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Design recommendations and cost assessment for non-stop off-grid plants of seawater desalination based on PV-driven with wind/diesel energy backup

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ABSTRACT

An off-grid multi-generation model (solar photovoltaic, wind power, and diesel) has been used to assess the performance of a low scale (up to 250 m^3/d) seawater reverse osmosis desalination plant with four different operating modes: fix, variable (180–250 m^3/d), modular-fix (100 + 150 m^3/d) and modular-variable operation (100 + 115–150 m^3/d). The high-pressure pump and energy recovery system have been selected for each case according to the flow requirements; reverse osmosis membrane simulations have been made to know the power demand, product water flow and quality for the whole operating range of each option. The use of real solar and wind data allows to preliminarily assess the performance of the system. A specific battery charge/discharge strategy has been considered to take maximum advantage of wind and solar available energies. The most relevant technical and economic results have been presented, finding out the pros and cons of the different analyzed cases. A sensitivity analysis complements the study to identify the key parameter values addressed to achieve a minimum water cost under 2.2 €/m^3. A new index is proposed to assess the performance of the whole system.

Keywords: PV powered desalination; Seawater reverse osmosis; Water cost; Off-grid multigeneration for 24/365 operation

1. Introduction

This paper deals with off-grid multigeneration (solar photovoltaic (PV) with wind and diesel energy backup) systems coupled to seawater reverse osmosis (SWRO) plants to increase market opportunities of PV-powered reverse osmosis (RO) systems. Not only the multigeneration system is analyzed but also the specific design of the SWRO desalination plant.

1.1. General background

The coupling of off-grid solar PV and RO is one of the most used and analyzed combinations of renewable energy (RE)-powered desalination combinations. It corresponds to about 30% of the total RE driven desalination units [1]. There are some reasons to explain this fact; on the one hand, the wide range of water production capacity of the RO process and its applicability to different raw water salinities, and on the other hand, the easy access and installation of the PV system.

This solar desalination combination has been selected to produce water in many locations (Middle East, North of Africa, Central America, India, Indonesia, North America, Australia, and South of Europe) [2–4]. The only required conditions are the availability of salty water and abundant solar radiation. PV-RO systems were installed and tested since the end of the 70's with capacities from 150 L/h up to

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2,100 L/h ([3]). Table 1 presents a selection of PVRO units in operation.

One of the weakest points of the PV/RO technology is the cost of produced water; there is a wide range of cost, depending on the salinity of the feed water and the capacity of the RO plant, among other variables. Water cost for operating systems commissioned after the year 2000 with a nominal water production over 1 m^3/d are 3.0–10.6 €/m^3 for the case of seawater, and 2.5–9.8 €/m^3 for the case of brackish waters [4]. A long time of testing and improving has been necessary to reach the current level of maturity and to identify the particularities of the control system for a stable operation [5]. Later, the high experience of this technology has made possible the water supply in remote locations along the last decades [1,3,6].

1.2. Basic operation concept

Solar radiation is converted into DC electricity in the PV panels, allowing different options of voltage and current outputs depending on the connection of the PV modules. This electricity can be stored in a battery rack through a charge controller to provide power along low radiation periods; nonetheless, and despite most of the installed systems include it, the incorporation of this backup system is optional, and there is some experience under this battery-less concept. Then DC power is converted to AC in an inverter to supply electricity to the RO plant. Fig. 1 presents a selection of pictures showing the different components of the system.

The stable operation for long periods or 24/365 - uninterruptedly along the full-year - operation requires the incorporation of additional energy sources, like wind energy and diesel generation along with batteries for energy storage.

1.3. Implications for RO operation

As already cited and presented in previous publications, the variable operation of an RO plant leads to a set of operating implications: affection to the performance due to the daily starts and stops in terms of water production and water quality.

Table 1
Summary of main data of a selection of PV/SWRO systems in operation

Nominal capacity (L/h)	PV (kW)	Salinity of raw water (g/L)	Location	Year of installation	Reference
2,100	10.5	4.28	Ksar Ghilène (Tunisia)	2006	[3]
1,000	4	2.9	Amellou (Morocco)	2008	[3]
1,250	5.6	35	Pozo Izquierdo (Gran Canaria Island, Spain)	2006	[5]

PV field on the roof of the building

RO desalination plant

Control room with the inverter

Batteries room

Fig. 1. Selection of pictures of the main components of the PVRO system operating in Ksar Ghilène (Tunisia).

In the case of PV driven RO systems, the average operation time is about 5–8 h/d, since the solar energy has a natural cycle (not like the wind that can be present along nights); this time is reduced in the case of battery-less systems. As a representative example, Table 2 collects the main operation data of the PV/RO unit installed in the remote village of Ksar Ghilène (Tunisia), which has been operating since 2006 [6]. The most relevant variation is in the quality of water.

In wind-powered RO systems, the operation time can be higher due to the longer availability of wind energy throughout the year. Table 3 presents a selection of data of an SWRO system coupled to an off-grid wind farm under a low and fluctuant wind speed period (15 min) in which the stand-alone grid frequency oscillated from 52 to 48 Hz [7].

1.4. Implications for the generation system in the case of continuous operation

Since electricity generation should provide from several sources (PV energy, wind energy, and diesel) the following issues must be considered:

- Incorporation of batteries with high efficiency and discharge depth as medium-term (hours) energy storage technology. According to the specific literature [8], flow and Li-ion batteries can be used in off-grid applications; the first group can be used in island grids (100 kW–100 MW) and village electrification (10–100 kW), whereas, Li-ion is selected in small off-grid systems (20 W–1 kW) as well. Both technologies are expensive in comparison with conventional lead-acid batteries. A summary of the main technical characteristics and costs of selected technologies is presented in Table 4 [8].
- Incorporation of maximum power point tracking system to optimize the DC output energy from the PV field in each moment. Furthermore, solar tracking systems (one or two axes) can be considered to extend the collection of solar radiation, provided that the local wind speed range is acceptable for the mobile structures [5].
- Incorporation of high-quality control and monitoring system. Considering that there are several important components with a high diversity of equipment, the selection of good sensors and the preparation of tailor-made control software are key points for the success of the operation [9]. Control strategy has to consider all the possible situations (for instance, cases of lack of solar energy, lack/excess of wind or batteries completely charged) and transitory periods (as starts, stops, peak wind moments, among others).

1.5. Potential improvements in off-grid low scale multigeneration powered RO systems

The expectations of this RE-desalination technology can be summarized according to the following issues:

Table 2
Operational values in the PVRO plant operating in a remote location of Ksar Ghilène (Tunisia)

Parameter	June 2006	June 2013	Variation (%)
Feed flow (m^3/h)	5.2	5.5	5%
Operation pressure (bar)	12	12.9	7.5%
Product water flow (m^3/h)	2.1	1.9	–9%
Total recovery (%)	70	67.9	–3%
Product water conductivity (μS/cm)	170	210	23%
Specific energy consumption (kWh/m^3)	1.7	1.91	12%

Table 3
Selection of operation values of a seawater RO plant tested in Pozo Izquierdo (Gran Canaria, Spain)

Parameter	Low wind power moment	Normal wind power moment
Operation pressure (bar)	58	61
Product water flow (L/h)	890	980
Product water conductivity (μS/cm)	925	900

Table 4
Main data of selected technologies of batteries

Type	Efficiency	Depth discharge	Installation cost (USD/kWh)
Li-ion	92%–96%	80%–100%	480–1,200
Lead-acid	80%	50%–60%	105–475
Flow batteries	70%–80%	100%	310–1,680
NaS, NaNiCl	8%0–85%	100%	170–750

