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Influence of wind energy in a seawater desalination plant by reverse osmosis

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ABSTRACT

The objective of this work is to investigate the contribution of renewable energy to a desalination plant that uses reverse osmosis technology. During the development of this research study and after the analysis that was undertaken of the wind conditions in which the reverse osmosis plant is located, it was determined that the best option was to discard the use of photovoltaic energy as a source and instead install a wind turbine. As it is a large capacity reverse osmosis plant, it was necessary to consider the entire desalination process of the facility, which comprises several phases. After a seawater capture process using an intake tower, the water is then transported and stored before passing through a physical and chemical pre-treatment stage where the highest possible percentage of impurities and organic material is eliminated to prevent fouling of the reverse osmosis modules. After carrying out plant sizing and calculating the energy that the plant consumes, it was determined that a 15% renewable energy contribution to plant operation was feasible, corresponding to 1,194 MWh y^{-1}. As there is already a wind power installation in the area, it was decided to use one of the installed wind turbines, more specifically the Ecotecnia (20/150) which provides 1,920 MWh y^{-1}. That is, for this installation only a single wind turbine is needed.

Keywords: Seawater; Reverse osmosis; Desalination; Renewable energies

1. Introduction

Around 70% of the Earth's surface is covered with water. Of that, just 2.5% is freshwater and 90% of it is inaccessible; found in the subsoil, in the atmosphere and frozen in the polar caps or in glaciers. In short, less than 1% of the world's water is readily available for consumption [1,2].

As specified in the previous paragraph, less than 1% is the percentage that corresponds to drinking water and much of this water is far from populated areas, which makes its use practically impossible [1,2]. Global warming, climate change, drought, increased birth rates according to the latest United Nations report [3,4], the advance of agricultural, livestock and urban borders, deforestation, pollution and mismanagement, have combined to bring this resource to a crisis point. To tackle this urgent problem, engineers have designed technological alternatives which allow potable water to be obtained from brackish waters, as well a more equitable distribution of the water resources on which we depend as a population [5,6]. By taking advantage of such technologies, the seas and oceans can become infinite sources of water apt for human consumption.

Water is a totally necessary resource, and, in the future, its scarcity is likely to be one of the greatest environmental problems that exist. As a consequence, desalination and water treatment facilities are becoming an essential asset for economic and cultural development [7,8].

Due to its geographical location and orography, the Canary Islands (Spain) constitute an ideal site for the installation of desalination technologies, allowing the development

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of the integration of renewable energy sources to make them more sustainable and generate a lower environmental impact on the archipelago's ecosystem.

In response to the COVID-19 crisis, the archipelago has seen its water consumption reduced, mainly due to the lack of tourists on the islands. In addition, the possible measures that the Government of Spain could adopt may lead to water supply problems in the eastern islands, due to crude oil shortages [9,10].

Therefore, using renewable energy to power or help power desalination plants is not only an environmentally beneficial measure, it can even be considered a measure for the survival of islands in periods of greater vulnerability. In addition, when the present crisis ends it is to be assumed that the same flow of tourists will return, and that the demand for water will increase again [6,11].

The general objective of the present study is to demonstrate the feasibility of using wind energy to provide 15% of the energy required to power a reverse osmosis (RO) desalination plant located in the municipality of Granadilla de Abona (Tenerife, Canary Island, Spain).

2. Material and methods

The RO process is used to make brackish water or seawater suitable for human consumption.

To carry out this work, it is necessary to consider the transformation process that takes place in a desalination plant and to understand the concept of reverse osmosis, a commonly used technology in desalination plants.

Osmosis is a natural process by which a solvent passes through a semi-permeable membrane from a dilute solution to a more concentrated one. The RO process is one in which the flow rate is already reduced. Through a semi-permeable membrane, a force greater than the osmotic pressure is exerted in the opposite direction to the osmosis process. In this way, it is possible to separate the water on one side of the membrane (concentrate) from a dilute solution on the other side of the membrane low in dissolved solids (permeate) [11,12].

The membrane is a key element of RO, as it is the device used to treat and obtain drinking water. The process is based on forcing the passage of water through a membrane and trapping impurities [12–14].

One of the most important aspects to consider is the selection of the membrane according to the process that will be carried out, as well as aspects related to the installation itself and its cost [15,16].

