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

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ABSTRACT

A technical and economic assessment of wind-powered seawater reverse osmosis (SWRO) systems is presented to identify the best combination of coupling between wind power and demanded power for a 5,000 m^3/d SWRO unit. Three situations have been studied: Reference or Case 0) SWRO plant operating at the nominal point all of the time; Case 1) SWRO plant operating with 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 at four different values of power consumption by means of configuring two units of 1,250 m^3/d and a unit of 2,500 m^3/d. Power and fresh water production are calculated through a year based on experimental data of wind availability with time steps of 1 h. A comparative techno-economic analysis is performed to identify the best configurations along with recommendations on nominal values of desalination capacity and battery capacity in relation to the nominal power of the wind turbine installed.

Keywords: Wind-powered desalination; Seawater desalination; Reverse osmosis; Design configurations; Water cost

1. Introduction

According to related technical reports and papers, autonomous wind-driven reverse osmosis (RO) desalination is possible but not economical, in comparison with conventional on-grid medium and large capacity seawater reverse osmosis (SWRO) plants. The main opportunities of reducing costs rely on selection of configurations 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 availability, should be developed.

Within this framework, this chapter deals with an assessment of the 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 unforeseeable) generation source. The fluctuating nature of wind leads to a set of technical factors 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. Machines normally stop when they are out of these extreme situations.

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

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- Generation > demand: Excess of wind 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, that is, cut-out speed range (mean value of 28 m/s or peak value of 34 m/s) the control system will cut out the generator.
- Demand > generation: In this case, the load must be reduced. Considering the SWRO plant consisting of several identical RO trains, these can be stopped one by one in a descending power step process [2]. Besides, when the RO trains are driven by frequency converters, it is possible for continuous load reduction [3]. Systems with such configurations are called gradual-capacity plants.

2. Gradual operation in RO: options and limitations

RO plants are designed to operate under a set of stable conditions, such as the feed water composition and flow, or the specific pressure to achieve the target values of product water output. 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 within certain flexibility (Table 1).

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

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

In consequence, a close monitoring and control system must be implemented to avoid 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 two different power consumptions:

- Hydraulic modifications to operate with one or two pressure vessels
- Incorporation of a frequency converter in the HPP to operate within a range of pressure/flow values with three different operating 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.

2.1. Power control regulation in wind system generation: the necessity of storing energy

Wind generators comprise 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 within 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-compression are options to allow for this process by consuming/supplying

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]

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

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

energy when there is excess/lack of wind power. Thus, an instantaneous power balance is reached in a 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 periods (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:

2.2. 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 deal of high-quality experience has been accumulated; Table 4 summarizes a selection of the tested units.

Concerning the plant operation, the practical experience has allowed as 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 min) led to a rapid reduction in the grid frequency (52–48.5 Hz) since the flywheel speed had to supply the demanded energy. The associated variations were detected in the feed pressure (61–58.5 bar), in the product conductivity (910–970 μS/cm) and the product flow (980–890 L/h).
- Other results were obtained in the tests presented in Tzen [10]; the variable power operation conditions during a 15 min low wind period (off-grid frequency shifted from 51.7 to 49 Hz) indicating 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 the theoretical level, a techno-economic study was carried out within the TECOAGUA project, an 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 and synchronous machine, wind farm and batteries, wind farm and 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 had already been carried out 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 paper is inspired by that analysis [13].

3. Description of the wind-powered medium-scale SWRO plant

3.1. 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.

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

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 × 25	2 × 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]

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

3.2. Generation system

Based on the experience of the SDAWES and TECOAGUA projects, the proposed generation system is represented in Fig. 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 motor through the DC line; the movement is transmitted to the flywheel, which is accelerated progressively.
- When the rotation speed is high enough to generate the stand-alone electric grid, the wind turbine is stopped, and the synchronous machine, coupled to the flywheel, generates the grid; then the wind generator is restarted and output power is connected to the AC grid.
- Power flows to the battery system and then, from that to the loads by a bidirectional DC/AC converter and an isolation transformer (included to generate 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 rapid fluctuations of power: excess and lack of output power accelerates and decelerates the flywheel, respectively.

The battery storage system complements the generation system by providing a source of energy during 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 year or 4,500 cycles), high efficiency (80%–85%), suitable discharge time (4 h), almost nil daily self-discharge, high discharge depth (90%).