- Reduction in the water cost. The Levelized Cost of electricity from PV power (residential sector) has been decreasing along the last years (reduction of 23%–73% for EU and USA for the period 2007–2017, reaching values under 0.2 USD/kWh in 2017 (Year of reference: 2016); wind electricity has experimented a strong decrement as well: from 0.4 to 0.06 USD/kWh (weighted average value for the period 1983–2017), [10]. Estimations for the year 2025 indicate lower values: 0.06 for PV electricity and 0.05 for wind electricity (units: 2015 USD/kWh) [11].
- Simplification of the installation and minimum use of electronic devices. The use of DC engines in the RO plant; this option avoids the use of the inverter (DC/AC converter) to supply the RO unit [12] or the use of a frequency converter. The elimination of batteries is under study; a battery-less technical and economic model was carried out by CREST for low scale SWRO PV powered unit (3 m^3/d), concluding hopeful results: 2.9 UK pounds/m^3–2.9 UK pound = 3.3 € (15 October 2018). 1.137 €/UKP -, for a feedwater salinity of 40 g/L and an average annual radiation of 5 kWh/m^2 [13]. Besides that, an experimental test campaign for another small unit (108 L/d of water production), but with brackish water (3.5 g/L) led to a water cost of 3.64 $/$m^3$, [14] –3.64 $ = 3.15 € (15 October 2018). 0.865 €/$ -.
- Wider commercial availability of low scale wind generators (range of 20–100 kW). There is a very low commercial offer, and in general, not focused on the tough design concept for operation in remote locations.
- Higher energy efficiency. Module efficiencies for mono and multi-crystalline cells are expected to increase along the period 2015–2025: from 16% to 19.5% and from 17% to 21.5% respectively [11]. On the other hand, innovative technologies in batteries (NaS, Ni-Cd, lithium, vanadium) can offer better performance than traditional lead/acid [15].
- New RO membranes and the use of axial piston pumps. The RO membranes are under a continuous process of improved performance in terms of salt rejection, operation pressure, and product water quality. On the other hand, the high-pressure pumps (HPP) based on axial pistons provide better efficiencies and fewer maintenance requirements.
- Specific integrated multi-generation and batteries control system: the presence of more than one generation system requires the incorporation of a more sophisticated power control system.

2. Technical concept of the multigeneration powered low-scale SWRO plant

2.1. Objective

Solar PV or wind supply for RO units is associated with isolated, inland or coastal, sites with low, but stable demand for freshwater. The main inconvenience of standalone PV or wind supply is the limitation of the operation time to 8–18 h/d in the best case, even including the batteries for energy storage. The autonomous water supply to cover the hourly water demand, particularly in touristic settlements, requires the support of multi-generation sources (including diesel generator), the use of batteries and an adequate water storage tank. A basic electric diagram for hybrid systems based on the information of a wind generator manufacturer [16] is illustrated in Fig. 2.

The objective of this section is to present and describe the technical concept of autonomous multigeneration energy

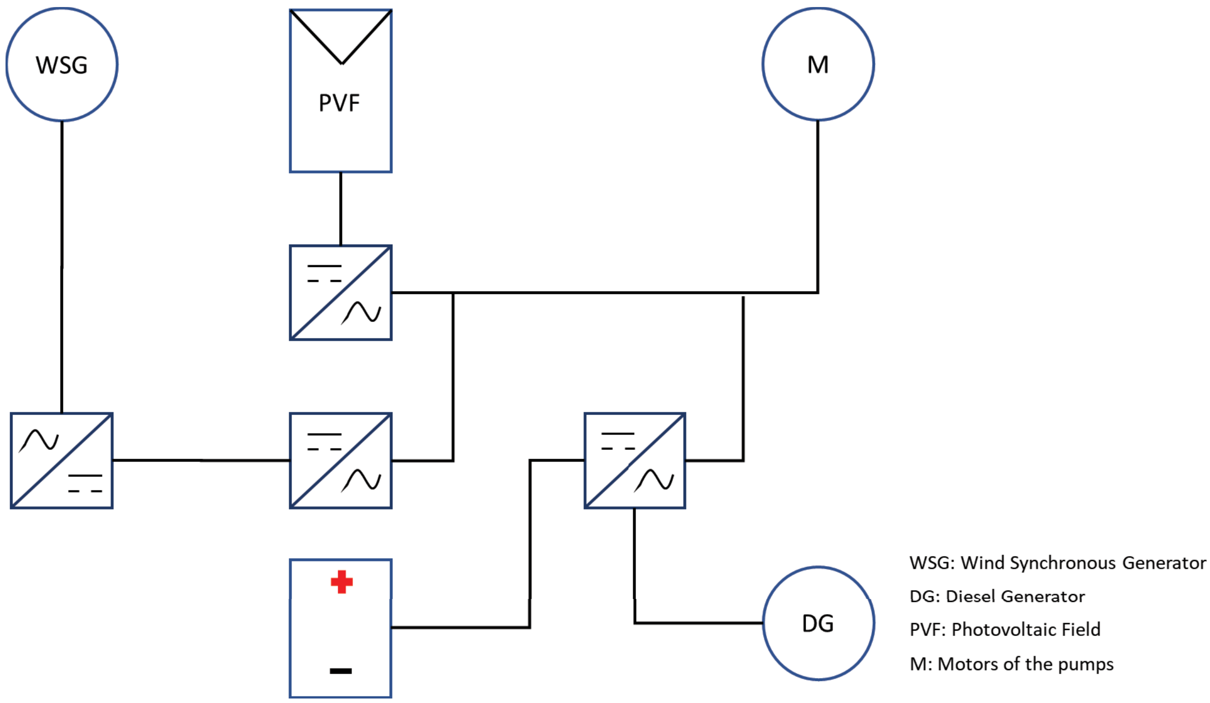


Fig. 2. Electric diagram of the system (simplified version).

systems to power low scale SWRO plants addressed to optimize the design and operation according to the following target points:

- Technical aspects:
  - □ Water production to guarantee the local water demand throughout the year.
  - □ Continuous and maximum daily operation time (reaching 24 h/d).
  - □ Identification of variation of operating parameters.
  - □ Optimization of storage energy capacity.
  - □ Minimization of energy supplied by diesel generator throughout the year.
- Economic aspects
  - □ Minimization of water cost.

2.2. Identification of the SWRO plant nominal capacity

Given the wide range of RO capacities, the decision of the nominal size of the low capacity desalination plant comes from the commercial availability of small HPP with high efficiency and energy recovery units. Table 5 summarizes the feed flows associated to each equipment and the corresponding nominal capacity of the SWRO plant; as a reminding indication, the feed flow of the HPP has the same value than the product flow of the SWRO plant, and the feed flow of the energy recovery device (ERD) corresponds to the rejected flow of the plant.

According to this information, the selected range of nominal production to study the system will be 100–250 m^3/d.

2.3. Reference case and analyzed options

The input data for the analyzed cases are the following:

- *Feed water type*: Atlantic seawater beach well located in Pozo Izquierdo, Gran Canaria Island (Spain). Salinity: 38 g/L of total dissolved solids and silt density index < 2.
- Energy consumption:
  - □ RO rack power demand: values given by the RO simulation software (see sections 3.5–3.7).
  - □ Feedwater pumping has been calculated considering an efficiency of 50% and a head of 5 bar.
  - □ Product water pumping to storage tank has been calculated considering an efficiency of 50% and a head of 2.5 bar.
- Energy consumption associated with standard seawater pre-treatment and desalted water post-treatment energy requirement is included in the previous ranges.
- Solar radiation and wind speed data: from the data monitored in the facilities of the Canary Islands Institute of Technology (ITC) located in Pozo Izquierdo, Gran Canaria Island (Spain).

