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Configurations of reverse osmosis with variable energy consumption for off-grid wind-powered seawater desalination: system modelling and water cost

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Abstract

A technical and economic assessment of wind powered seawater reverse osmosis systems is presented to identify the best combination of coupling between wind power and demanded power for a 5,000 m^3/d SeaWater Reverse Osmosis (SWRO) unit. Three situations have been studied: Reference or Case 0) SWRO plant operating in the nominal point all the time; Case 1) SWRO plant operating in variable power demand (up to 67 % of the nominal point) by reducing the rotation speed of the high pressure pump, and Case 2) use of a modular SWRO plant, able to operate in 4 power flow & demand stages by a configuration of two units of 1,250 m^3/d and one unit of 2,500 m^3/d. Power and fresh water production are calculated through a year based on experimental data of wind resource with time step of one hour. A comparative techno-economic analysis is performed to identify the best configurations along with recommendations on nominal values of desalination capacity and batteries capacity in relation to the nominal power of the wind turbine installed.

Keywords: *wind-powered desalination, seawater desalination, reverses osmosis, design configurations, water cost.*

1. Introduction

According to related technical reports and papers, autonomous wind-driven Reverse Osmosis (RO) desalination is possible but uneconomical, in comparison with conventional on-grid medium and large capacity Sea Water Reverse Osmosis (SWRO) plants. Main opportunities of reducing costs rely on configuration selection in order to decrease both, running costs and capital costs. To this end, minimizing plant stoppages and optimizing nominal capacity of the desalination system are essential issues. Hence, innovative configurations to achieve maximum water production under conditions of low wind resources, should be developed.

Within this framework, this chapter deals with an assessment of different configurations of an off-grid wind powered system for medium-scale RO desalination. A techno-economic analysis mainly based on the know-how of the Canary Islands Institute of Technology is carried out with the main objective of proposing the optimum configuration.

Wind-powered SWRO desalination implies the coupling of a generally constant load to a variable (and little foreseeable) generation source. The fluctuant and inconstant nature of wind leads to a set of technical details to be considered in each part of the system.

Wind availability comprises a wide range of wind speeds: from periods of total calm (under 3 m/s) to peak points over 30 m/s. As it can be observed in any output power curve, machines are stopped out of these extreme situations.

Nonetheless, there are several experiences of these combined systems that have been possible thanks to a double control power: regulation of wind production and load consumption. The two basic situations and subsequent actions are the following:

- Generation > Demand: Excess of power must be redirected to a dumping load [1] or the wind power must be reduced by changing the blades position (pitch control): an external signal indicates the maximum required output power to the control system of the wind generator, which acts on the motor of each blade [2]. On the other hand, under very high wind speed, i.e. cut-out speed range (mean value of 28 m/s or peak value of 34 m/s) the control system will stop the generator.
- Demand > Generation: In this case, the load must be reduced. Considering the SWRO plant consisting in several identical RO trains, they can be stopped one by one in a descending power steps process [2]. Besides, when the RO trains are driven by frequency converters, it is possible a continuous load reduction [3]. Systems with such configurations are called gradual-capacity plants.

1.1. The gradual operation in RO: options and limitations

RO plants are designed to operate under a set of stable conditions, as the feed water composition and flow, or the specific pressure to achieve the target values of product water. On the other hand, the High-Pressure Pump (HPP) and energy recovery systems have to work within a certain range of feed flow. Although a constant power supply is required for stable / nominal working conditions, it is possible to modify the operation point with certain flexibility (See Table 1).

Table 1. Operation ranges of main RO train parameters

Variable	Operation range	Reference
Operation pressure of SWRO membranes	Up to 70 bar	DOW Filmtec: model SW30ULE-440i [4]
Flow through Energy Recovery System	20 – 40 m^3/h (model iSave 40)	Depending on the rotation speed [5]
Flow through Energy Recovery System	45.4 – 68.1 m^3/h (model PX-Q300)	[6]
Head of HPP	60 – 85 bar	Model 125-10.1. [7]
Flow of HPP	160 – 400 m^3/h	Model 125-10.1 [7]

Technical limitations and associated maintenance implications are linked to the following potential troubles:

- Scaling under high recovery operation in membrane modules placed in the last position of the pressure vessels, where there is the highest salts concentration.
- Insufficient flux (flow per active membrane area, in $L/(m^2 \cdot h)$ under low feed flow operation; the minimum recommended flux is 12 $L/(m^2.h)$
- Insufficient product water quality / quantity under low pressure operation periods.
- Internal leakage from brine side to seawater side in the energy recovery devices.
- Lifetime reduction of RO membranes due to discontinuous operation.

In consequence, a close monitoring and control system must be implemented to prevent these risks.

An interesting control load regulation was implemented and tested in an on-grid 18 m^3/d SWRO unit to simulate different operation points under variable power supply [3], installed at the Pozo Izquierdo facilities of the Canary Islands Institute of Technology. The original unit was modified to operate with a double power consumption concept:

- Hydraulic modifications to operate with one or two pressure vessels
- Incorporation of a frequency converter in the high-pressure pump to operate with a range of pressure / flow values with three different operations modes:
  - Constant flow / variable pressure.
  - Constant pressure / variable flow.
  - Constant recovery / variable flow and pressure.

After the testing period, the ranges of variation of different parameters are summarized in Table 2.

Table 2. Experimental values under variable operation conditions (SWRO 18 m^3/day)

Parameter	Pressure Vessel No.1	Pressure Vessels No.2	Nominal value
Feed flow (m^3/h)	1 – 3	3.5 – 5.5	3.125
Operation pressure (bar)	40 - 56	42 - 51	64
Power consumption (kW)	2.4 – 6.8	6.0 - 10.2	6.3
High pressure pump efficiency (%)	48 – 68	72 – 75	75

1.2. *Power control regulation in wind system generation. The necessity of storing energy*

Wind generators include one motor per blade to modify the position accurately. This change in the angle of attack leads to a corresponding change in the power output, increasing or decreasing it accordingly with a wide range of regulation depending on the wind generator.

As this shift is not immediate, an intermediate element to transfer / recover the energy is required. For short power supply periods, flywheels, super capacitors and air-compressed are options to allow this process by consuming / supplying energy when there is excess / lack of wind power respectively. Thus, an instantaneous power balance is reached in very few seconds according to the necessities of the system.

On the other hand, some longer time backup systems are required to guarantee the operation of the RO plants under low wind moments (minutes / hours). New technology batteries (mainly NaS, flow system and Vanadium redox technologies) and hydrogen production are the recommended solutions [8].

The main features of these systems are indicated in Table 3:

Table 3. Summary of main characteristics of selected energy storage systems.

Energy Storage Technology	**Energy capacity** [9]	**Discharge Time** [9]	**Cost ($/kW)** [8]
Flywheel	0.1 – 60 MJ	1 – 30 s	300 – 25,000
Super Conducting Magnets	0.1 – 60 MJ	1 – 30 s	500 – 72,000
Hydrogen / Fuel Cell	50 – 8,000 kWh	0 – 500 h	15 - 725
Compressed Air	10 – 8,000 MWh	1 – 8 h	3 - 100
NaS Battery	up to 2,000 MWh	1 - 8 h	245 - 500

1.3. Background: Summary of experiences on off-grid wind powered RO systems

Not many real off-grid wind driven RO systems have been installed and operated. Nevertheless, a high-quality experience has been accumulated; Table 4 summarizes a selection of the tested units.