3.3. SWRO concepts

The analysis has been made by 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, and silt density index < 2.
- SWRO capacity: 5,000 m^3/d (208 m^3/h).
- Energy recovery device (ERD) based on pressure exchangers: 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 HPP).
  - 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 permeate 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

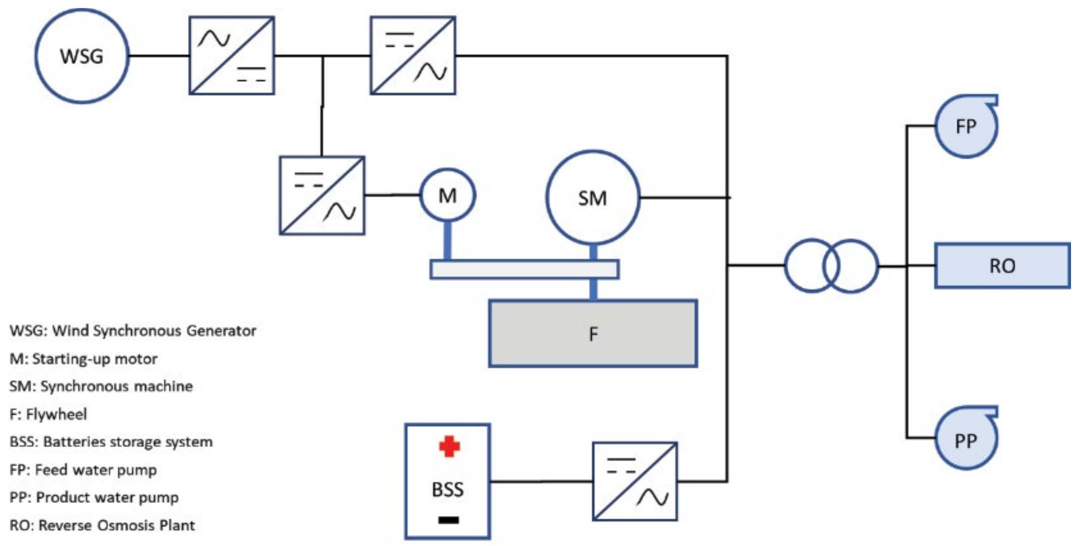

Fig. 1. Basic electric diagram of the generation system and loads.

- Case 1 (variable flow point): Use of HPP at variable power demand (66%–100%)
- Case 2 (Modular plant): an RO plant consisting of a set of 3 units: 2 × 1,250 m³/d + 1 × 2,500 m³/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.

Fig. 2 illustrates the basic diagrams of the different RO configurations associated with each case.

3.4. Calculation procedure

3.4.1. 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 throughout 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 (Table 7).

From the wind turbine specifications, a power balance model will be used to calculate the time in operation of the RO plant and the associated annual water production through 1 year. The picture in Fig. 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 estimates the optimal back-up energy size. From these results, the associated costs are calculated for the economic comparison.

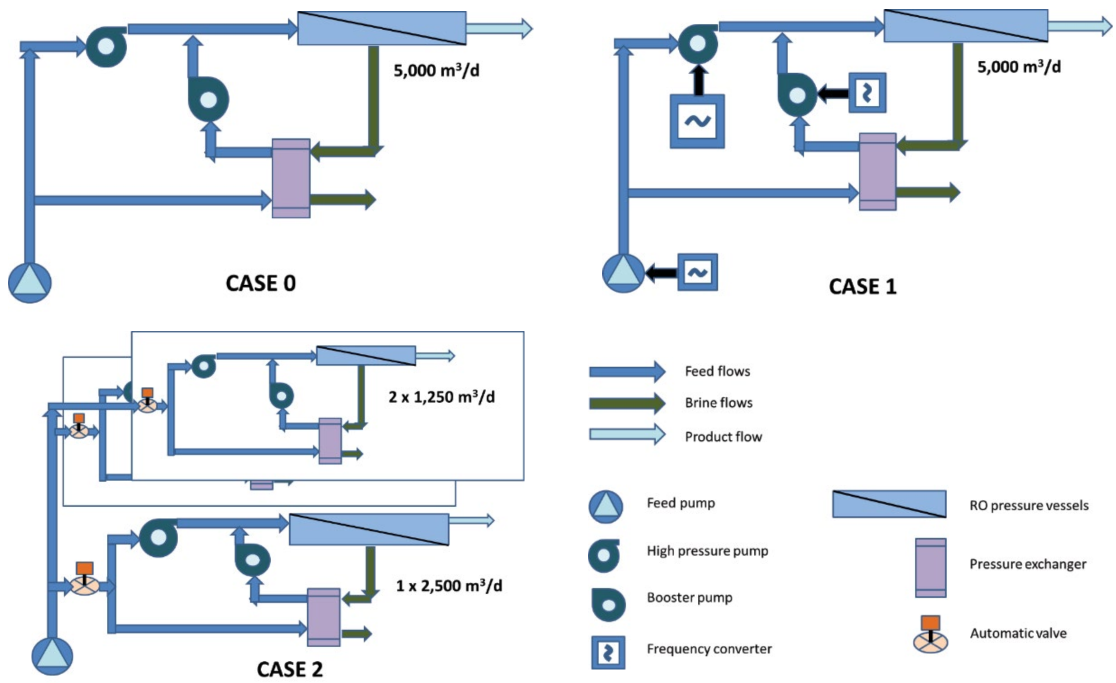

Fig. 2. Basic hydraulic diagrams of the RO configurations or cases.

