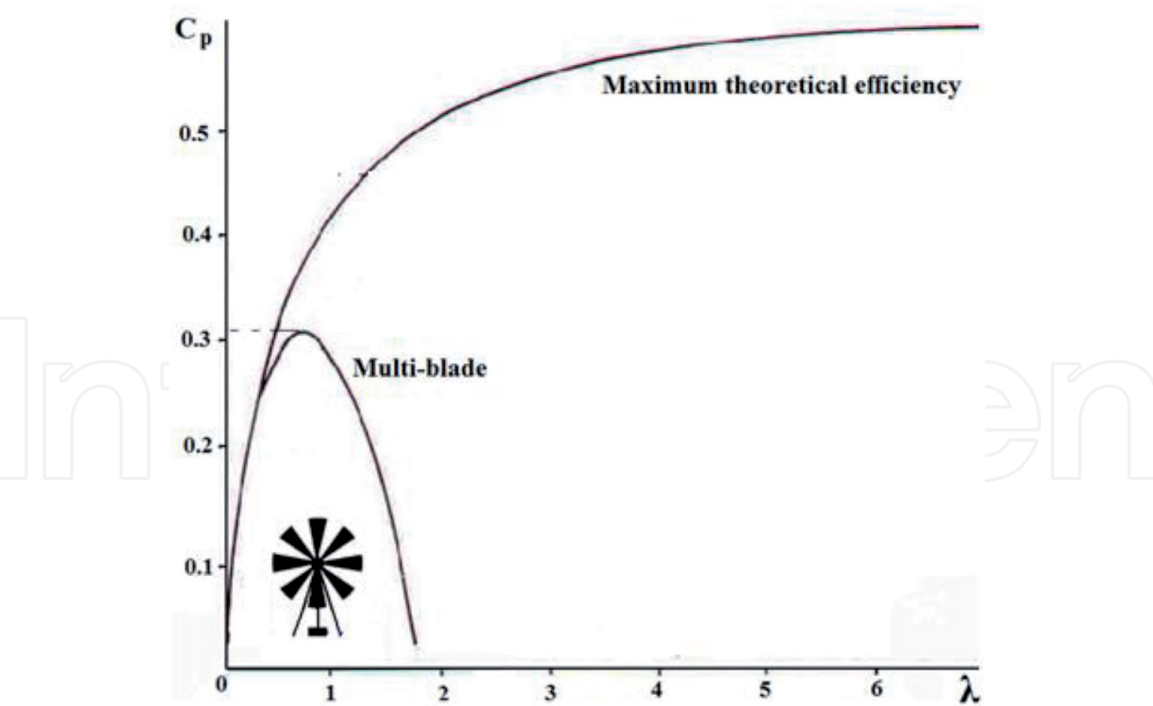


Figure 11.
Aerodynamic efficiency of wind machines: Source [5] with our drawings.

where C_p is the power coefficient of the machine. C_p can generally be expressed as a function of the tip speed ratio, λ , defined by [5]:

$$\lambda = \text{blade tip speed/wind speed} = \Omega R/V \tag{6}$$

where Ω is the angular velocity of the wind rotor and R is the radius of the wind rotor.

Figure 11 illustrates the aerodynamic efficiency of a windmill which is characterized by its power coefficient C_p . Resorting to **Figure 11**, a windmill's C_p can be compared with Betz's maximum theoretical efficiency.

According to **Figure 10**, taking into account the efficiencies of the gear η_m and that of the piston pump η_p , the pumping power P_p is given by [6]:

$$P_p = P_r \cdot \eta_m \cdot \eta_p \tag{7}$$

So, the pumping power of the system with windmill is:

$$P_p = C_p \frac{1}{2} \rho A V^3 \eta_m \cdot \eta_p \tag{8}$$

Eq. (8) represents the theoretical pumping power P_p at the end of the chain of conversions shown in **Figure 10** for the system. However, in practice one can resort to other equations that are based on the characteristics of each wind machine used by the system. Since windmills are generally used to pump water, it is sufficient to determine its pumping power P_p . For S2, first it is necessary to determine the electric power P_e delivered by the wind turbine and then estimate the efficiency of its connection with the electric pump in order to find the pumping power.