Table 5
List of feed flow values of different models of HPP and ERD and the associated nominal SWRO capacity

Type of equipment	Model	Feed flow (m^3/h)	Associated SWRO nominal capacity (m^3/d)[a]
HPP	APP 5.1	2.79–4.18	67–100
HPP	APP 6.5	3.57–5.36	86–129
HPP	APP 7.2	4.01–6.01	96–144
HPP	APP 8.2	4.62–6.93	111–166
HPP	APP 10.2	5.83–8.75	140–210
HPP	APP 11/1500	7.5–11.25	180–270
ERD	i-Save 21	6–22	109–399
ERD	PX30	4.5–6.8	82–123
ERD	PX45	6.8–10.2	123–185
ERD	PX70	9.1–15.8	164–286
ERD	PX90	13.6–20.4	246–369

[a]Considering a recovery rate of 43% and a single SWRO train.

Table 6
Selection of HPP and ERD for the different cases of the SWRO plant

Case	Minimum water production (m^3/d)	Maximum water production (m^3/d)	HPP	ERD
0	0	250	APP 11/1500	i-Save 21; PX70
1	180	250	APP 11/1500	i-Save 21; PX70
2	100	100 + 150	APP 6.5 + APP 8.2/10.2	PX30 + PX45/iSave 21
3	100	100 + (120 – 150)	APP 6.5 + APP 8.2	PX30 + iSave 21

The analyzed design options have been the following:

- *Case 0 (Reference case)*: use of HPP at 100% of its nominal operation point for a nominal water production of 250 m^3/d.
- *Case 1*: identical to the plant of case 0, but using the HPP at variable operation to reduce the power demand.
- *Case 2*: modular operation by two RO trains, one unit of 100 m^3/d and another unit of 150 m^3/d.
- *Case 3. (Combination of cases 1 and 3)*: operation at the nominal point of the small unit and variable operation point of the HPP for the large unit.

From data collected in Table 5, the selection of HPP and ERD for each case has been made and is presented in Table 6.

In all cases, the energy storage in batteries is included. For easier comprehension, Fig. 3 presents a basic diagram for each case.

3. Methodology

3.1. Calculation procedure: generalities

As the objective is to run the SWRO plant uninterruptedly throughout the full year, the calculation methodology includes the three-generation sources: PV supply, wind generation, and diesel energy contribution.

The strategy of the connection of the different generation systems is the following: Whereas there is wind and/or solar energy availability, the wind generator and the PV field produce power respectively; if there is enough total renewable power to run the SWRO plant, considering the losses of the converters, then the desalination plant is started-up and surplus of power is directed to the batteries. In case of the availability of renewable power is less than the minimum demand of the SWRO plant, then the unused power is transferred to the batteries as well. Under lack of RE periods, SWRO is supplied by batteries or, when the energy stored in the batteries is under the minimum to run it, by the diesel generator.

A power balance model has been used to calculate the operation time of the RO plant and the associated annual water production throughout one year. The diagram of Fig. 4 indicates the calculation flows mentioning the main variables. An example of energy flows for a one-year balance is illustrated in Fig. 5. The PV and solar energy generation have specific losses, due to the efficiency in the converters to provide the AC output that supplies the RO plant; similarly, a specific loss and net energy supply to RO has been considered for the diesel generator. Part of

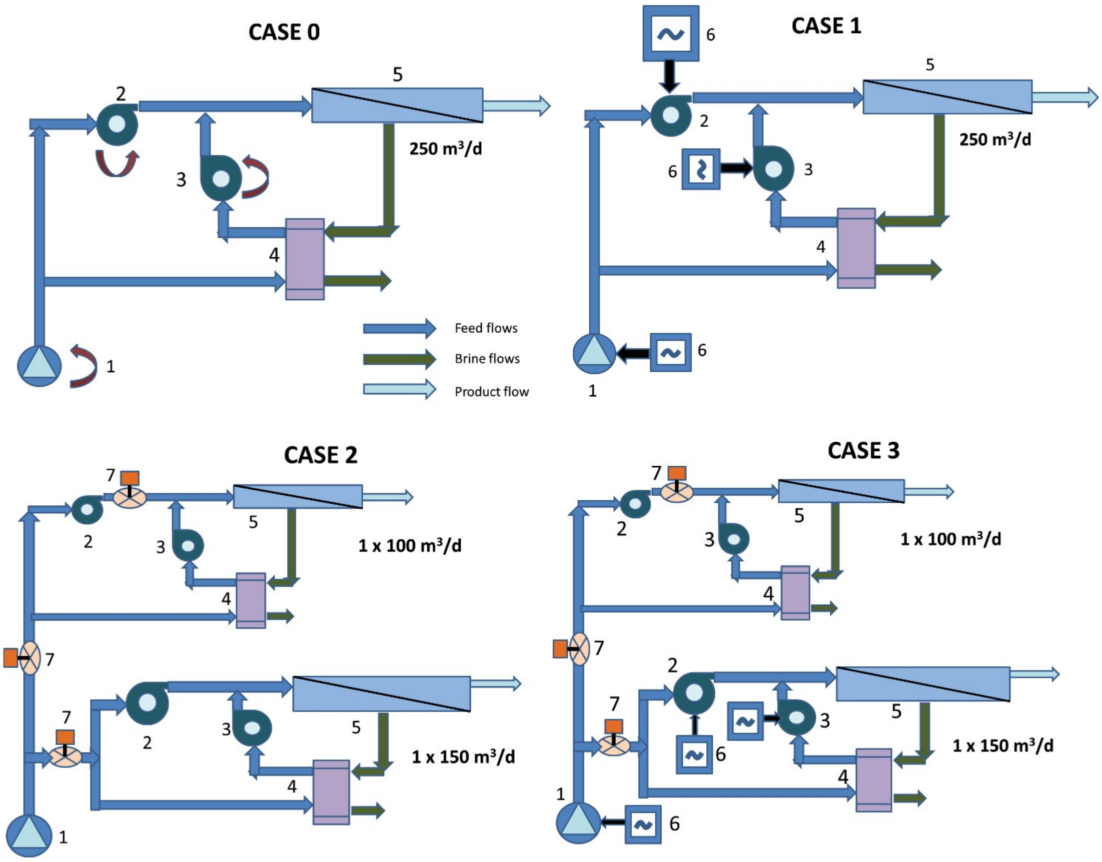


Fig. 3. Basic hydraulic diagrams. Case 0 (Reference case): RO unit of 250 m^3/d operating at the nominal point. Case 1: RO unit of 250 m^3/d with variable operation. Case 2. Modular RO unit (100 + 150 m^3/d) at the nominal point. Case 3: Modular RO unit (100 + 150 m^3/d) at variable operation. List of equipment: 1. Feed pump, 2. High-pressure pump, 3. Booster pump, 4. Energy recovery system, 5. Pressure vessels, 6. Frequency converter, 7. Automatic valves.