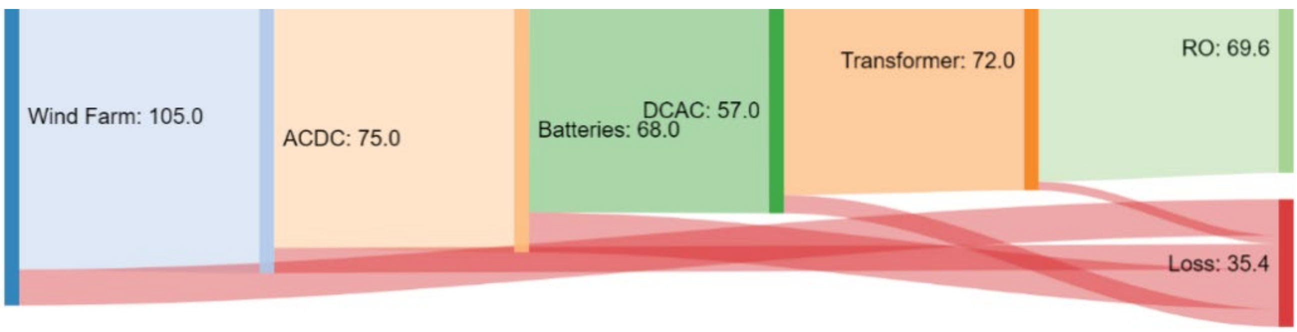

Fig. 3. Example of the energy flows through the main elements of the system.

3.4.2. SWRO demanded power

Power demand in RO plant is calculated from this expression:

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

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 HPP (head and flow); Q: Product flow, variable for cases 1 and 2.

3.4.3. 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.

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

$$Q = a\cdot W + b \quad (2)$$

where $a = 1/3$ and $b = 13.9$.

3.4.4. SWRO performance (case 2)

This case is the most relevant since it presents a different RO operational concept, consisting of 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.

3.4.5. Wind speed correction

As wind speed varies with altitude and wind data, they are 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].

$$\frac{V_h}{V_{\text{ref}}} = \left(\frac{H_h}{H_{\text{ref}}}\right)^k \quad (3)$$

where V_h: wind speed at the hub altitude; V_{ref}: wind speed at the reference altitude (raw wind data); H_h: altitude at the hub (55 m); H_{ref}: altitude at the reference altitude (where wind speed data are taken) (10 m); k: parameter to consider the soil roughness.

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

The place selected (Pozo Izquierdo, Gran Canaria Island, Spain) is a flat coastal windy area with very little vegetation;

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

Type of operation	Production (m^3/h)	Total power demand (kW)	SEC (kWh/m^3) (RO + pumping)	Pressure (bar)	Recovery	Number of pressure vessels	Average flux (L/m^2 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

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

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

average value of k varies from 0.116 to 0.149 and usually the selected value is 1/7 (0.142).

3.4.6. Energy balance and power flow

This subsection describes the calculation procedure of power production. As the sample time is 1 h, 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 throughout 1 h, which is the same as an energy flow of N kWh produced, consumed or lost in that hour; in other words, energy and power flows are equal.

Table 7
Values of k parameter depending on the type of the topography

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

Table 8
Efficiencies considered in the generation system

Component	Energy efficiency
Transformer	98%
Bidirectional converter	90%
NaS batteries	85%
Total system	67.4%

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 (Fig. 3). Power losses are produced in each conversion and calculated according to the efficiencies considered in Table 8.

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

Given the simplicity of the calculations, the complete process is explained in Fig. 4. 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 the RO plant is running, a water production counter is activated to calculate the total water production over 1 year. The decision of starting-up the RO unit has been made considering two strategies:

- Anytime when there is enough energy in the storage system
- Only when a minimum operation time of 8 h 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 realistic situation (only for the reference case).