Table 4. Summary of main data of a selection of wind / SWRO tested systems

Nominal capacity (m^3/d)	**Wind power (kW)**	**Regulation in generation**	**Regulation in load**	**Location/ Year of installation**	**Ref.**
65	225 wind + 105 (diesel engine)	Dumping load	Inexistent	Punta Jandía - Fuerteventura Island (Spain). 1994	[1]
8 x 25	2 x 230	Pitch control	Disconnection of one or more units	Pozo Izquierdo - Gran Canaria Island (Spain) 1999	[2]
60 - 900	500 (wind diesel + batteries + flywheel)		Disconnection of one or more units	Syros island, Greece / 1998	[10]

Concerning the plant operation, the practical experience has allowed to identify the modifications in the parameters due to the variability of the power supply. Two examples are presented:

- According to the data plotted and commented in Carta et al [2], a no-wind brief period (about 10 minutes) leaded to a fast reduction in the grid frequency (52 to 48.5 Hz) since the flywheel speed had to supply the demanded energy. The associated variations were detected in the feed pressure (61 to 58.5 bar), in the product conductivity (910 to 970 μS/cm) and the product flow (980 to 890 L/h).
- Other results were obtained in the tests presented in Tzen [10]; the variable power operation conditions during a 15-minute low wind period (off-grid frequency shifted

from 51.7 to 49 Hz) indicate relevant changes that took place in the main operation parameters: Respective reductions of 3 % in the water quality; 9% in the water production and 4% in the feed pressure to membranes.

As expected, less power supply implies less operation pressure, and consequently, less production at lower quality.

At theoretical level, a techno-economic study was carried out within the TECOAGUA project, a R&D multi-partner Spanish initiative focused on the use of sustainable technologies in the water cycle [11] [12]. The study analyzed the operation of a wind powered SWRO plant to cover a water demand of 5,000 m^3/d under 8 m/s of annual average wind speed. Three options of wind generation (wind farm & synchronous machine, wind farm & batteries, wind farm & diesel generators) coupled to a multi-modular SWRO plant (12 units of 550 m^3/d each), including a water storage tank, were modeled and simulated. An estimated cost of 2.3 € / m^3 was concluded.

On the other hand, a thorough analysis was already made in 2011 to compare the performance of two SWRO concepts: a 1,000 m^3/d unit operating in nominal point or as a modular plant; this chapter is inspired in that analysis [13].

2. Description of the wind powered medium scale SWRO plant

2.1. Objective

The objective of this section is to present and describe the autonomous wind powered medium scale RO systems addressed to achieve an optimal operation according to the following goals:

- Technical aspects
    - Maximization of annual water production.
    - Maximization of annual operation time.
    - Minimization of energy storage capacity.
- Economic aspects
    - Minimization of water cost.

2.2. Generation system

Based on the experience of the SDAWES and TECOAGUA projects, the proposed generation system is represented in Figure 1. The basic operation process is the following:

- As soon as wind speed is high enough, power generation from the wind machine is supplied to the starting-up motor through the DC line; the movement is transmitted to the flywheel, which is accelerated progressively
- When the rotation speed is high enough to create the stand-alone electric grid, the wind turbine is stopped, and the synchronous machine, coupled to the flywheel, creates the grid; then the wind generator is restarted and output power is connected to the AC grid
- Power flows to the batteries system and then, from them to the loads by a bidirectional DC/AC converter and an isolation transformer (included to create a neutral line for the loads side and to protect the generation system).

The purpose of the flywheel is to store kinetic energy to maintain the grid frequency within the operation range (48 – 52 Hz); the frequency is modified by small but fast fluctuations of power: excess and lack of output power accelerates and decelerates the flywheel respectively.

The batteries storage system complements the generation system by providing a source of energy along low wind periods. The option of Sodium Sulphur batteries (NaS) has been selected due to the good performance as energy backup in off-grid wind power systems, [14]: long lifetime (15 years or 4,500 cycles), high efficiency (80-85%), suitable discharge time (4h), almost null daily self-discharge, high discharge depth (90%).

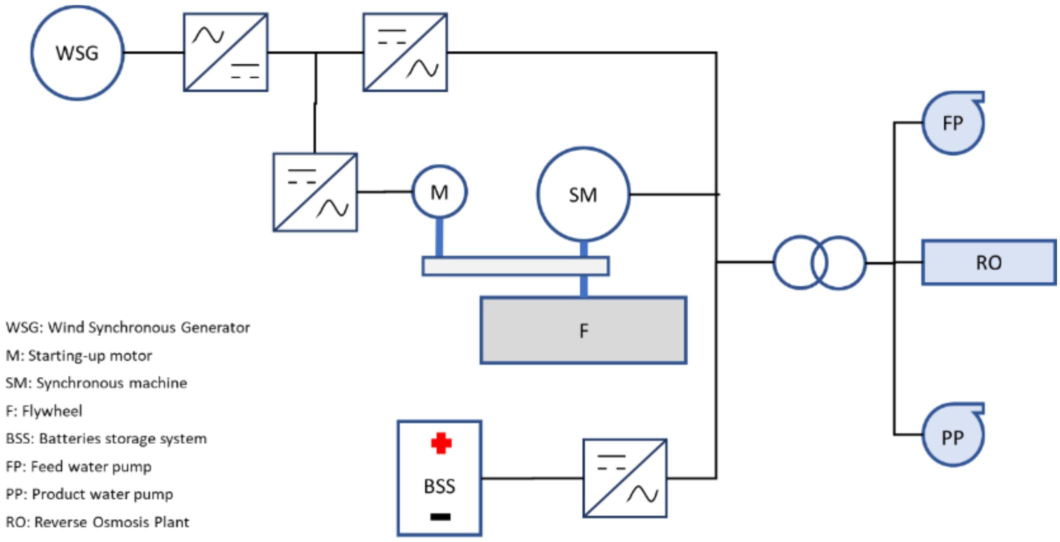

Figure 1. Basic electric diagram of the generation system and loads

2.3. *SWRO concepts*

The analysis has been made considering a reference case with the following main characteristics:

- Feed water type: seawater beach well located in Pozo Izquierdo, Gran Canaria Island (Spain). Salinity: 38 g/L of Total Dissolved Solids (TDS), and Silt Density Index (SDI) < 2.
- SWRO capacity: 5,000 m^3/d (208 m^3/h).
- Energy Recovery Device (ERD) based on pressure exchangers: Included; efficiency higher than 97%.
- Specific Energy Consumption (SEC):
    - Feed water pumping (at 5 bar, pump efficiency: 50%, recovery ratio – ratio of product to feed water flows -: 43%) and auxiliary equipment: 0.7 kWh/m^3.
    - RO rack power demand: 1.7 – 1.8 kWh/m^3 (depending on the efficiency of the ERD and high-pressure pump).
    - Product water pumping (at 5 bar, pump efficiency: 50%) to storage: 0.3 kWh/m^3.
    - Total SEC: 2.7 – 2.8 kWh/m^3
- Standard seawater pre-treatment and desalted water post-treatment energy requirement are included in the previous ranges.
- Wind data location: wind tower with sensors at 4 heights, in Pozo Izquierdo (UTM: X: 458361 Y:3077058), Gran Canaria Island (Spain). Annual average: 9.04 m/s at 40 m, and

9.6 at 60 m [15].

- Selection of wind turbine: model ENERCON E44, with nominal power output of 900 kW for a high wind location (IEC Class IA), and model E53 (800 kW, IEC/NVN Class S) for a medium-low wind conditions. The power curve and technical data are taken from reference [16] and presented in Annex A.

The configurations that have been analyzed are the following:

- Case 0 (Reference case): RO unit operating always at its nominal power and flow point
- Case 1 (Variable flow point): Use of high-pressure pump at variable power demand (66% - 100%)
- Case 2 (Modular plant): a RO plant with consisting of a set of 3 units: 2 x 1,250 + 1 x 2,500 m^3/d to operate at 25 % - 50 % - 75 % and 100% of the nominal capacity. This configuration allows a wide flexibility and a better adaptation to low wind periods.