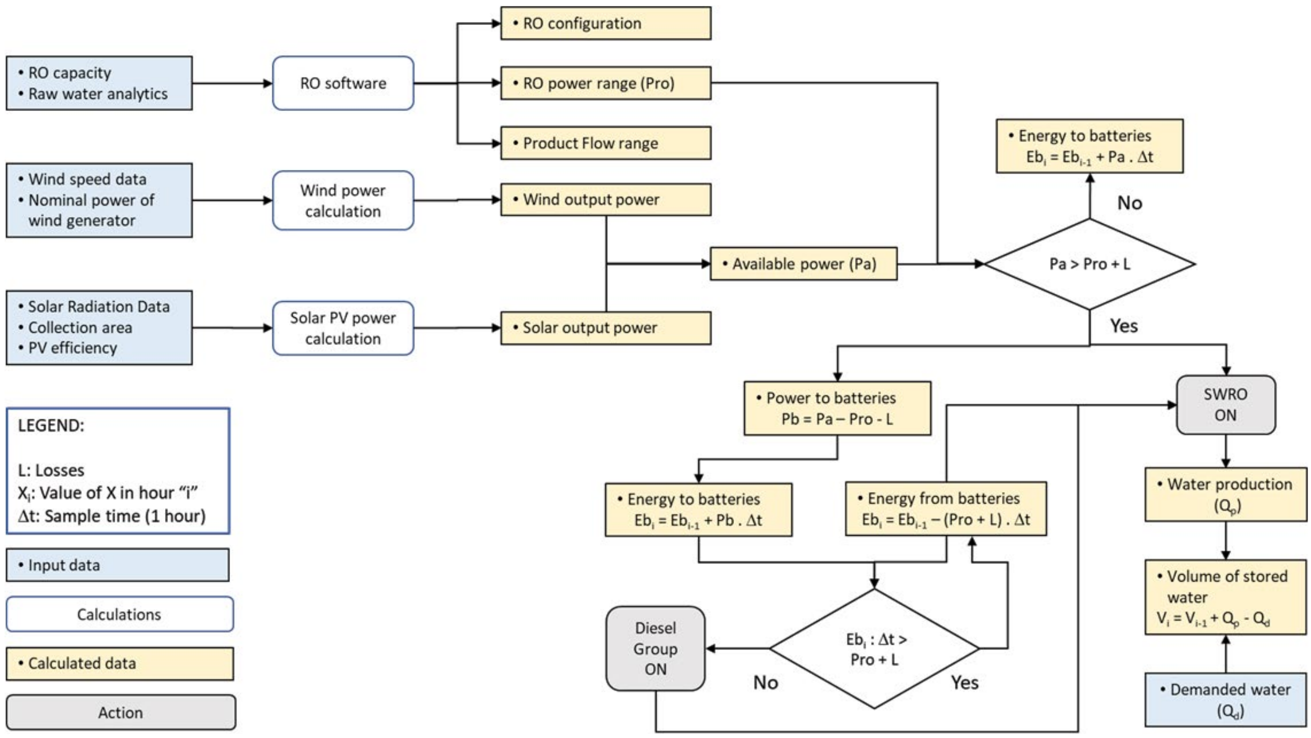


Fig. 4. Graphic representation of the calculation and power/energy flows.

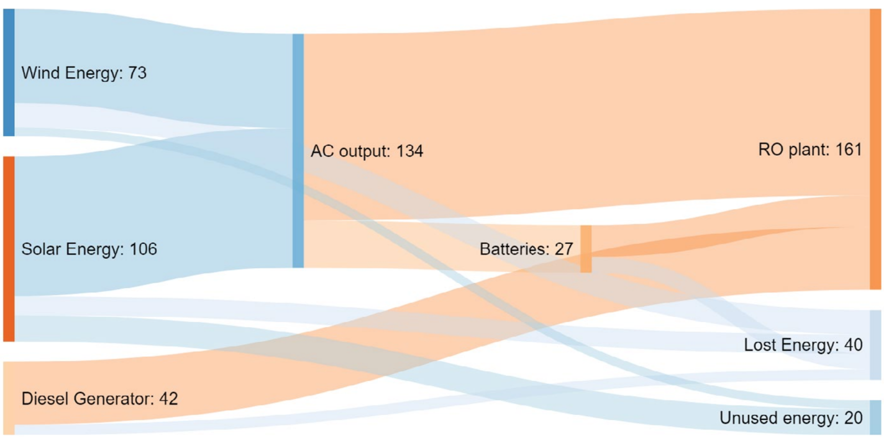


Fig. 5. Illustrations of power flows. Case of generation > demand (Figures in MWh/a).

the net RE output is used to store energy in the batteries, from where it is partially redirected to the RO plant due to the internal efficiency of batteries and DC/AC conversion. As RE generation cannot be totally consumed, either in the RO plant or in the batteries, a small amount (about 11%) is unused energy, lost in dumping loads or by the control regulation of the RE power output to operate under the maximum possible point.

A complete description of calculations is given in Annex A.

3.2. RO demanded power

From the specific chemical analysis of the seawater and the nominal capacity of the SWRO unit, a set of simulations have been made (one for each case study) with the support of a membrane software (Q+; [17]). The software allows different combinations and testing options: type of membranes, range of recovery, the efficiency of pumps, number of pressure vessels and number of elements per vessel, among other variables, and indicates which options are acceptable to avoid malfunctions warnings. The simulations allow to identify the following outcomes:

- Optimal hydraulic configuration of the high-pressure rack to respect the recommended average flux: 12–18.5 L/(m² h).
- Predicted water product quality (under 400 ppm in all the cases).

- Specific energy consumption to calculate the total demanded power.
- Identification of other operating parameters.

Detailed figures are presented in sub-sections 3.4–3.6.

Calculation of total demanded power is made from the flow, operation pressure and efficiency of the different pumps: feed water pump, HPP, booster pump, product water pump.

3.3. Generated power

Calculations of renewable power output have been used following the same location, criteria, and methodology than a previous study [18], but with the selection of the appropriate equipment:

- *PV field*: Collection area 300 m^2, peak power: 45 kWp. From panels of unitary power of 300–500 W and nominal efficiencies from 17% [19]. Nonetheless, the efficiency used in the calculation for the total PV field has been 15%, to consider the effects of dust on the panel surface, losses in the DC electric cabling and other inefficiencies. Calculations of output PV power from solar radiation has been made by using the following items:
  - Solar vector calculation according to the methodology described in [20].
  - Irradiance on the tilted planes calculated from the Pérez model [21].
  - Azimuth and albedo taken from [22].
- *Wind generation*: nominal power 17.5 kW (Model e200l, [16]).
- *Off-grid inverter*: SPO-M series of controller and inverter series with a wide range of output AC power (20–120 kW) and integration of input power from diesel generator.
- *Converters*: efficiency of 90% has been considered for AC/DC and DC/AC conversions.
- *Batteries*: efficiency: 85% and discharge depth: 100%.

3.4. Energy storage

There are two main ways of calculating the energy storage: either considering the capacity to store the total generated power along a certain time or considering the capacity to store the power demand along a specific period. The option two has been considered in this study. On the other hand, the management strategy to store energy in each moment can be made in diverse ways. In this study, the target point is to have energy stored as much time as possible, in other words, if there is not sufficient availability of solar and wind power to run the SWRO plant, and the batteries are partially charged, the decision is to recharge the batteries up to the maximum capacity instead of discharging them to supply energy to the SWRO plant.