8. From pumping power to potential gravitational energy stored in R1

After finding the pumping power P_p , one has to find the flux of pumped water to R1 as a function of the manometric height H_m (head) as well as the volume of

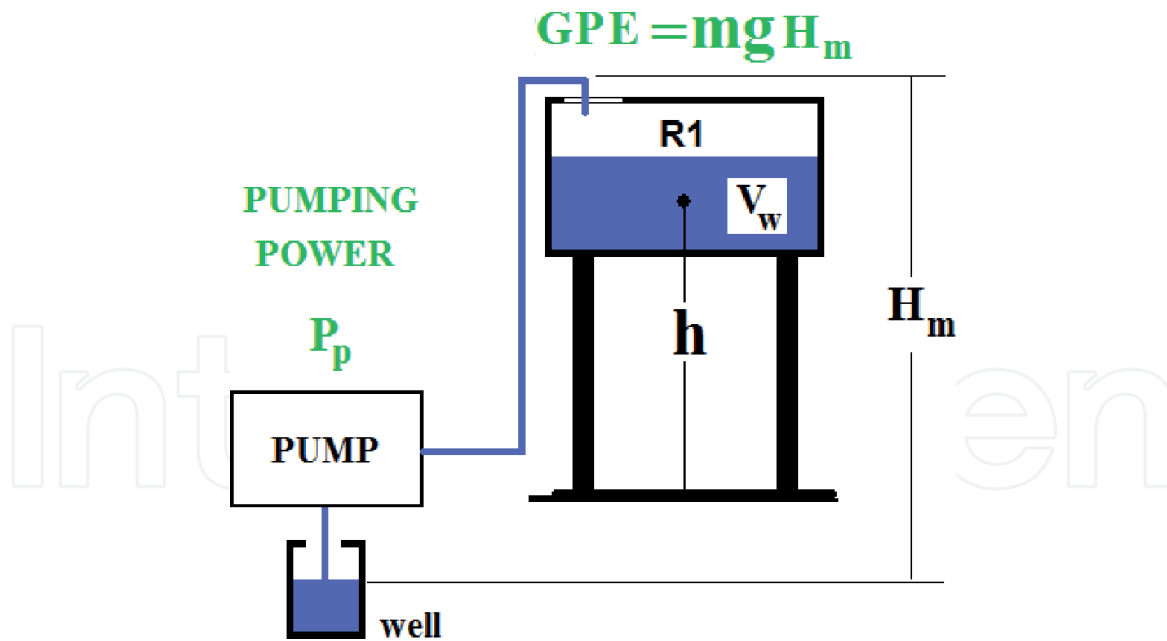


Figure 12.
Storage of gravitational potential energy in reservoir R1.

water V_w stored in R1 (**Figure 12**). During the pumping process, the work done by the pump is equivalent to energy transferred (E_{tra}) to the water which will be stored in R1 as gravitational potential energy (GPE).

The energy transferred E_{tra} to the water during the pumping process is:

$$E_{tra} = P_p \cdot \Delta t. \quad (9)$$

where Δt is time (in seconds) corresponding to the period of operation of the pump [hour(s), day(s), month(s), year(s), etc.].

As mentioned, the transferred energy is stored as potential gravitational energy (GPE) in R1. Therefore one has:

$$E_{tra} = GPE, \quad (10)$$

or

$$P_p \cdot \Delta t = m \cdot g \cdot H_m. \quad (11)$$

where H_m (the head) is the height that the pump must overcome in order to force water from the well to the top reservoir R1 (**Figure 12**).

Since mass of pumped water is the product of the specific mass for its volume ($m = \rho_w V$), Eq. (11) becomes:

$$P_p \cdot \Delta t = \rho_w V_w g H_m. \quad (12)$$

Solving Eq. (12) to obtain the volume of a pumped water, one has:

$$V_w = P_p \cdot \Delta t / (\rho_w \cdot g \cdot H_m) \quad (13)$$

where V_w is the volume of pumped water (stored in R1); P_p is the pumping power; ρ_w is the water density; g is the acceleration of gravity; and H_m is the manometric height.

If one considers the time of operation of 1 hour ($\Delta t = 3600 \text{ s}$), Eq. (13) becomes:

$$V_w = 3600 P_p / (\rho_a \cdot g \cdot H_m) \tag{14}$$

With $\rho_w = 1025 \text{ kg/m}^3$ corresponding to the density of seawater to be pumped to R1, and.
 $g = 9.81$, Eq. (14) reduces to:

$$V_w = P_p / (2790 H_m) \tag{15}$$

Eq. (15) yields the volume of pumped water per hour. Therefore the result of this equation should be multiplied by 24 to obtain the volume of water stored in R1 during a day. Once there is enough water in R1, to make the hydraulic power column work, as already proven with the prototype, the reverse osmosis process will occur as long as the special piston exerts the necessary pressure. For that, the pressure is previously calculated according to the design of the piston and using Eqs. (2) and (3).