In this section, we will describe the design equations, for micro, ultra and nanofiltration (NF) membranes, used in the pre-treatment stage, as well as those that define RO itself.

The most commonly used membrane technologies correspond to microfiltration (MF), ultrafiltration (UF) and NF. The latter type of membrane creates new possibilities when it comes to the pre-treatment of seawater [9,17–19].

The flow of water J, through MF and UF membranes, can be expressed through:

$$J = \frac{\Delta P}{\eta \times R_T} \tag{1}$$

where J is the water flow (m^3 m^{-2} s^{-1}); ΔP is the differential pressure or applied transmembrane pressure (TMP) in N m^{-2}; η is the dynamic viscosity N s m^{-2}; R_T is the total membrane resistance (m^{-1}).

The net applied pressure is proportional to the flow of water and inversely proportional to the viscosity, temperature, and total resistance of the membrane.

Non-cross flow at transmembrane pressure can be determined from:

$$\text{TMP} = P_i - P_p \tag{2}$$

where P_i is the inlet pressure; P_p is the permeate pressure.

If the flow is crossed:

$$\text{TMP} = \frac{P_e \times P_s}{2} - P_p \tag{3}$$

where P_e is the diaphragm inlet pressure; P_s is the diaphragm outlet pressure.

Finally, considering the previous equations, the flow corresponding to the membranes will be determined by the following equation:

$$Q_P = J \times S \tag{4}$$

where S is available membrane surface (m^2); Q_P is treated or permeated water flow (L h^{-1}).

2.1. Reverse osmosis formulas: solution-diffusion model

The formulas used for the calculations of the RO process are based on the solution-diffusion model. In this model, there is a salt flow, J_s, and a water flow, J_w, as shown in Fig. 1.

One of the main equations is the water or solvent flow equation:

$$J_w = A(\Delta P - \Delta\pi) \tag{5}$$

where J_w is the water flow in liters (m^2 h^{-1}); A is the membrane permeability coefficient (L m^{-2} bar^{-1}); ΔP is the transmembrane differential pressure, bar; $\Delta\pi$ is the osmotic pressure difference, bar.

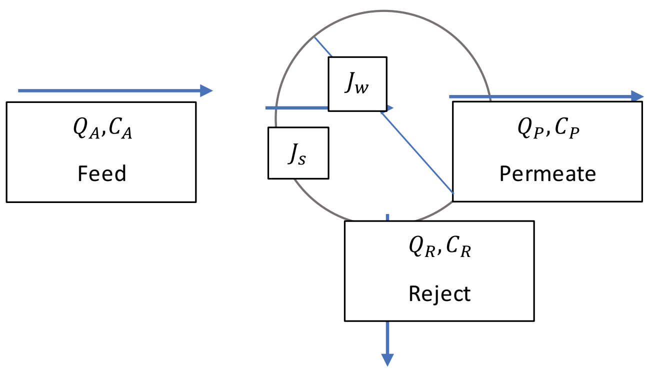

Fig. 1. Simplification of the desalination process.

To correctly carry out the calculations, it is necessary to consider the concept of networking pressure.

From this formula, it follows that the higher the networking pressure, the higher the productivity of the membrane.

Considering these points, the following equation is obtained:

$$J_s = B \times \Delta C \quad (6)$$

where J_s is the salt flow (kg m^{-2} s^{-1}); B is the mass transfer coefficient (m s^{-1}); ΔC is the transmembrane differential mean concentration (kg m^{-3}).

The characteristics of the membranes depend on factors A and B, in addition to temperature, pH, conversion factors and salinization concentrations, which can be modified.

For the development of an RO plant, therefore, it should be considered that the higher the concentration of salts in the feed, the greater the passage of the salts will be, which will cause an increase in salinity in the permeate.

2.2. Material balance

Based on Fig. 1, two types of balance can be developed:

- *Solvent balance*:

$$Q_A = Q_p + Q_r \quad (7)$$

- *Solute balance*:

$$Q_A C_A = Q_p C_p + Q_r C_r \quad (8)$$

where Q_A is the feed flow (m^3 h^{-1}); C_A is the feeding solute concentration (kg m^{-3}); Q_p is the permeate flow (m^3 h^{-1}); C_p is the permeate solute concentration (kg m^{-3}); Q_r is the reject or permeate flow (m^3 h^{-1}); C_r is the solute concentration in the reject or concentrate (kg m^{-3}).