3.5. Considerations for case 1 (SWRO plant under variable operation point)

In case 1, the SWRO desalination plant operates under the nominal point of 250 m^3/d (10.42 m^3/h). The variable operation is achieved by driving the HPP with a frequency converter, this allows a reduction in the power demand and a modification of the operation parameters. Table 7 presents the values of the main operating variables for a selection of operation pressure values:

The relation between total power and product flow can be easily evaluated for the complete range by using a linear equation:

$$P\ [\mathrm{kW}] = a \cdot Q\ [\mathrm{m^3/h}] + b \tag{1}$$

where "a" and "b" has the values of 3.2136 and –3.8909 respectively ($R^2 = 0.9995$).

3.6. Considerations for case 2 (modular SWRO plant in nominal point)

In the case 2, the SWRO plant has a modular configuration: one unit of 100 m^3/d and another unit of 150 m^3/d, allowing three possible situations: only the unit of 100 m^3/d is running, only the unit of 150 m^3/d is running, both units are running. Table 8 summarizes the operation variables for these three possibilities.

3.7. Considerations for case 3 (modular SWRO plant under variable operation point)

Case 3 is the combination of cases 1 and 3, that is, the 150 m^3/d unit of the modular plant operates at a variable point (from 115 to 150 m^3/d), and the 100 m^3/d operates at the nominal point. The different combinations and the values of

Table 7
Range of operation parameters for the 250 m^3/d SWRO plant (Case 1. variable operation)

Input pressure	Nominal product flow	Recovery	Total power	SEC (total)	Average flux	Product water salinity	Number of pressure vessels	Number of elements per vessel	Total number of elements
bar	m^3/d	%	kW	kWh/m^3	L/(m^2 h)	ppm	uds	uds	uds
56.3	250	44.0%	29.7	2.85	18.2	238	2	7	14
54.2	233	42.5%	27.2	2.81	16.9	249	2	7	14
52.1	215	41.0%	24.8	2.77	15.7	263	2	7	14
50.2	198	39.5%	22.5	2.74	14.4	278	2	7	14
48.3	180	38.0%	20.3	2.71	13.1	298	2	7	14

Table 8
Range of operation parameters for the 100 + 150 m³/d SWRO (Case 2. modular plant in nominal operation)

Input pressure	Nominal product flow	Recovery	Total power	SEC (total)	Average flux	Product water salinity	Number of pressure vessels	Number of elements per vessel	Total number of elements
bar	m³/d	%	kW	kWh/m³	L/(m² h)	ppm	uds	uds	uds
54.1	100	44%	11.5	2.75	14.59	299	1	7	7
51.1	150	40%	16.9	2.71	15.31	268	2	5	10
N/A	250	N/A	28.4	2.73	N/A	N/A	3	5/7	17

the operation parameters are summarized in Tables 9 and 10, respectively.

As the case 1, a linear equation has been used to simulate the variable operation range of the large unit (115–150 m³/d) (Eq. (1)). In this case, $a = 2.8731$ and $b = -1.0686$ ($R^2 = 0.9984$).

A graphic summary indicating the operation points of the SWRO for each case is presented in Fig. 6.

3.8. Economic considerations

As many factors affect the calculation of costs (location, taxes, administrative processes, etc.) there are several components of the final capital expense which are difficult to evaluate: costs of transport, customs, civil works, installation, commissioning and engineering. On the other hand, there is a wide set of aspects that influence on the operation and maintenance (O&M) expenses; for instance, the variable O&M costs of wind power in UE vary from 0.01 to 0.04 USD/kWh, depending on the country; similarly, the range of fixed costs is 37–75 USD/kW [11]. Thus, the final water cost

Table 9
Connection of SWRO units in case 3

Daily production	Unit of 100 m³/d	Unit of 150 m³/d
100 m³/d	On	Off
From 115 m³/d	Off	On (partial operation)
150 m³/d	Off	On (nominal operation)
From 215 m³/d	On	On (partial operation)
250 m³/d	On	On (nominal operation)

Table 10
Range of operation parameters for the 100 + 150 m³/d SWRO (Case 3. modular plant in variable operation)

Input pressure	Nominal product flow	Recovery	Total power	SEC (total)	Average flux	Product water salinity	Number of pressure vessels	Number of elements per vessel	Total number of elements
bar	m³/d	%	kW	kWh/m³	L/(m² h)	ppm	uds	uds	uds
54.1	100	44%	11.5	2.75	14.6	299	1	7	7
50.2	115	40%	12.8	2.67	12.3	336	2	5	10
51.1	150	40%	16.9	2.71	15.3	268	2	5	10
N/A	215	N/A	24.3	N/A	N/A	N/A	3	5/7	17
N/A	250	N/A	28.4	N/A	N/A	N/A	3	5/7	17

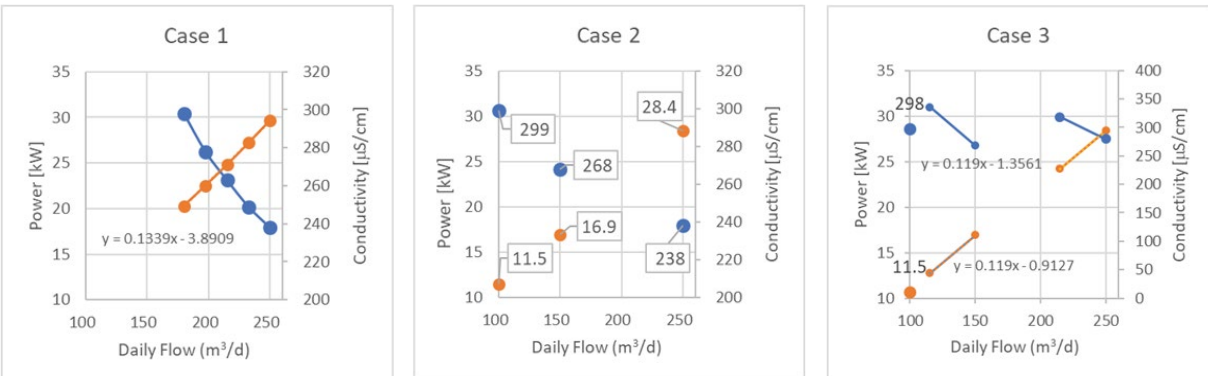


Fig. 6. Charts illustrating the operation points of the SWRO plant for each case (Power: orange points; Conductivity: blue points).

will depend on the specific particularities of each project. Consequently, the figures presented in this study are estimations. For the economic calculations, the following assumptions have been considered:

- Specific investment costs of equipment estimated according to conventional values (Table 11).
- Other costs (transport, customs, taxes, administrative management, engineering, control, and monitoring system) estimated in 20% of the investment in equipment (from real data presented in [9]).
- Interest rate: 2%.
- Amortization cost: linear amortization throughout 15 years.
- Extra cost for RO investment in cases 2 and 3 (modular plant): 25%.
- Currency exchange rate: 1 USD = 1 €.
- Price of fuel: 0.81 €/L.

Operation costs are different for each component; the values used to calculate the O&M costs have been taken from the direct and wide experience (more than 20 years) of the ITC (Water Department) in the field of solar PV powered RO units [5]. This set of values (Table 12) incorporates the information collected from several O&M staff working in different installations and own data from ITC autonomous desalination systems.