Figure 2 illustrates the basic diagrams of the different RO configurations associated to each case.

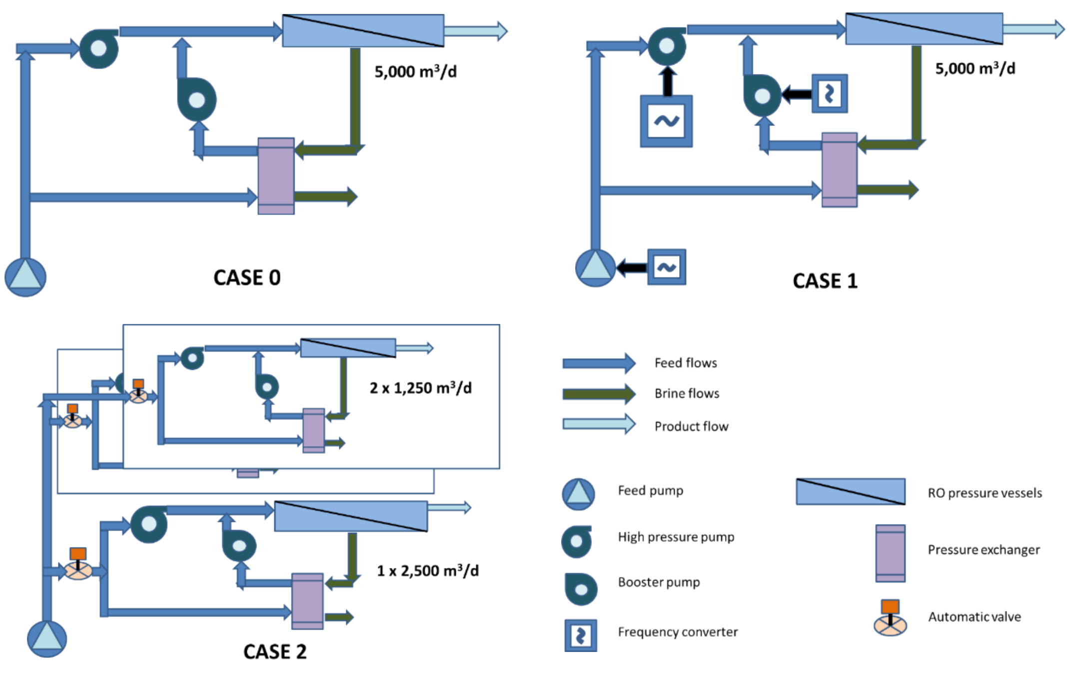

Figure 2. Basic hydraulic diagrams of the RO configurations or cases

3. Calculation procedure

3.1. General concept

For each case, the software FILMTEC ROSA [17] was used to identify the main operation parameters of the RO plant (power demand, Specific Energy Consumption (SEC), foreseen product salinity and recovery ratio) and their possible variations along the operation range without malfunction warnings. The configuration to minimize the SEC, avoiding too low transmembrane flux, is a 48 pressure vessels rack with 7 elements per tube for the cases 0 and 1; the modular option (case 2) has a different number of vessels according to the respective water production of the SWRO modules (See Table 7).

From the wind turbine specifications, a power balance model will be used to calculate the operation time of the RO plant and the associated annual water production along one year. The picture of Figure 3 shows an example of the energy flows, including the estimated lost energy in each element of the system.

Considering the criteria of maximum production and minimum water cost the model estimate the optimal back-up energy size. From these results, the associated costs are calculated for the economic comparison.

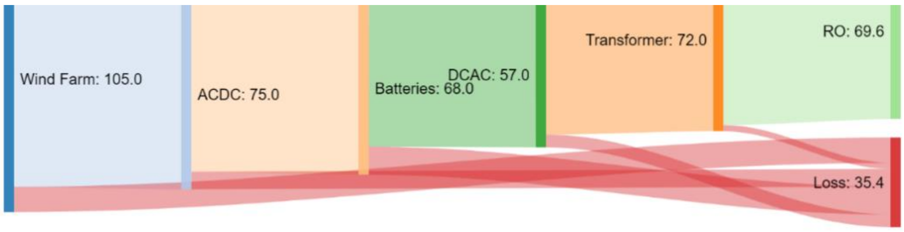

Figure 3. Example of the energy flows through the main elements of the system.

3.2. SWRO demanded power

Power demand in RO plant is calculated from this expression:

$$P_{W,RO} = SEC \cdot Q \qquad \text{(Eq 1)}$$

Where:

- $P_{W,RO}$: Power demanded by the RO desalination plant
- SEC: obtained from ROSA simulations, which is different in each case, variable for case 1, due to the modification of the operation point of the high-pressure pump (head and flow)
- Q: Product flow, variable for cases 1 and 2.

3.3. SWRO performance (Cases 0 and 1)

The operation under the nominal conditions leads to a reduction in the power demand. This modification is possible by driving the HPP with a frequency converter to reduce the rotation speed of the pump, and consequently the flow, affecting the head and, thus, the instantaneous power demand. Nonetheless, the head can be maintained by modifying the position of the rejected flow valve, achieving a linear relation between speed and power.

The main operation parameters of the cases 0 (reference) and 1 are presented in Table 5.

Table 5. Results obtained for the main operation parameters of SWRO plant (Cases 0 and 1)

Type of operation	**Production [m³/h]**	**Total power demand [kW]**	**SEC [kWh/m³] (RO + pumping)**	**Pressure [bar]**	**Recovery**	**Number of pressure vessels**	**Average Flux [L/m².h]**	**Product salinity [mg/L]**
Constant power (Case 0)	208	547	1.8 + 0.8	53.3	43%	48	15.17	374

Variable power (Case 1)	139 - 208	346 - 547	1.7 – 1.8 + 0.8	49.5 – 53.3	43%	48	10.11 – 15.17	374 - 556

For the case 1, a linear equation is used to calculate the flow (Q) of water produced for each value of consumed power (W):

$$Q = a \cdot W + b \qquad \text{(Eq. 2)}$$

Where a = 1/3 and b = 13.9

3.4. SWRO performance (Case 2)

This case is the most relevant since presents a different RO operational concept, consisting on a modular plant of 3 units, installed to operate at different capacities. Table 6 shows the main operation parameters for the different combinations calculated from ROSA software.

Table 6. Calculated main operation parameters in modular operation (case 2).

Combination of modules	**Production [m³/d]**	**RO Power demand (HPP + Booster) [kW]**	**Total Power Demand (RO + feed pump) (kW)**	**SEC [kWh/m³] (RO + pumping)**	**Number of pressure vessels**	**Energy Recovery Device [m³/h]**	**Product salinity [mg/L]**
1 x 1,250	1,250	96.3 + 6.8	137	1.8 + 0.8	12	2 x PX180 (72 m³/h)	374
1 x 2,500	2,500	193 + 13.5	273	1.8 + 0.8	24	4 x PX180 (145 m³/h)	374
1 x 2,500 + 1 x 1,250	3,750	289.3 + 20.3	410	1.8 + 0.8	36	6 x PX180 (216 m³/h)	374
1 x 2,500 + 2 x 1,250	5,000	386 + 27	547	1.8 + 0.8	48	8 x PX180 (290 m³/h)	374

3.5. Wind speed correction

As wind speed varies with height and wind data is taken at a different vertical position than the hub, a correction has been made. There are several models to estimate wind profile, the simplest way has been selected [18].

$$V_h / V_{ref} = (H_h / H_{ref})^k \qquad \text{(Eq 3)}$$

Where:

- V_h: Wind speed at the hub height
- V_{ref}: Wind speed at the reference height (raw wind data).
- H_h: Heght at the hub (55 m)
- H_{ref}: Height at the reference height (where wind speed data is taken) (10 m)
- k: parameter to consider the soil roughness.