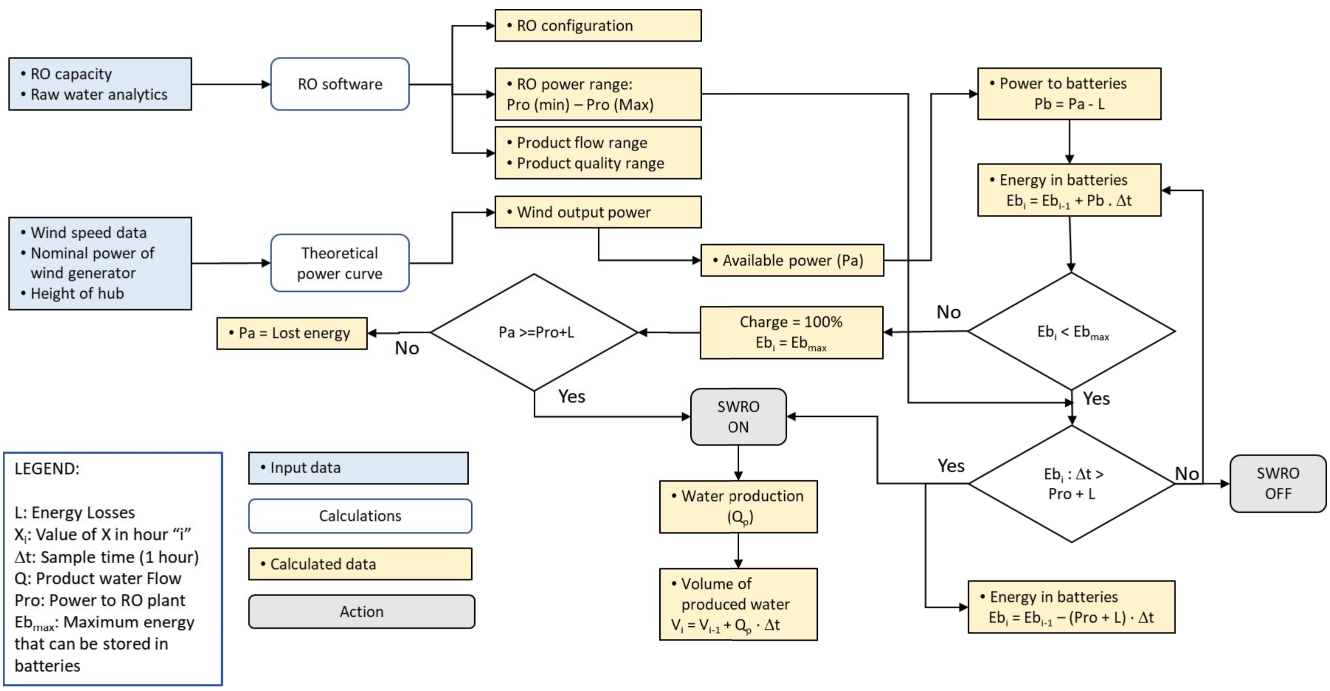

Fig. 4. Flow diagram indicating the calculations.

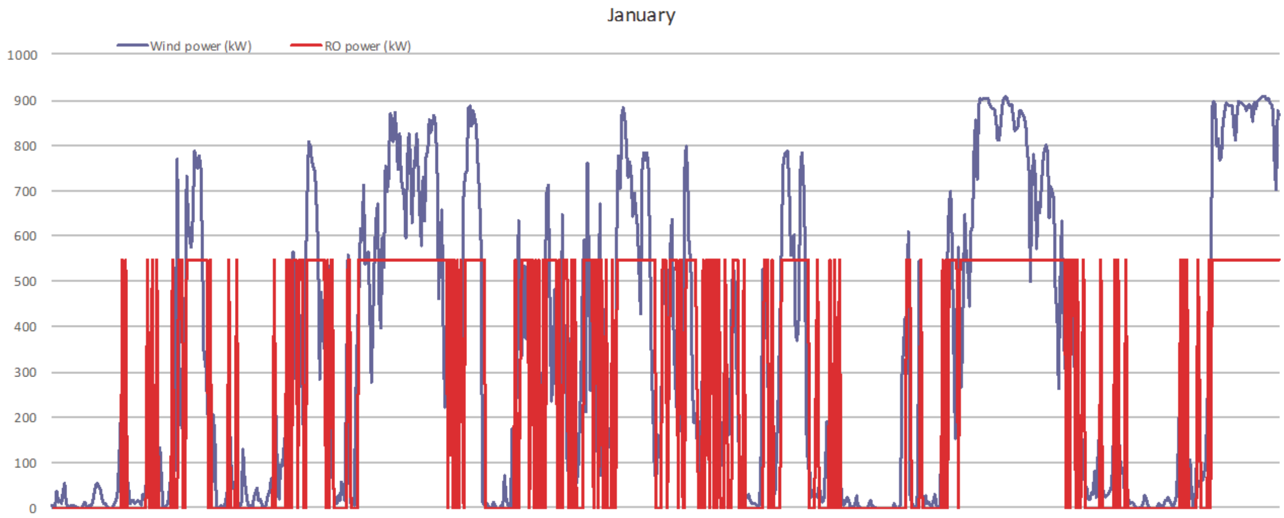

Fig. 5. Power evolution in January for the case 0 – reference case- (option of discontinuous operation).

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 the study by Beaudin et al. [8] and IRENA [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

Table 10
Running costs values considered for the economic analysis

O&M costs of wind power	Fixed costs: 66 €/kW/year; variable costs: 0.03 €/kWh (case of Germany, 2016) [23]
O&M costs of SWRO	33 c€/m^3 (estimated from the study by Bernat et al. [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/year; variable costs: 0.56 c€/kWh [12]

3.4.7. Economic considerations

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

- Specific costs of equipment estimated according to conventional values. The additional cost associated with 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 (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: 1 USD = 1 €

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

4. Discussion of results

4.1. RO operation

From ROSA simulations, the best operation point (minimum energy demand at acceptable levels of flux) was

Table 11
Main results of energy balance along the year

Category	Case 0 Constant flow	Case 0 Non-stop in 8 h	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