2.3. Conversion factor and concentration factor

The percentage of permeation is obtained from a certain feed flow. This can be expressed as a percentage between the permeate flow rate and the feed flow that reaches the membrane. It is also known as the conversion factor.

$$Y = \frac{Q_p}{Q_A} \times 100 = \left(1 - \frac{Q_p}{Q_A}\right) \times 100 \quad (9)$$

The concentration factor is directly related to the conversion factor and is based on the following formula:

$$\text{CF} = \left(\frac{1}{1-Y}\right) \quad (10)$$

where CF is the concentration factor; Y is the conversion factor

2.4. Rejection factor (R) and passage of salts (SP)

The formula for determining rejection corresponds to:

$$R = \frac{C_A - C_p}{C_A} \times 100 \quad (11)$$

where R is the salt rejection, %.

And, as a result, the passage of salts:

$$\text{SP}(\%) = 100 - R \quad (12)$$

2.5. Tension curve – module intensity

Data from the stress curve of the solar module are determined by:

$$\text{FF} = \frac{I_{\text{mpp}} \times V_{\text{mpp}}}{I_{\text{sc}} \times V_{\text{oc}}} \quad (13)$$

$$P_{\text{mpp}} = \text{FF} \times I_{\text{sc}} \times V_{\text{oc}} \quad (14)$$

where V_{mpp} is the voltage at the maximum power point; I_{mpp} is the intensity produced at the maximum power point; V_{oc} is the unloaded voltage; I_{sc} is the short-circuit intensity; P_{mpp} is the maximum produced power under standard conditions (STC); FF is the form factor.

3. Results

The results demonstrate the contribution of renewable energy to a desalination plant that uses RO technology. Various distinct environmental, strategic and socioeconomic benefits are seen to arise from the use of renewable as opposed to conventional energies. These are shown in Tables 1–3, respectively:

In brief, renewable energies do not produce emissions of polluting gases and do not depend on the production of other countries. Moreover, they contribute to the creation of employment opportunities and the development of specific new technologies.

In the Canary Islands, a mixture of renewable and conventional energy is consumed. The electrical power installed

Table 1
Environmental benefits

Environmental	
Renewable	Conventional
They do not produce emissions of polluting gases	Obtained from fossil fuels
They do not generate hard-to-treat waste	Generate waste that is difficult to remove or that poses a threat to the environment
	They are finite

in the Canary Islands is 3,308.7 MW, distributed as shown in Table 4:

The energy sources on which this project will focus are determined by the energy supply of the two renewable sources mentioned above, photovoltaic (PV) solar and wind energy, both of which are currently used in the archipelago.

Table 5 shows the advantages and disadvantages of PV solar energy installations.

With respect to the results obtained for the design and creation of a PV installation, the following considerations are made:

3.1. Peak rated power

The power of a photovoltaic installation is determined by the peak rated power, which is conditioned by:

- Irradiation $\rightarrow G_{stc} = 1{,}000$ W m^{-2} with normal incidence;
- Temperature in normal conditions;
- Air mass (AM), which usually corresponds to a value of 1.5, but can be modified by atmospheric pressure (P) or the zenith angle (h):

$$\text{AM} = \frac{P}{\left(P_0 \times \text{sen}\left(h\right)\right)} \tag{15}$$

Table 6 shows the definitions of the different parts of a wind turbine. As discussed with PV solar energy, wind energy has certain advantages and disadvantages typical of the technology, shown in Table 7.

A minimum wind speed is required for a wind turbine to operate. Because the wind changes depending on the height, Hellmann's exponential law has to be taken into consideration.

Table 2
Strategic advantages

Strategic	
Renewable	Conventional
They are indigenous	They exist in a limited number of countries
They do not depend on the production of other countries	Energy imports rise

Table 3
Socioeconomic advantages

Socioeconomic	
Renewable	Conventional
Job creation	Compared to renewables, they do not create as many jobs
Developing own technologies	Mostly imported technology
Their use in rural areas contributes decisively to the interterritorial balance	They are in developed areas

Table 4
Power installed in the Canary Islands

Electrical power installed in the Canary Islands (MW)		
Thermal origin	Thermal power plants	2,606.4
	Refinery	25.9
	Cogeneration	64.1
	Total	2,696.4
Renewable origin	Wind	397.3
	Photovoltaic	186.5
	Mini hydraulics	2.0
	Wind-hydro	22.8
	Biogas	3,7
	Total	612.3
Total		3,308.7