Value of "k" varies according to the type of ground (Table 7).

Table 7. Values of "k" parameter depending on the type of ground

Landscape type	**Friction coefficient α**
Lakes, ocean and smooth hard ground	0.1
Grasslands (ground level)	0.15
Tall crops, hedges and shrubs	0.2
Heavily forested land	0.25
Small town with some trees and shrubs	0.3
City areas with high rise buildings	0.4

The place selected (Pozo Izquierdo, Gran Canaria Island, Spain), is a flat coastal windy area with very few vegetation; average value of "k" varies from 0.116 to 0.149 and usually selected value is 1/7 (0.142).

3.6. Energy balance and power flow

This subsection describes the calculation procedure of power production. As the sample time is one hour, energy (calculated in kWh) and power (calculated in kW) have the same values. Thus, there is a constant power flow (produced, consumed or lost) of N kW along one hour, which is the same than an energy flow of N kWh produced, consumed or lost in that hour; in other words, energy and power flows are equal.

Power flows from the wind generator to the batteries through a DC/AC bidirectional converter, and as soon as there is enough available stored energy, from batteries to the RO plant, through the converter and the isolation transformer (See Figure 3). Power losses are produced in each conversion and calculated according to the efficiencies considered in Table 8.

Table 8. Efficiencies considered in the generation system

Component	**Energy efficiency**
Transformer	98%
Bidirectional converter	90% · 90%
NaS Batteries	85%

Total system	67.4%

Power curve of the wind generator is estimated by a proposed equation (See Annex A), and calculated from the wind speed at the hub (See Eq. 3)

Given the simplicity of the calculations, the complete process is explained in the diagram of Figure 5. The moment of the connection of the SWRO plant is different for each case, depending on the minimum available power required to connect the desalination plant, which is minimum for the modular option and maximum, for the plant operating at the nominal point.

Complementary technical information is given in Annex C.

When RO plant is running, a water production counter is activated to calculate the total water production along one year. The decision of starting-up the RO unit has been made considering two strategies:

i) Anytime when there is enough energy in the storage system
ii) Only when a minimum operation time of 8 hours is guaranteed, to avoid situations of frequent start/stop cycles, and the associated damages in membranes. In this case, the annual operation time is shorter but estimates a more real situation (only for the reference Case)

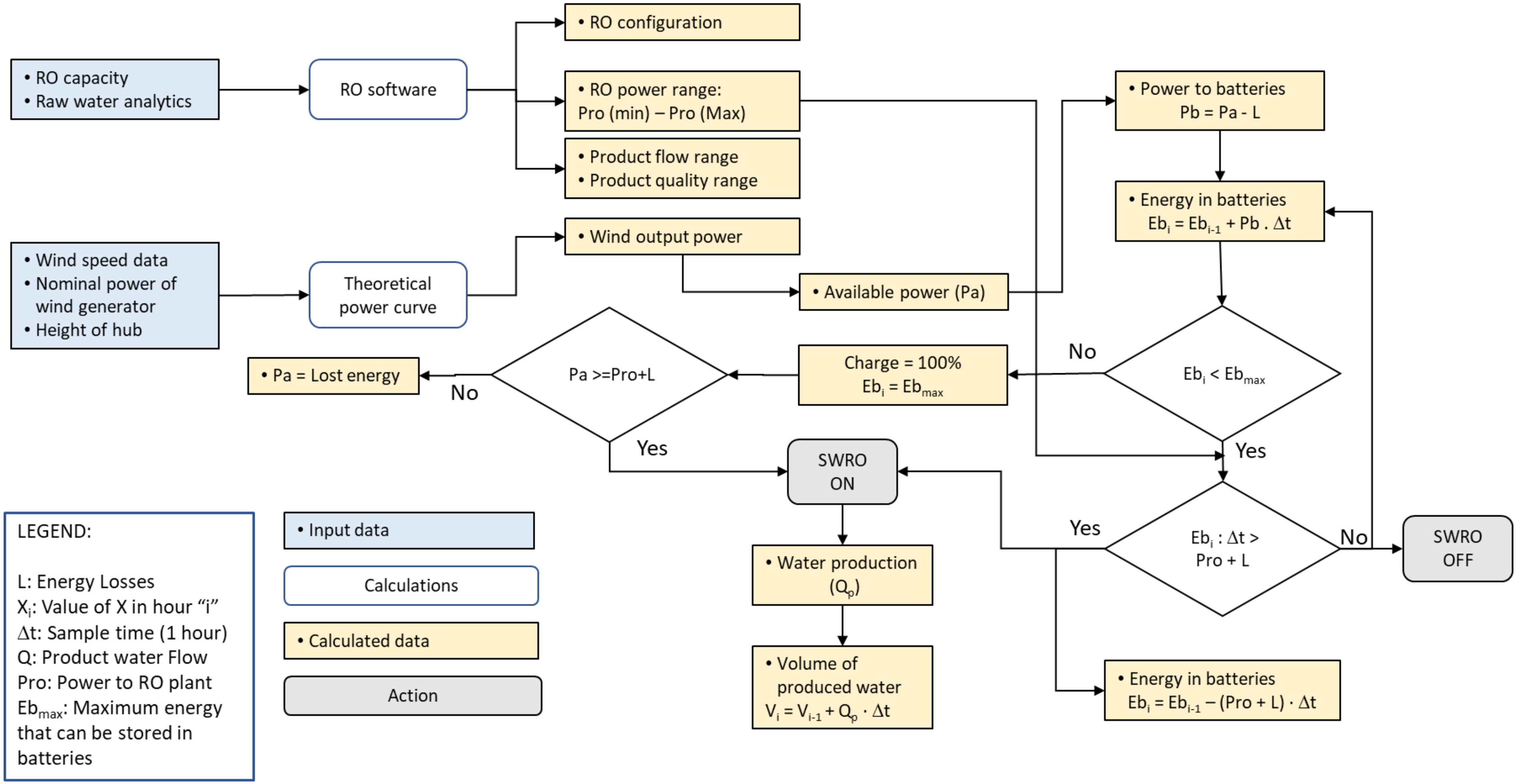

Figure 4. Flow diagram indicating the calculations

3.7. Economic considerations

For the economic calculations, the following assumptions have been considered:

- Specific costs of equipment estimated according to conventional values. The additional cost associated to the stand- alone system (synchronous machine, flywheel and isolation transformer) is about 10% of wind generator CAPEX [12], and are included in the wind power cost (See Table 9).
- Interest rate: 2%.
- Amortization cost: linear amortization along 15 years.
- Estimation of additional cost for RO investment in case 2 (modular plant): 35%.
- Currency equivalences: 1USD = 1 €

Table 9. Specific costs of equipment

Equipment	**Cost**	**Value used in the calculations**	**Reference**
Wind power	1,200 – 1,700 €/kW	1,700 €/kW	[19] [20]
Batteries	400 – 2,500 € / kWh	500 €/kWh	Average estimation from data collected in [8] and [14]
Specific cost of RO plant	729 – 1,250 € / (m^3/d)	875 €/(m^3/d)	[21] Range of average values depending on the location, [22] considering a conversion factor of 1.2 €/USD

The operation and maintenance costs for the wind generator and RO plant are presented in Table 10.

Table 10. Running costs values considered for the economic analysis

O&M costs of wind power	Fixed costs: 66 €/kW/yr ; Variable costs: 0.03 €/kWh (case of Germany, 2016). [23]
O&M costs of SWRO	33 c€/m^3 (estimated from [24], -case of on-grid conventional SWRO plants- but excluding amortization and electricity costs, and doubling the cost of the rest of items: labour, chemical products, membrane replacement and others, since the SWRO plant will operate with interruptions)
O&M costs of batteries and converter	Fixed costs: 1.96 €/kW/yr; Variable costs: 0.56 c€/kWh. [12]

4. Discussion of results

4.1. RO operation

From ROSA simulations, the best operation point (minimum energy demand at acceptable levels of flux) was identified for each case. The main operation parameters can be consulted in Tables 5 and 6.