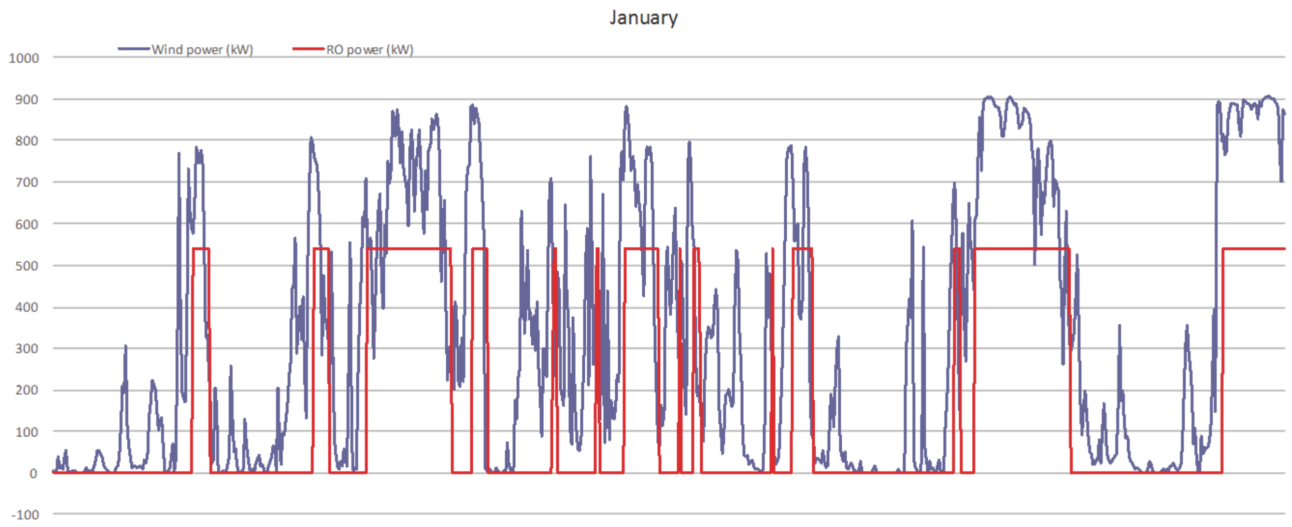

Fig. 6. Power evolution in Januaryfor the Case 0 – Reference Case- (operation under a minimum time of 8 h)

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 with 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.

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

Energy consumed in each case is very similar; the relevant differences are in the time in operation throughout the year and the annual water production. The largest water production is for case 1, since the average SEC is lower than the other cases. The hours in operation per year are maximum for 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 with the energy balance for each case. Despite the simulation considering 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 in the summer months.

Power from the wind generator (blue line) and power to the RO plant (red line) are plotted against 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 throughout the month.

When the RO plant is connected only if a minimum period (8 h) of available power is guaranteed, the number of starts and stops is radically reduced, particularly for the month of January (Figs. 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.

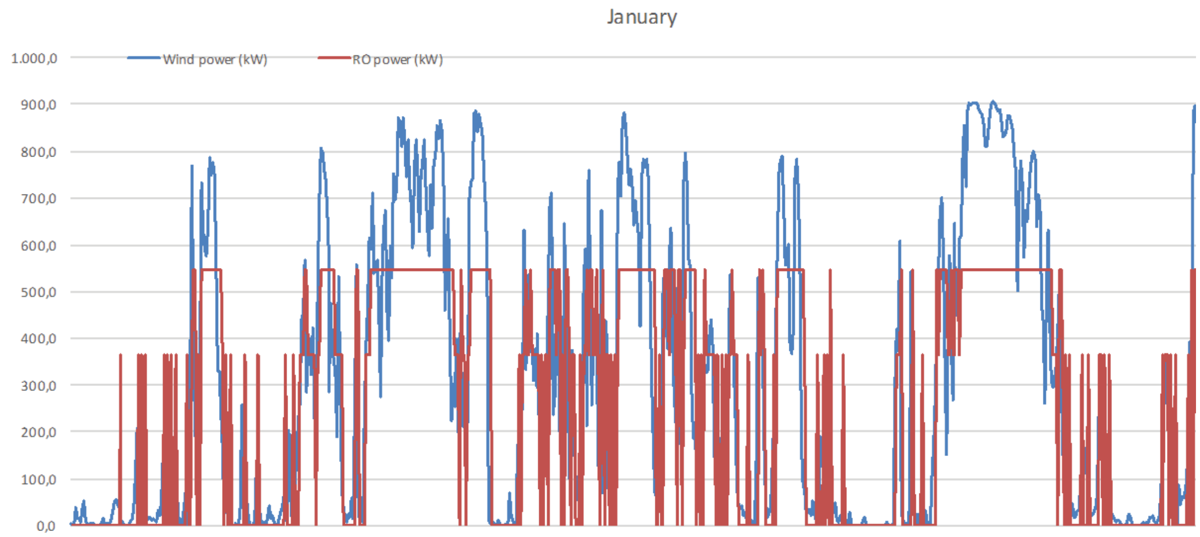

Fig. 7. Power evolution in January for the case 1 – variable operation of high-pressure pump- (option of discontinuous operation