Table 5
Advantages and disadvantages of photovoltaic solar energy

Advantages	Disadvantages
Long service life	High initial cost
Low maintenance and costs	Power generation is not constant due to the variability of the power source
Modularity	

Table 6
Definition of the parts of a wind turbine

Blade	Like the wings of an airplane, built with relatively light materials
Nacelle	Inside the nacelle are the different components of the wind turbine. Its exterior has a vane and an anemometer that allows its control
Rotor axle and control	Connects the blades and bushing. Transforms kinetic energy into mechanical energy
Tower	Supports the nacelle and rotor
Generator	Transform mechanical energy into electrical energy
Guidance system	Situates the mechanism perpendicular to the wind
Foundation	High-strength platform that supports the wind turbine assembly
Electric regulation system	Maintains rotation speed and limits wind power

$$V(h) = V_0 \times \left(\frac{h}{h_0}\right)^{\alpha} \tag{16}$$

where $V(h)$ is the wind speed to be determined by height; V_0 is the known wind speed at a height; h is the height at which you want to estimate the speed; h_0 is the reference height; α is the terrain roughness: site-dependent and determined as shown in Table 8.

Three types of wind speed can be considered to understand the operation of a wind turbine (Fig. 2):

- *Connection speed*: the speed at which energy can begin to be generated.
- *Nominal speed*: the speed at which the wind turbine reaches its rated power.
- *Disconnection speed*: a high speed at which the wind turbine disconnects and stops generating power.

Table 7
Advantages and disadvantages of wind energy

Advantages	Disadvantages
Low cost of generation	Wind is not guaranteed
Creating specific jobs	Energy cannot be stored
Energy independence	Impact on the landscape
Increased wealth in rural areas	Affects birds

Table 8
Values of α

Types of land	α
Smooth (sea, sand, snow)	0.10–0.13
Moderate roughness (boiling, crops)	0.13–0.20
Rough (forests, buildings)	0.20–0.27
Very rough (cities)	0.27–0.40

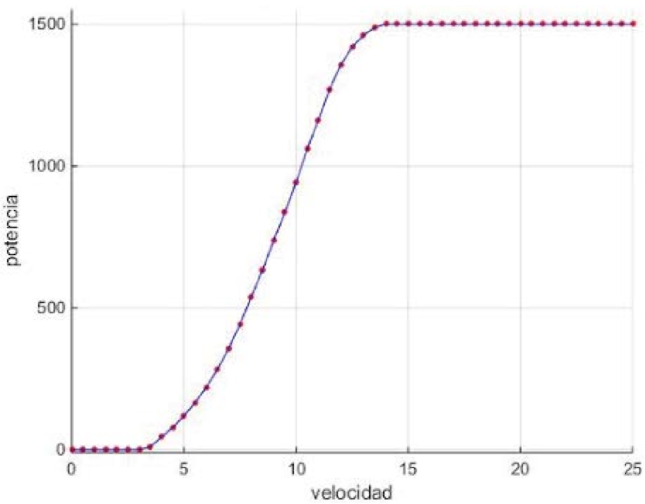

Fig. 2. Energy produced by a wind turbine.

3.2. Wind power

The power generated by a wind turbine is dependent on the winds of the installation area, considering the wind speed, the rotor swept area and the air density, among other variables. The corresponding equation for determining the power of a wind turbine is determined by:

$$P = \frac{1}{2} \times \rho \times A \times V^3 \tag{17}$$

where ρ is the air density = 1.225 kg m^{-3}; P is the power (W); A is the rotor swept area = π × r^2; V is the wind speed (m s^{-1}).

3.3. Turbine power: power coefficient C_p

Mechanical rotational energy is called the power coefficient, and is determined through:

$$P_t = C_p \times P \tag{18}$$

3.4. Estimating energy productivity

The productivity of a wind turbine is determined by the following equation:

$$E = 8{,}760 \times \int_0^{\infty} P(v) \times f(v) dv \tag{19}$$

where 8,760 is the number of hours corresponding to 1 y; $P(v)$ is the power (kW); $f(v)$ is the Weibull distribution, which is used to estimate the energy production of a wind turbine. To determine this distribution it is necessary to have a series of wind speed data corresponding to the area where the wind turbine is to be installed.