The minimum power demand is for the case 1 (63 % of the nominal operation point), but it is associated to a worse water quality (49% increase in product flow salinity) and lower membrane flux (50 % less than the reference case), since pressure and feed flow have been reduced. The best combination quality and energy efficiency would be for case 1

4.2. Energy balance and water production

The energy balance for the different cases is illustrated in Table 11.

Table 11. Main results of energy balance along the year

Category	Case 0 Constant flow	Case 0 Non-stop in 8h	Case 1 Variable flow	Case 2 Modular plant
Generated energy (MWh), GE	3,689	3,689	3,689	3,689
Consumed energy (MWh), CE	2,617	1,558	2,630	2,674
Lost energy (MWh)	1,072	2,130	1,058	1,015
Energy Ratio (%) CE / GE	71%	42%	71%	72%
RO operation time (h)	4,462	2,720	4,820	6,037
Water production (m^3)	929,583	566,667	966,597	949,844

Considering the local wind at Pozo Izquierdo, the generated energy is quite high: the performance ratio (relation between energy production and installed power) is lightly over 4,400 kWh / kW.

Energy consumed in each case is very similar; the relevant differences are in the operation time along the year and the annual water production. The largest water production is for the Case 1, since the average specific energy consumption is lower than the other cases. The hours of operation per year is maximum for the Case 2, due to the widest range of power demand.

4.3. Wind and SWRO power evolution

As the graphic information is very extensive, this document collects the figures associated to the energy balance for every case. Despite the simulation considers an entire year, only a variable wind period (month of January) has been selected to illustrate the variation of power balance; the RO plant has a non-stop operation along the summer months.

Power from the wind generator (blue line) and power to the RO plant (red line) are plotted versus the time (one point per hour).

For all the cases, the chart of January illustrates a much higher number of starts and stops of the RO unit due to the fluctuations and interruptions of the wind power, while the case of July is practically a conventional operation along the month.

When the RO plant is connected only when a minimum period (8 hours) of available power is guaranteed, the number of starts and stops is radically reduced, particularly for the month of January (see Figures 5 and 6). However, the consumed energy is reduced to 1,558 MWh, and the annual water production and the operation time decreases to 60 % of the values of the reference case; the total energy lost reaches more than 2,000 MWh (58 % of the generated energy); more details in Table 11.

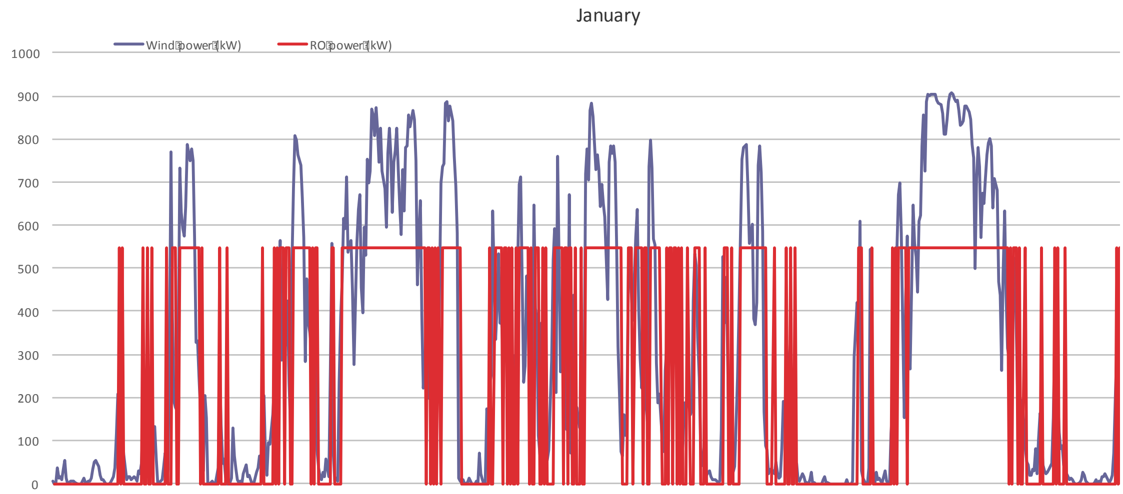

Figure 5. Power evolution in January for the Case 0 – Reference Case- (option of discontinuous operation)

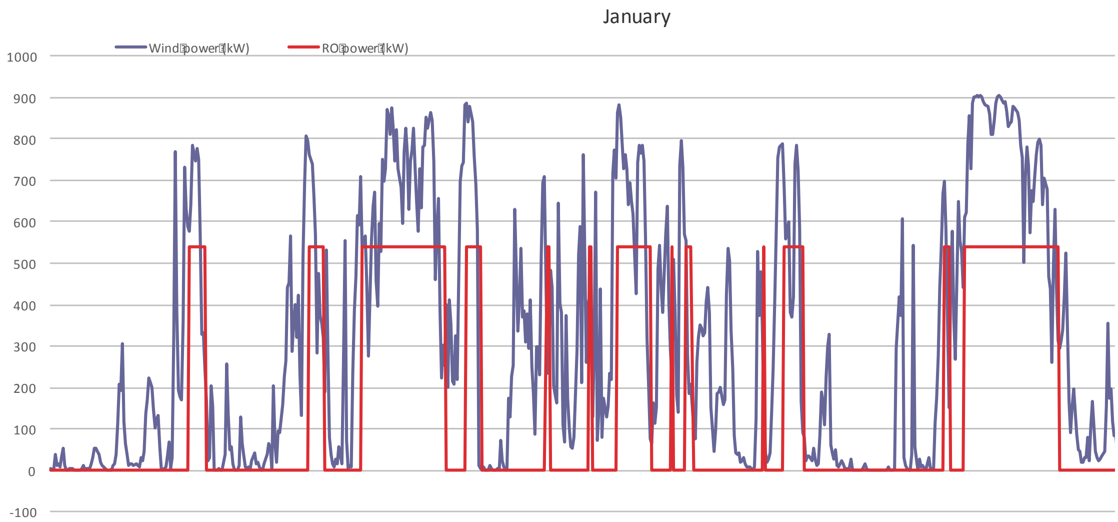

Figure 6. Power evolution in January for the Case 0 – Reference Case- (operation under a minimum time of 8 hours)

The operation points of Case 1 can be appreciated in Figure 7, especially in the low wind month; this fact allows a higher number of operation hours.