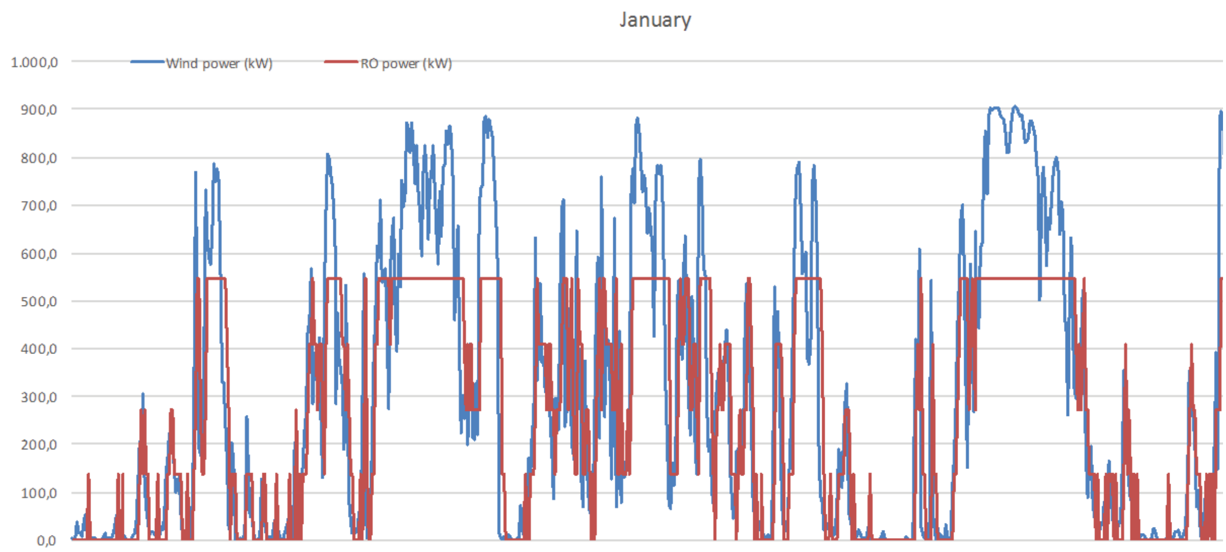

Fig. 8. Power evolution in January for the case 2 (modular SWRO plant).

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

Finally, Fig. 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 than in July, this stepped connection of loads is practically nonexistent, that is, RO plant operates at 100% of power in almost the whole period, except some hours at the end of the month.

4.4. Costs

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

Water cost is particularly relevant case 2, considering 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 due 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 location, 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.

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 by more than 30%. Concerning the water costs, the increment is 36% for Case 0, 27% (Case 1) and 43% (Case 2) in respect of the high wind location.

4.6. 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:

- SEC remains constant.
- Specific investment costs remain constant.

4.7. Water cost variations

Fig. 9 illustrates the chart of the water cost vs. 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, thus raising the water cost. For capacities higher than 6,000 m^3/d, the power demand increases, leading to less time in operation, and then less total annual production and therefore, 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.

The water cost for cases 1 and 2 (variable operation point of the SWRO plant) is presented in the charts of Fig. 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 water production reduction 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 outside the range 4,000–6,000 m^3/d is quite pronounced.

4.8. Annual time in operation

Fig. 11 illustrates the time in operation time against 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 at which the operation time is reduced sharply. This reduction is delayed if large battery capacity has been selected.

The influence of the size of desalination plant and energy storage system in the operation time has also been analyzed for cases 1 and 2 (Fig. 12). It can be easily appreciated in

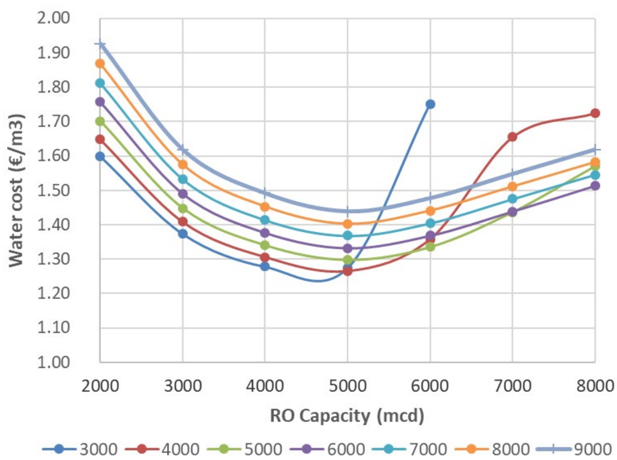

Fig. 9. Chart of water cost against RO capacities as a function of capacity of batteries (Ah) (Case 0).