3.5. Renewable energy results

Some general features of the RO desalination plant that need to be considered are shown in Table 9.

Open water intakes are used for large capacity plants, and these are also considered for this installation.

In this section, the energy consumed by the different elements and the supply of renewable energy to be applied to the plant will be determined.

Table 9
Features of reverse osmosis installation

Plant production (m^3 d^{-1})	10,000
Operating lines	5
Operating time (h)	24
Feed water	Seawater
Product water	Potable water
Salt concentration (mg L^{-1})	36,662,391
Design temperature (°C)	20
Minimum temperature (°C)	18
Maximum temperature (°C)	23

To do this, the number of units used, the rated power of each element (obtained from the corresponding data sheets) and an average of 12 h of daily operation work (as RO membranes take approximately 3–4 h to fill) are considered.

Table 10 shows the data for each item.

The operating hours per day and the energy consumed are shown in Table 11.

As specified in previous sections, the renewable energy supply of the plant in Table 12 will correspond to 15% of the plant.

The Granadilla de Abona industrial estate in Tenerife is an area known for the presence of strong and constant winds which have resulted in severe damage to previously installed PV installations, with fragments even found in underwater clean-up operations off the coast. In consequence, it was decided to discard the option of the use of PV solar power.

For these processes, Spanish Royal Decrees 1955/2000 and 1699/2011 were followed, with the latter allowing the sale of surplus energy when such energy is produced. The wind system is therefore interconnected with the grid, with most of the energy that would be supplied to the plant coming from the grid and around 15% from the wind installation. This 15% may be variable, as full wind turbine efficiency cannot be guaranteed due to the variability of the wind resource. Such interconnections bring with them several advantages, including the non-requirement of the presence of energy storage devices. The energy required by the plant amounts to 1,194 MWh y^{-1}. The Institute for Technology and Renewable Energy (Spanish initials: ITER) run by the Tenerife Island Government provides a series of wind turbines for installation according to the particular characteristics of the site in question. The Ecotecnia (20/150) wind turbine was selected on this basis in Table 13.

Given the need to supply 1,194 MWh y^{-1}, a single wind turbine was chosen with a 30 m height, 20 m diameter and 150 kW rated power. This is sufficient for the correct development of the installation of the sea water reverse osmosis desalination plant in Granadilla with a nominal production of 10,000 m^3 d^{-1}.

Table 10
Power consumption of the different elements of an RO desalination plant

Element	Total power (kW) (unit × P_N)
Sand filter	32.5
Membrane	11.12
Energy recovery device	96
Catchment pump	550
Transfer pump	550
High-pressure pump	350
Booster pump	150
Chemical wash pump	55
Water pump product	37.5
Total	1,832.12

4. Conclusions

This work demonstrates the contribution of renewable energy to a desalination plant that uses reverse osmosis technology.

Table 12
Renewable energy supply

Total power (kW)	1,832.12
Energy consumed (kWh)	21,811.15
Renewable energy supply (kWh d^{-1})	3,271.67

Table 13
Ecotecnia (20/150) wind turbine data

Manufacturer	Ecotecnia
Diameter (m)	20
Height (m)	30
Power (kW)	150
Rotor	Horizontal axis
Energy generated/year (MWh)	1,920
Number of blades	3
Generator	Asynchronous

Table 11
Energy consumed per day

Element	Operating hours per day (h)	Energy consumed per day (kWh) (h × P_N)
Sand filter	12	390
Membrane	10	111.15
Energy recovery	10	960
Catchment pump	12	6,600
Transfer pump	12	6,600
High-pressure pump	12	4,200
Booster pump	12	1,800
Chemical wash pump	10	550
Water pump product	16	600
	Total	21,811.15

For a large capacity reverse osmosis plant, it is recommended to divide the desalination process of the entire facility into several lines of work.

Islands are key sites for the development of desalination technologies. The development of the integration of renewable sources which provide energy to make them more sustainable and generate a lower environmental impact is therefore recommended.

The energy consumed by the seawater reverse osmosis plant and the amount of energy that could be supplied from renewable sources were determined. In this particular project in the Canary Islands, it was found that a single wind turbine (Ecotecnia 20/150) was able to supply 15% of the energy requirements of the plant.

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