4. Discussion of results

4.1. RO operation

From the simulations, the different operation points, at acceptable levels of flux (always over 12 L/m^2 h), were identified for each case (sections 3.4–3.6). The most remarkable findings for each case are the following:

- *Case 1 (variable operation of 250 m^3/d unit)*: Pressure and product water values can be reduced up to 86% and 72% of the respective nominal value. This allows an operation range of 68%–100% of the total demanded power, reaching acceptable levels of the desalinated water conductivity in the worst situation (25% of increase respect the nominal point).
- *Case 2 (modular plant of 100 + 150 m^3/d units operated at the nominal point)*: There are only three possible situations: operation of unit 1, unit 2 or both units. The total maximum power is lightly lower than case 1 but with higher product water salinity: this is due to the configuration of the individual units. The main advantage of this case is the possibility of producing water at low levels of renewable power.
- *Case 3 (modular plant of 100 + 150 m^3/d units in variable operation)*: This case combines cases 1 and 2, allowing a wider range of operation: only unit 1 (constant demand of 11.5 kW; only unit 2: 12.8–16.9 kW; both units: 24.3–28.4 kW). High values of conductivity appear for unit 2 when it works at the lowest load point (76% of nominal power, and 77% of nominal flow).

4.2. Energy balance

The energy balances are presented and discussed in this sub-section. The nominal power of the RE generation sources is the same for all the cases: 17.5 kW for wind power, 52.3 kWp for PV power; the nominal power for the diesel generator is calculated to supply the minimum possible demand within

Table 11
Specific investment costs

Equipment	Range of values	Value used in calculations	Unit	Reference
Wind generator	3,250–6,000	3,250	€/kW	[23,24]
PV field (installed)	1,100	1,100	€/kW	[10]
Converters	130–850	500	€/kW	[25]
SWRO plant	1,000	1,000	€/(m^3/d)	[a]
Batteries (Li-ion)	473–1,260	500	€/kWh	[8]
Water storage tank	5	–	€/m^3	Own calculations from data presented in [26]
Diesel generator (20–40 kW)	600–1,000	800	€/kW	[27]

[a]Current common value of investment; variations depending on the location of the SWRO plant and characteristics of seawater intake.

Table 12
Values to calculate the O&M costs

Part of the system	Fix O&M costs	Variable O&M costs	Observations	Other values of O&M costs
PV installation	1.91%	0.02 €/kWh	Fix cost as % of CAPEX	0.02–0.125 €/kWh [10], calculated from 25% of levelized cost of electricity (LCOE)
RO installation	452 €/m^3	0.078 €/m^3	Case of a 100 m^3/d unit	
Wind installation	2.19%	0.016 €/kWh	Fix cost as % of CAPEX	0.03 €/kWh (case of Spain) [10]
Diesel generator	2.72%	0.305 €/kWh	Fix cost as % of CAPEX	

the operation range of the SWRO plant, thus, it depends on the case: 33.2 kW for the case 0, 23.7 kW for the case 2, and 13.4 kW for cases 2 and 3.

The charts of Fig. 7 illustrates the input and output energy flows for the different cases, and the main figures are indicated in Table 13 (units: MWh/year).

The RE generation is the same for each case since the wind and solar resources do not change. As diesel generator is used to cover the minimum demand, there is less diesel use in the modular cases (2 and 3) due to the option of the connection of the small SWRO unit (100 m^3/d and 11.5 kW).

The highest RE supply to the SWRO unit is for case 3, due to the wide range of power demand associated to the combination of variable operation and modularity; 71% of RE energy is used in the desalination plant, more than other cases: 60% for case 0, 69% for case 1, and 68% for case 2. According to this, flexible operation (case 1) has a little bit more influence than a modular concept (case 2) in terms of the final use of the RE resources.

The flexible operation of case 1 leads to lower energy production from diesel than case 0. On the other hand, there are no relevant differences between cases 2 and 3; the variable operation option of case 3 allows a little bit more use of renewable sources; on the other hand, there is also more diesel generator, since there are some few more hours per year with more energy demand to batteries, and then more moments with no available stored energy.

A complementary vision of the energy balance is given in Fig. 8, which exemplifies the evolution along 96 h (four winter days) for case 3. The values of wind and solar power

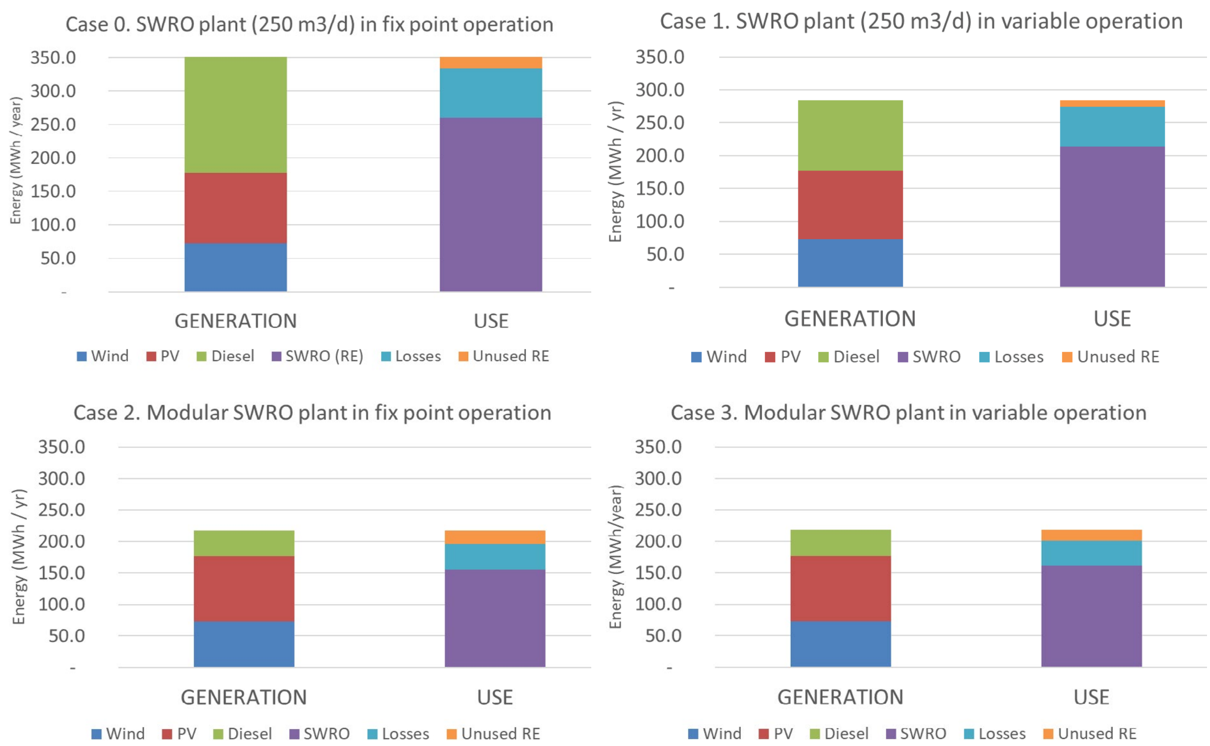


Fig. 7. Charts of the annual energy balance for each case (units: MWh/year).

Table 13
Values of the annual energy flow for each case (unit: MWh/year)

	Case 0		Case 1		Case 2		Case 3	
	Generation	Use	Generation	Use	Generation	Use	Generation	Use
Wind	72.7		72.7		72.7		72.7	
PV	104.6		104.6		104.6		104.6	
Diesel	179.0		107.2		40.4		41.4	
RO (PV-wind)		107.2		122.1		120.3		126.3
RO (diesel)		153.0		91.6		34.5		35.4
Losses		73.4		60.6		40.6		40.1
Unused RE		22.6		10.1		22.2		16.9
Total	356.2	356.2	274.9	274.9	217.6	217.6	218.6	218.6

consumed by the SWRO plant and energy available in the batteries are plotted. The periods with lack of wind, the variations in the solar power and the moments of charge-discharge of batteries can be identified.