Table 12
Investment and water cost

Variable	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

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) and increment vs. Pozo Izquierdo location	1.77 (36%)	1.62 (26%)	1.98 (41%)

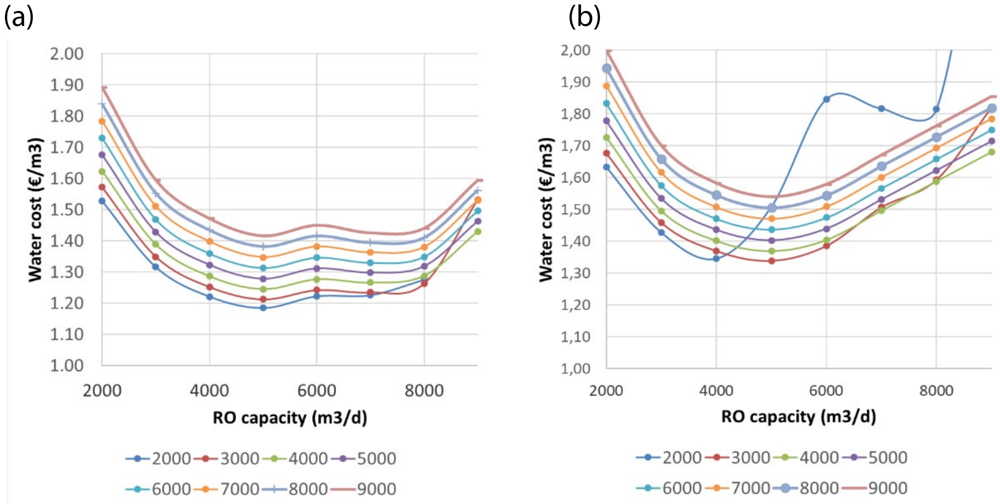

Fig. 10. Water cost vs. RO capacity for different energy storage sizes (in Ah): (a) Case 1, (b) Case 2.

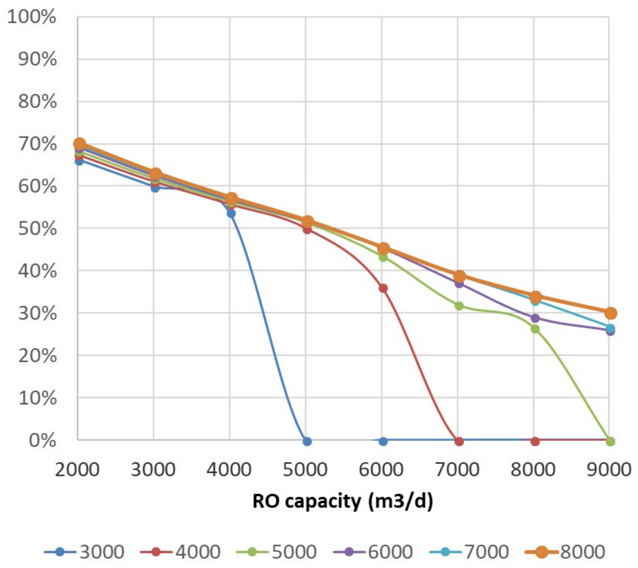

Fig. 11. Reference case: percentage of operation time vs. the nominal capacity of the RO plant (m^3/d) for different capacities of batteries (Ah).

comparison with the reference case that the time in operation decreases for large RO capacities; it never is nil. Case 2 represents the highest values of the operation time since the range of power demand is much lower.

5. Conclusions

A 1-year model of a wind-powered SWRO plant has been developed to determine 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. Also, energy losses in individual components were included in the model. Moreover, the power consumption of the SWRO plants in 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 HPP at 2/3 of its nominal capacity.
- Case 2: Modular operation by several RO trains was 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 battery size (2,000–4,000 Ah). For larger RO plants, the investment is higher, furthermore, the power demand increases, reducing the time in operation, and thus, the annual water production. For smaller RO sizes, the time in operation is longer, but the total production is not large enough to achieve a lower water cost.

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

For all the cases, water production is about 1 million cubic meters per year but operating time (50% for the reference case) can be incremented by a variable operation of the RO plant: up to 55% for 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/year.