9. Alternatives to get the potential gravitational energy stored in R1

The HPC is designed so that it works as long as there is enough water stored in the reservoir R1 regardless of how water was put in it. This characteristic yields a certain versatility to the whole system. This means that one could feed R1 with other sources of energy such as wind, sea waves, sun, etc. In this regard, it is interesting to consider the possibility of using a device similar to the HPC's plunger pump to harness sea wave power to pump water to reservoir R1. Such device is currently a reality due to the invention of Alvin Smith who developed the Searaser (**Figure 13**). This feature is especially important if the system is to be designed for seawater desalination with the RO module and brackish water for the ED module.

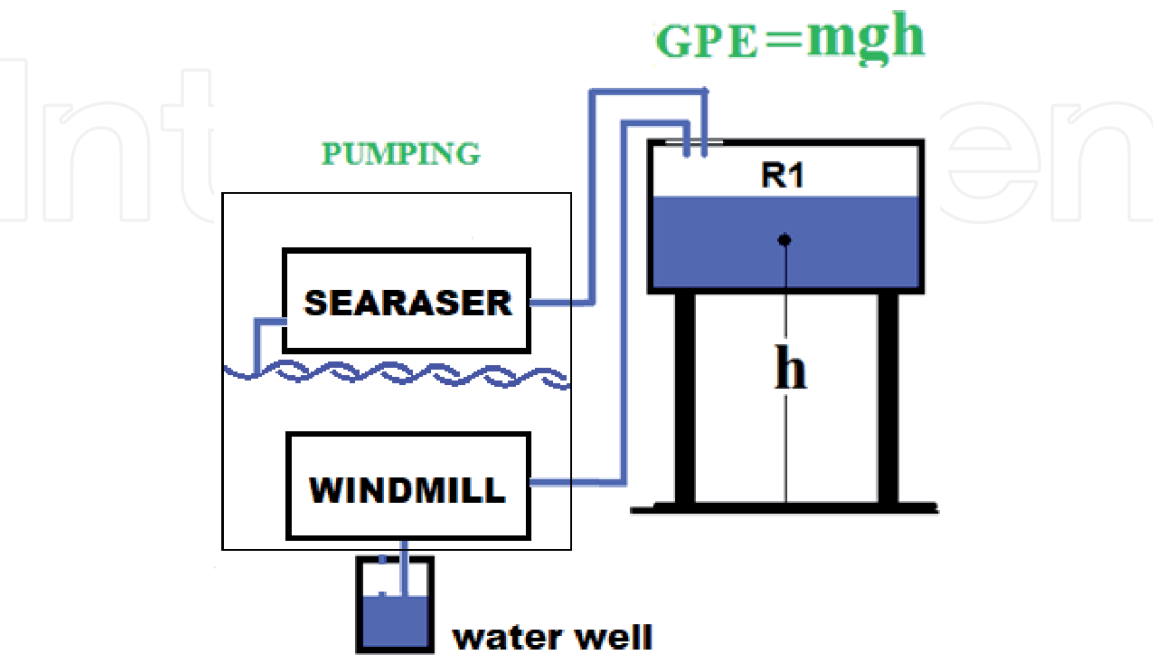


Figure 13.
Feeding of reservoir R1 with windmill and Searaser.

10. Conclusion

From what has been done so far, we conclude that the model is technically and economically practicable. The economic viability is supported, not only by the fact that the model uses a renewable “free” source of energy, but also because of a predicted low specific energy consumption (around 2.811 kWh/m³) for the RO module, regardless of which system is used to feed the top reservoir R1. Taking into account the ED module, we can predict an overall energy consumption about 3 kWh/m³ of drinking water.

Inherent to the use of wind gravitational potential energy is the reduction of emissions of CO₂ which is an environmental advantage compared to conventional RO plants. Another advantageous fact is a low cost of maintenance due to the simplicity of the hydraulic power column. The major drawback of the model is the need for a big area to install the windmills if one needs to desalinate a large quantity of water. This disadvantage can be overcome using a hybrid source of energy to feed R1 such as Wind-Sea-Sun combination. The constructed prototype has proven that the system is practicable.

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