4.3. Operation time and water production

The operation time has two main periods for each case: supply by RE or supply by diesel. On the other hand, the amounts of produced water can be divided as well under RE or diesel generator periods. Fig. 9 summarizes the values for each case.

In coherence with the energy balance results, modular cases (2 and 3) have more time in RE operation and more associated water production (about 2/3); case 3 allows a little bit more RE water production and case 2, more RE operation time. On the contrary, cases 1 and 2 have more operation time with diesel (over 50%), and consequently, more total water

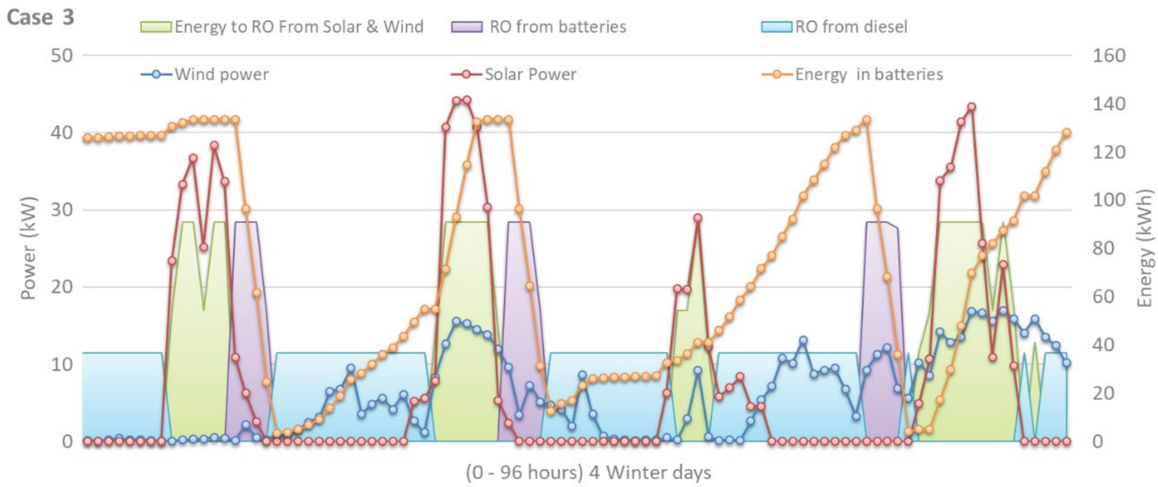
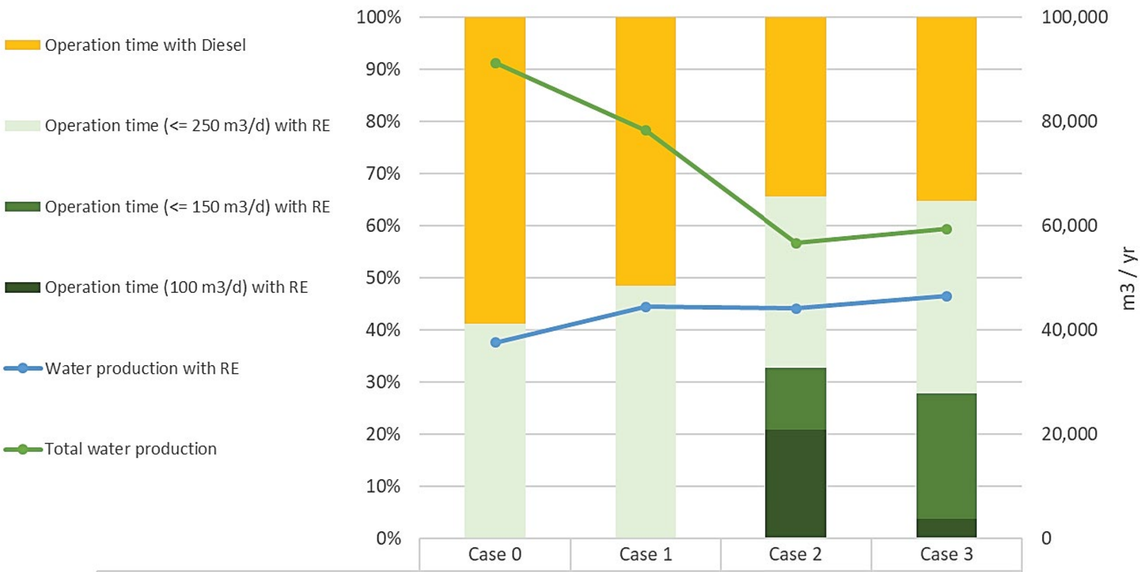


Fig. 8. Chart with the generated power (wind, solar PV), connection of RO, and energy in batteries (4 winter days) for case 3 (variable modular operation).



	Case 0	Case 1	Case 2	Case 3
Operation time with Diesel	5,152	4,514	3,014	3,089
Operation time (<= 250 m3/d) with RE	3,608	4,246	2,881	3,237
Operation time (<= 150 m3/d) with RE	0	0	1,037	2,108
Operation time (100 m3/d) with RE	0	0	1,828	326
Water production with RE	37,583	44,428	44,108	46,484
Total water production	91,250	78,283	56,667	59,355

Fig. 9. Operation time (in hours per year) and water production (m^3/a) for each case and type of energy supply.

production. In terms of water production from RE, it is very similar to the use of a modular plant (case 2) or the use of a variable operation point (case 1), nonetheless, the modular option allows more operation time under RE supply.

The daily average water production is presented in Table 14:

The modular option is associated with the diesel generator under the minimum water production (unit of 100 m^3/d); thus, cases 2 and 3 are the best options in terms of % of water production by RE.

4.4. Specific energy generation

We define "specific energy generation" (SEG) as the ratio between the total energy generation and the total water production for a certain period. This index is an option to assess the global performance of the system since considers the energy balance and the produced water. Table 15 summarizes the values for each case.

According to these results, the variable flow operation SWRO concepts (cases 1 and 3) are the most efficient options. In case 1, 3.63 kWh/m^3 are produced by the generation system, and 2.73 kWh/m^3 are consumed; that is, 33% of additional energy is required to be generated to produce each cubic meter of desalinated water.

4.5. Economic results

The main economic results are presented in Table 16. The investment for cases 2 and 3 is higher due to the extra cost associated with the modular SWRO plant. The most economical option is case 1 since it is not modular and the required diesel generator power to be installed in less than case 0.

The water cost of case 3 is lightly better than case 2 since there is more water production with this option. Nevertheless, there are no relevant differences between the four cases; minimum water cost is for case 1 since the total investment is the lowest and there is less diesel consumption than case 0. If at is foreseen, future price increases, the water cost of modular options (cases 2 and 3) will be more competitive.

The range of obtained water cost (1.93–2.29 €/m^3) is consistent with the results of previous research: 2.2 $/$m^3$, for a PV and wind and diesel-powered SWRO model, with a nominal capacity of 24 m^3/d [28].