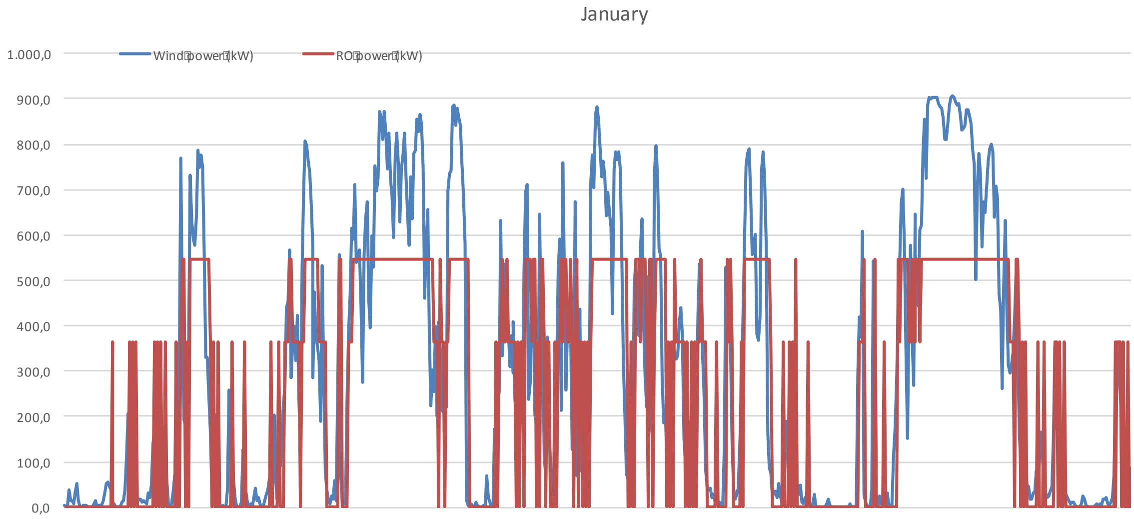

Figure 7. Power evolution in January for the Case 1 – variable operation of high-pressure pump- (option of discontinuous operation

Finally, Figure 8 illustrates the power balance for Case 2 as follows. The moments of connection of the different RO modules can be observed in several occasions in January. As wind speed is higher in July, this stepped connection of loads is practically inexistent, i.e., RO plant operates at 100 % of power along almost the whole period, except some hours at the end of the month.

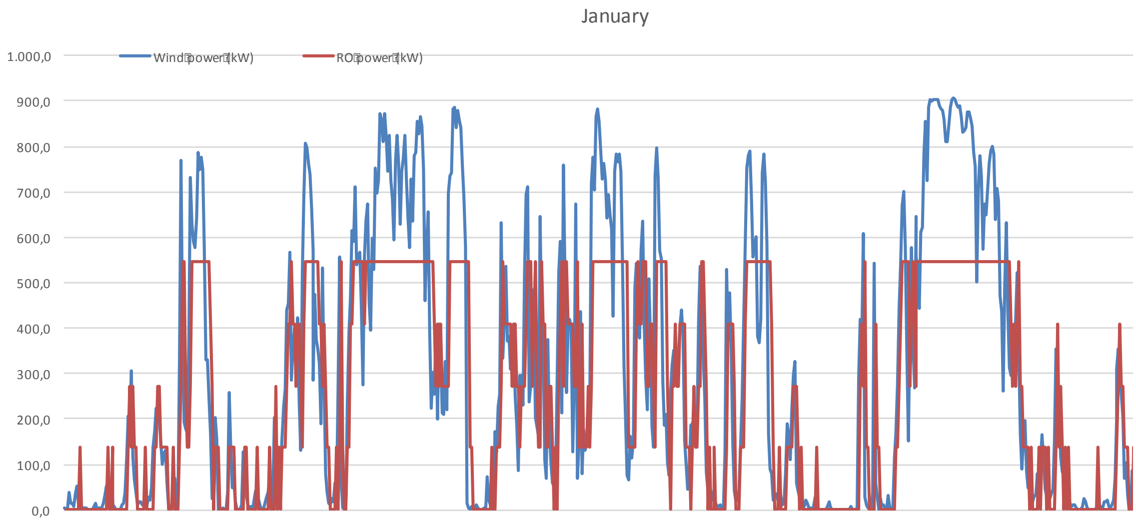

Figure 8. Power evolution in January for the Case 2 (modular SWRO plant)

4.4. Costs

Main output values for each case are presented in Table 12, where all the cases are compared respect the reference (Case 0).

Table 12. Investment and water cost

Variable	unit	Case 0	Case 1	Case 2
Investment	€	9,183,111 €	9,401,861 €	10,714,361 €
Water cost	€ / m^3	1.30 €	1.28 €	1.40 €

Water cost is particularly relevant in the case 2, for the consideration that a modular plant requires a higher investment.

4.5. *Case of medium-low wind speed location*

The results of the simulations are quite attractive in terms of energy and water balances and concerning the water costs thanks to the favorable wind conditions of the selected location. In this section, a summary of the technical and economic results is presented to consider the situation of a hypothetical low-wind place, wherein the profile of wind speed is obtained by modifying the available wind speed data using a reduction factor of 0.7 and updating the wind power curve to the model ENERCON E53, which is more appropriate for medium-low wind speed (IEC/NVN Class S).

Table 13 summarizes the main technical and economic outputs of the calculations.

Table 13. Summary of results for the case of low wind location

Category	Case 0 Constant flow	Case 1 Variable flow	Case 2 Modular plant
Generated energy (MWh), GE	2,192	2,192	2,192
Consumed energy (MWh), CE	1,618	1,618	1,618
Energy ratio (%), CE / GE	74%	74%	74%
RO operation time (h)	2,758	3,451	5,076
Produced water (m^3)	574,583	588,380	574,688
Water cost (€/m^3) & increment vs. Pozo Izquierdo location	1.77 (36%)	1.62 (26%)	1.98 (41%)

When these results are compared with those obtained under the real wind conditions (Table 11), wind energy is reduced in 41 % and water production decreases more than 30%. Concerning the water costs, the increment is 36 % for the Case 0, 27% (Case 1) and 43 % (Case 2) respect the high wind location.

5. Sensitivity Analysis

As complementary calculations, the reference case was considered to simulate the influence on the water cost of the nominal capacity of the RO unit and batteries. The associated assumptions were the following:

- Specific energy consumption remains constant.
- Specific investment costs remain constant.

5.1. Water cost variations

Figure 9 illustrates the chart of the water cost versus the nominal capacity of the RO plant for varied sizes of batteries (Reference case). Optimum size is in the range 4,000 – 6,000 m^3/d. Under these values, the capacity of the plant is too low and the annual production decreases, rising the water cost. For capacities higher than 6,000 m^3/d, the power demand increases, leading to less operation time, and then less total annual production and higher water cost.

For RO capacities over 5,000 m^3/d, water production decreases when the energy storage is reduced (3,000 – 4,000 Ah), leading to an increment of the water cost. Optimal combination of RO plant and batteries would be 5,000 m^3/d and 4,000 Ah respectively.

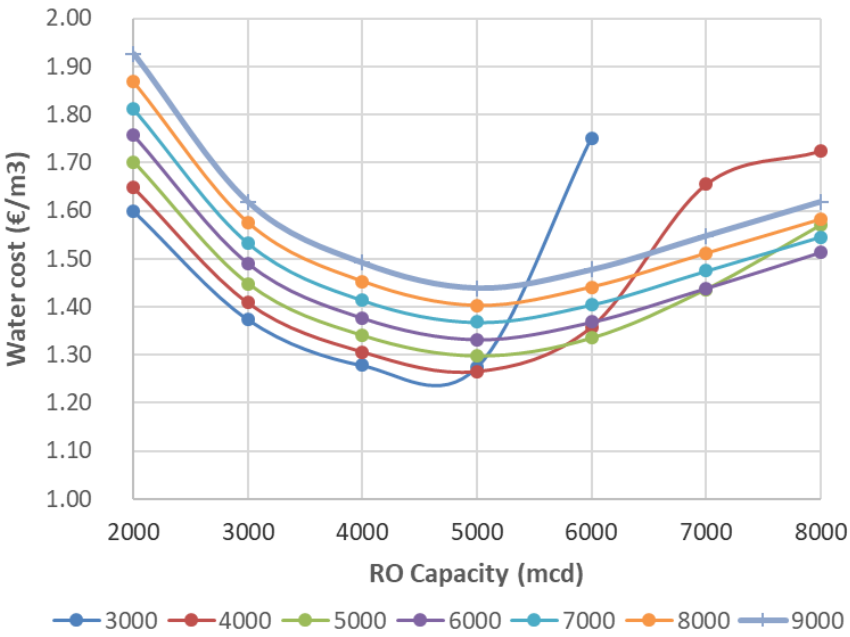

Figure 9. Chart of water cost versus RO capacities as a function of capacity of batteries (Ah) (Case 0)

The water cost for the cases 1 and 2 (variable operation point of the SWRO plant) is presented in the charts of Figure 10. In both cases it is possible to operate the SWRO plant with an energy storage of 2,000 Ah, whereas the reference case requires a minimum batteries capacity of 3,000 Ah. The left chart (Case 1) is quite similar to the reference case; however, the right chart (Case 2) shows higher values since an extra investment of 35 % has been considered for the modular SWRO plant. It is remarkable that for low values of batteries capacity, the reduction in the water production increases the water cost from a RO capacity of 8,000 m^3/d. In the modular case (right chart), the identification of the minimum water cost configuration is more specific; the increment of water cost for a nominal RO capacity out of the range 4,000 – 6,000 m^3/d is quite pronounced.