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

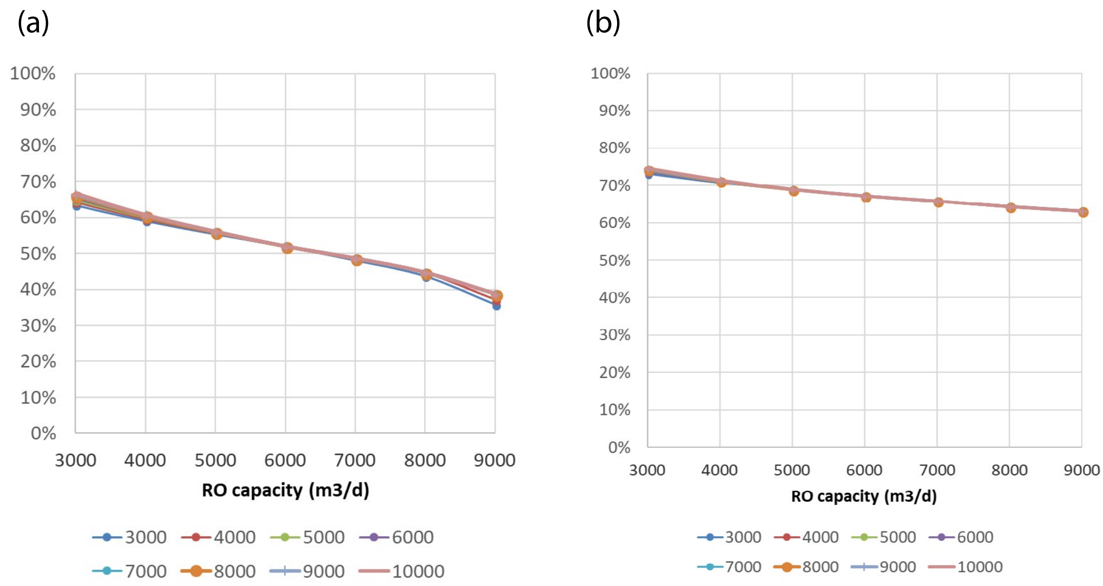

Fig. 12. Annual operation time vs. RO capacity for different energy storage sizes (Ah) ((a) Case 1, (b) Case 2).

higher final cost than the reference case and similar water production, but a longer operating time. Consequently, according to this study, the modular option is uneconomic but recommended to minimize the number of interruptions in the operation.

In addition, the nominal capacity balances recommended 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 availability 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 higher associated water cost.

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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:

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

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

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

$$P(V) = \frac{\text{Pn}}{\left(1 + \frac{\text{Pn}}{\text{Po}} \cdot e^{-rV}\right)} \tag{A.2}$$

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 Fig. 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.

Fig. A.1. Chart and data of output power curves (real form the manufacturer, and estimated), in kW vs. wind speed, in m/s.

Eqs. (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 the following equations and technical data (Table A.2):

$$\text{Zw} = \frac{\text{Cy}}{P} \tag{A.3}$$

$$Cy = \text{Cop} + C\text{am} \tag{A.4}$$

$$\text{Cop} = \sum z_{\text{fi}} \cdot X_i + \sum z_{\text{vj}} \cdot Y_j \tag{A.5}$$

Table A.1
Values of parameters for power curve adjustment

Parameter	Values for E44 curve	Values for E53 curve
a, kW (s/m)^2	7	5.57
b, kW (s/m)	–33	–16.17
c, kW (s/m)	40	4.85
r, s/m	0.5528	0.57
Po, kW	4	5
Pn, kW	900	800

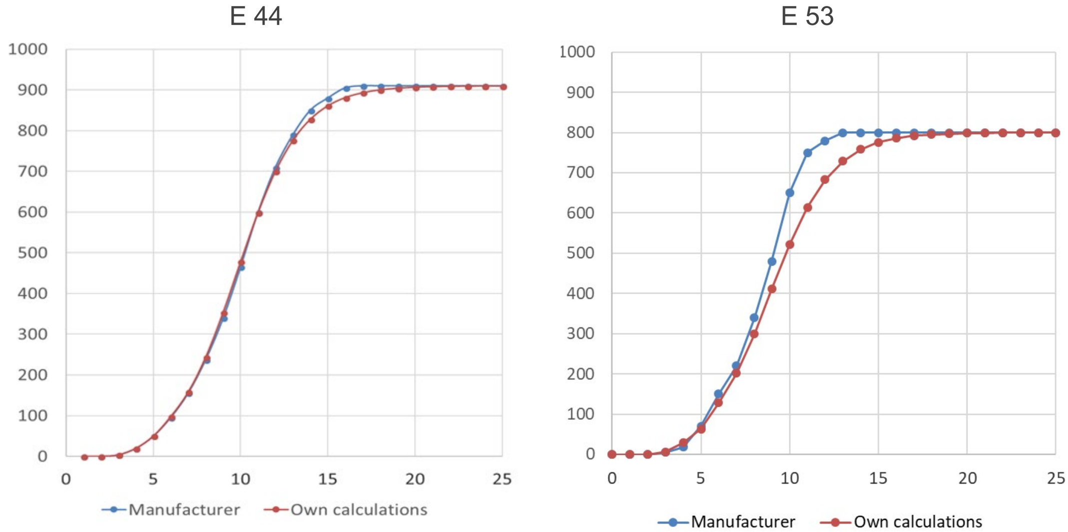

Fig. A.1. Chart and data of output power curves (real form the manufacturer, and estimated), in kW vs. wind speed, in m/s.

Table A.2
Summary of complementary technical data

Concept	Value	Observations
Batteries capacity[a], Ah	2,000–9,000	Range of variation in the study
DC voltage, *V*	450	
Bidirectional converter power, kW	1,100	Nominal wind power/converter efficiency

[a]A capacity of 2,000 Ah allows an operation of about 1 h for the nominal power demand of the RO plant.

$$\text{Cam} = \frac{r\,I\left(1+r\right)^{n}}{\left(1+r\right)^{n-1}} \tag{A.6}$$

where Zw: cost of water (€/m^3); Cy: total annual cost (€/y); *P*: annual water production (m^3/year); 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; Y_j: 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 (year).