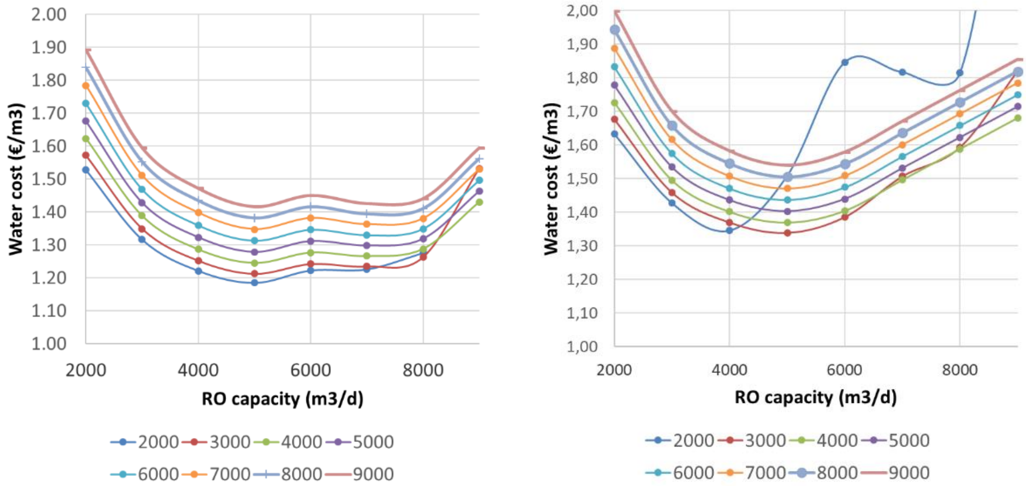

Figure 10. Water cost versus RO capacity for different energy storage sizes (in Ah): Case 1 in the left side, Case 2 in the right side.

5.2. *Annual operation time*

Figure 11 illustrates the operation time versus the nominal capacity of the RO plant for varied sizes of batteries (Reference case). When the RO capacity decreases, there is less power demand and, thus more time with available supply from the wind system. When the RO plant capacity increases, there is a point in which the operation time is reduced sharply. This reduction is delayed if large battery capacity is selected.

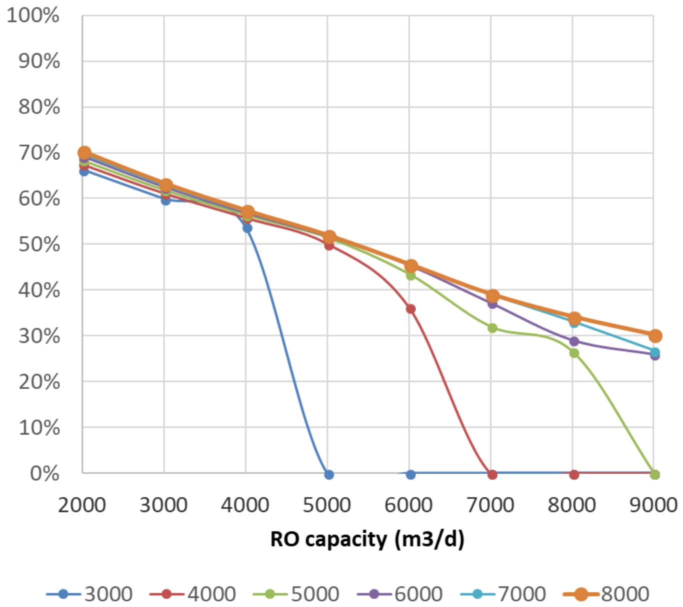

Figure 11. Reference case: Percentage of operation time versus the nominal capacity of the RO plant (m^3/d) for different capacities of batteries (Ah).

The influence of the size of desalination plant and energy storage system in the operation time has also been analyzed for the cases 1 and 2 (See Figure 12). It can be easily appreciated in comparison with the reference case that the operation time decreases for large RO capacities; it never is null. Case 2 represents the highest values of the operation time since the range of power demand is much lower.

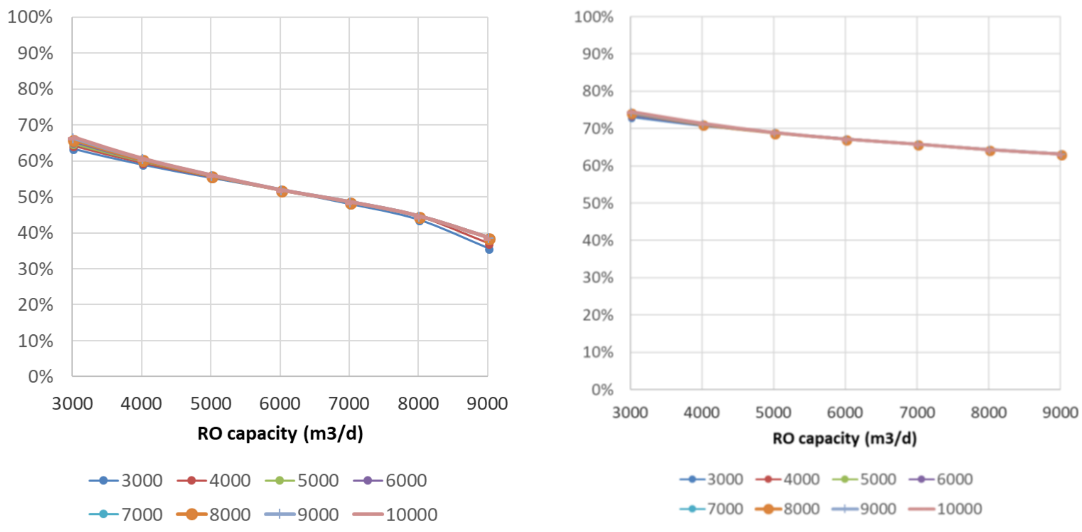

Figure 12. Annual operation time vs. RO capacity for different energy storage sizes (Ah) (Case 1 in the left side, Case 2 in the right side).

6. Conclusions

A year base wind powered SWRO plant model has been developed to find out the configuration option with minimum water cost. The model can be applicable to any wind powered SWRO system with a defined annual wind speed profile and power demand (variable or constant) since a high accuracy equation for the power curve has been proposed to calculate the output power of the wind generator. Besides that, energy losses in individual components were included in the model. Moreover, the power consumption of the SWRO plants of different cases was evaluated considering realistic performance models of commercial products.

For two wind conditions (high and medium) and two associated different wind generators (E44 - 900 kW and E53 – 800 kW respectively), three different options of the SWRO have been analyzed:

- Case 0 (Reference case): SWRO plant operating at nominal capacity: 5,000 m^3/d.
- Case 1: Use of high-pressure pump at 2/3 of its nominal capacity.
- Case2. Modular operation by several RO trains able to operate at 25 % - 50 % - 75 % and 100% of the nominal capacity.

Considering aforementioned wind turbines, the model can identify the best combination of batteries size and RO capacity for each case, leading to an estimation of the minimum water cost of 1.2 – 1.4 €/m^3, corresponding to a medium value of RO nominal capacity (4,000 – 6,000 m^3/d) and to a medium-low batteries size (2,000 – 4,000 Ah). For larger RO plants, the investment is higher, furthermore, the power demand increases, reducing the operation time, and thus, the annual water production. For smaller RO sizes, the operation time is longer, but the total production is not large enough to achieve a low water cost.

When the batteries capacity is reduced under 4,000 Ah, the operation time decreases, achieving null operation for the reference case; the variable operation of cases 1 and 2 allows more operation time for the different combinations of RO and batteries capacities.

For all the cases, water production is about one million of cubic meters per year but operation time (50% for the reference case) can be incremented by a variable operation of the RO plant: up to 55 % for the Case 1 and 69% in Case 2. Besides, consumed energy is 71% of generated energy; the total losses in the system are a little bit more than 1,000 MWh / yr.

Additional equipment included in the case 2 to obtain a better power balance (required extra installations for the RO modular operation) imply more investment, leading to a higher final cost than the reference case and similar water production, but a longer operation time. Consequently, according to this study, it is uneconomical the modular option but recommended to minimize the number of interruptions in the operation.

In addition, the recommended nominal capacity balances at Pozo Izquierdo (Gran Canaria Island) are as follows:

- Case 0: Nominal capacity of the wind turbine, 0.18 kW/(m^3/d) and nominal capacity of batteries, 0.80 Ah/(m^3/d).
- Case 1: Nominal capacity of the wind turbine, 0.18 kW/(m^3/d) and nominal capacity of batteries, 0.40 Ah/(m^3/d).
- Case 2: Nominal capacity of the wind turbine, 0.18 kW/(m^3/d) and nominal capacity of batteries, 0.60 Ah/(m^3/d).

Finally, a hypothetical location with less favorable wind resources was analyzed by considering a reduction factor of 0.7 applied to the wind speed profile of the first location. In this case, E53 wind turbine was considered, thus resulting a water cost range of 1.62-1.98 €/m^3. Also, case 2 (modular option) is the desalination plant configuration recommended despite the high associated water cost.

Acknowledgement

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ANNEX A. Calculations and complementary information

A.1. Simulation of the theoretical power curve of the wind generator

Considering:

- V: wind speed (m/s)
- P: nominal output power (kW).

A theoretical equation power curve has been obtained according to the following equations:

- When 3 m/s < V < 6 m/s, P(V) has been adjusted considering a four-grade polynomic function:

$$P(V) = aV^2 + bV + c \qquad \text{(Eq. A.1)}$$

  Where a, b, c, d, e are coefficients determined from the real power curve, using the values calculated by a spreadsheet.

- When V ≥ 6 m/s, P(V) has a very good approximation by using this equation:

$$P(V) = \frac{Pn}{(1+\frac{Pn}{Po}.\,e^{-rV})} \qquad \text{(Eq. A.2)}$$

  Where:

  - Pn: Nominal output power (kW)
  - r: coefficient determined from the real power curve, testing values to minimize the relative error.
  - Po: Output power at minimum wind speed (3 m/s)

A specific calculation has been made for the cases of the wind generator model E44 and E53 [15]. Table A.1 presents the parameters used for the estimation of the power curves, whereas Figure A.1 represents the values of output power given by the manufacturer and from the own calculations. The proposed equations allow a very good approximation for the E44 model (R^2 = 0.99998 for Eq A.1; R^2 = 0.9995 for Eq A.2), and 0.932; 0.98 for the E53 model respectively.

Table A.1. Values of parameters for power curve adjustment

Parameter	Values for E44 curve	Values for E53 curve	Unit
a	7	5.57	kW $(s/m)^2$
b	-33	-16.17	kW (s/m)
c	40	4.85	kW (s/m)
r	0,5528	0.57	s/m
Po	4	5	kW
Pn	900	800	kW

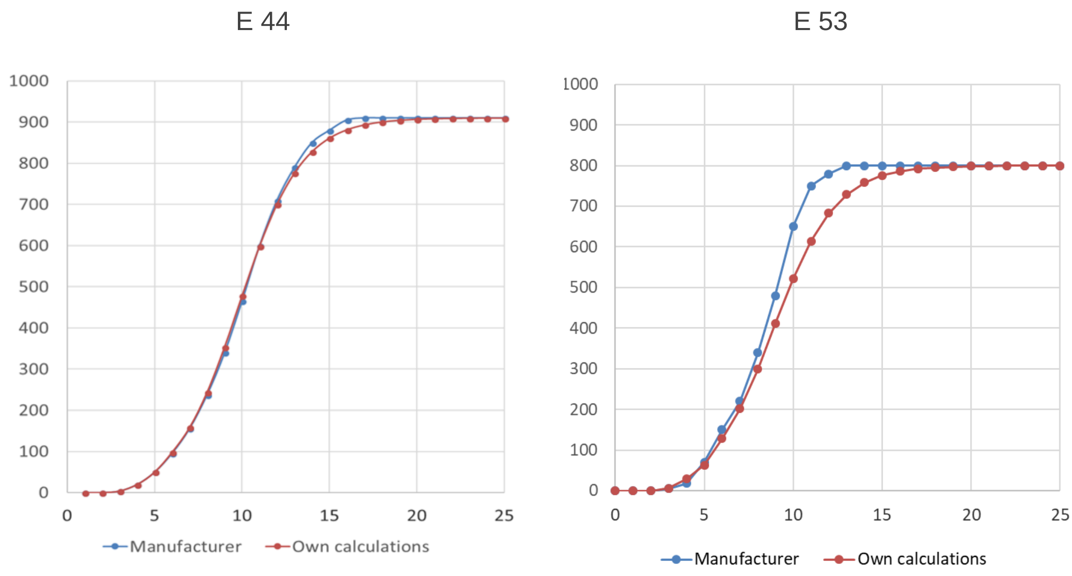

Figure 13. Chart and data of output power curves (real form the manufacturer, and estimated), in kW versus wind speed, in m/s

Equations A.1 and A.2 can be adapted easily for many other wind generators, by testing the values of the coefficients until reaching a good approximation to the theoretical values from the manufacturer.

A.2. Water cost

Water cost has been calculated according to following equations and technical data (Table A.2):

$$Zw = \frac{Cy}{P} \qquad \text{(Eq. A.3)}$$

$$C_y = C_{op} + C_{am} \qquad \text{(Eq. A.4)}$$

$$Cop = \sum z_{fi} \cdot X_i + \sum z_{vj} \cdot Y_j \qquad \text{(Eq. A.5)}$$

$$C_{am} = \frac{r\, I(1+r)^n}{(1+r)^{n-1}} \qquad \text{(Eq. A.6)}$$

Where:

- Zw: cost of water [€/m^3]
- Cy: Total annual cost [€ / y]
- P: Annual water production [m^3 / y]
- Cop: Operation & maintenance costs [€ / y]
- z_{fi}: ratios of fixed O&M costs
- X_i: Value of parameter associated to fixed O&M cost
- z_{vj}: ratios of variable O&M costs
- Yj: Value of parameter associated to variable O&M cost
- Cam: Amortization costs [€ / y]
- I: Total investment or capital expenses [€]

- r: Interest rate [-]
- n: amortization period [years]

Table A.2. Summary of complementary technical data.

Concept	Value	Unit	Observations
Batteries capacity (*)	2,000 – 9,000	Ah	Range of variation in the study
DC Voltage	450	VDC	
Bidirectional Converter power	1,100	kW	Nominal wind power / Converter efficiency
(*) A capacity of 2,000 Ah allows an operation of about 1 hour for the nominal power demand pf the RO plant			