Table 14
Average water daily production for each case and generation source

	Case 0	Case 1	Case 2	Case 3
Total water production (m^3/d)	250	214	155	163
Water production by RE (m^3/d)	103	122	121	127
Water production by RE (%)	41%	57%	78%	78%
Water production by diesel (m^3/d)	147	93	34	35

Table 15
Summary of main energy data, water production, and associated ratios

	Case 0	Case 1	Case 2	Case 3
Total energy generation (MWh/a)	356.2	274.9	217.6	218.6
Total energy demand (MWh/a)	260.2	213.7	154.8	161.7
Total water production (m^3/a)	91,250	78,283	56,667	59,355
Annual average SEC (kWh/m^3)	2.85	2.73	2.73	2.72
Annual average SEG (kWh/m^3)	3.90	3.63	3.84	3.68

Table 16
Summary of main economic results

	Case 0	Case 1	Case 2	Case 3
Total investment	682,509 €	661,349 €	721,904 €	721,904 €
Specific investment (€/d/m^3)	2,730 €	2,645 €	2,888 €	2,888 €
Diesel fuel expense (€/y), from a price of 0.81 €/L	10,649 €	6,377 €	2,403 €	2,463 €
Annual water production (m^3/y)	91,250	78,283	56,667	59,355
Water cost (€/m^3)	1.97	1.93	2.29	2.19
Water cost in Scenario 1: diesel price is 2 €/L (€/m^3)	2.15	2.05	2.35	2.25
Water cost in Scenario 2: non-refundable funding (€/m^3). (CAPEX are excluded)	1.39	1.27	1.29	1.25

Two hypothetical scenarios have been considered for further analysis: a future diesel price of 2 €/L (scenario 1) and non-refundable funding (scenario 2), in which the investment cost is excluded from the calculation of water cost. The last two rows of Table 15 present the water cost for these situations in each case. Under the scenario 1, the new diesel price increases the water cost proportionally to the diesel demand in each case; thus, it affects especially to case 0: almost 9%, with less influence in case 1 (6%), and less than 3% for cases 2 and 3. Scenario 2 leads to more economical water costs, benefiting those cases with high investment.

5. Sensitivity analysis

This section presents a sensitivity analysis to assess the optimization of the water cost, specific investment and operation time with RE generation. The parameters to be changed are the battery size, the diesel price, and the PV area. The study will be limited to case 3 to avoid an excessive extension of charts and comments.

5.1. Water cost and operation time vs. energy storage

The more installed PV power and batteries capacity, the more water production and more operation time by RE supply, however, it implies higher associated capital expenses. Water cost and operati1on time by RE supply are plotted in Fig. 10 for different values of the battery capacity (measured in supply hours) and for different nominal solar PV power (in kW). According to the left chart, there is a region of minimum water costs in the range of 3–5 h of battery capacity. On the other hand, the percent of operation by RE power

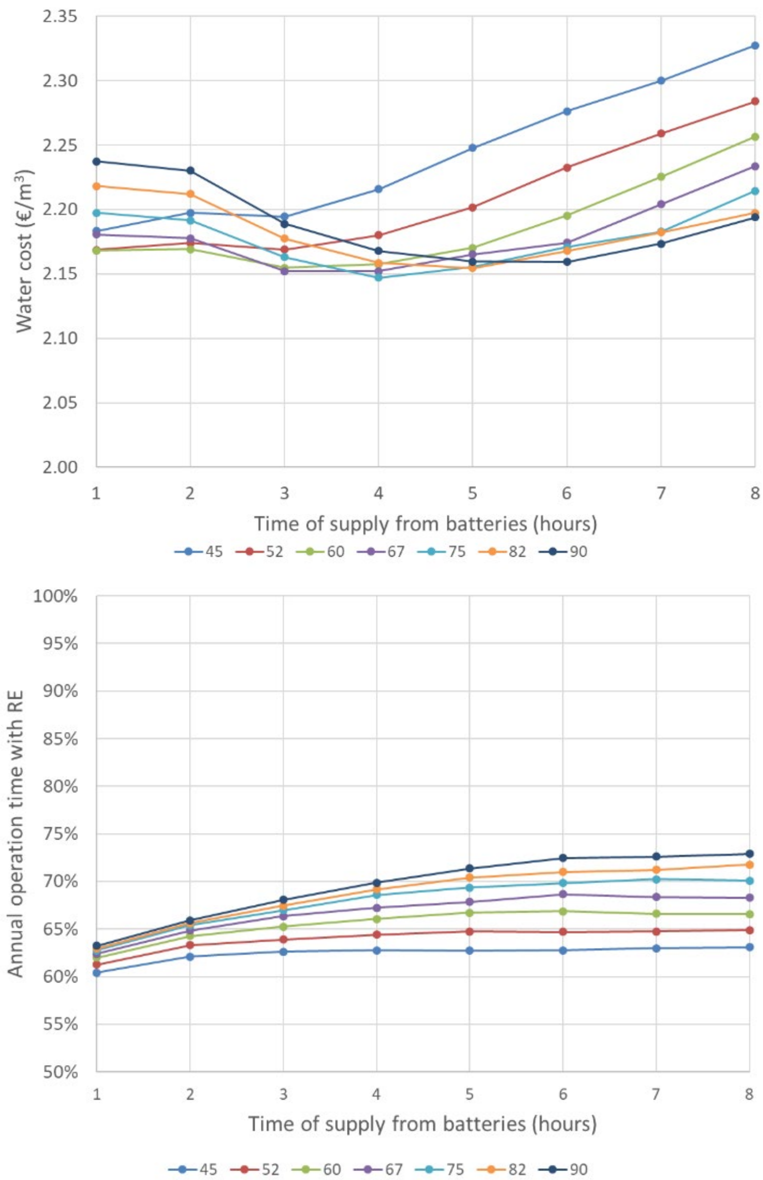


Fig. 10. Variation of water cost (top chart) and operation under RE supply (bottom chart) for different values of battery capacity (in hours of supply) and PV power (in kW).

generation starts to stabilize from 3–6 h, depending on the value of PV power; thus, for instance, in the case of 90 kWp of solar PV, the selection of a battery size of 6 h is enough to reach the 73% of RE operation.

5.2. Water cost and operation time vs. wind power

The influence of the variation of installed wind power is indicated in Fig. 11 for a fix nominal PV power of 52 kW and a battery capacity of 5 h. The charts represent the water cost and average daily water production (left side), the percent of operation time by RE supply and the lost RE (right side) for three different situations: no wind power, one wind generator, and two wind generators.

The inclusion of an additional wind generator leads to more water production (about 20%) and a significant reduction in the water cost (about 0.2 €/m^3). Furthermore, the increase in the installed wind power allows greater operation time by RE supply, but more amount of produced energy that is lost or cannot be used in the SWRO plant.

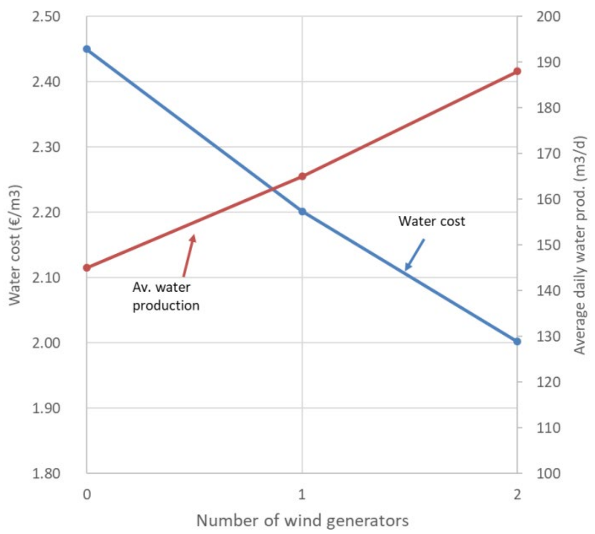
5.3. Water cost vs. diesel price

The probable increase in fossil fuel cost will modify the water cost, Fig. 12 illustrates the possible evolution of water cost for the reference case (case 0) and case 3, showing that there are more similar values for future water costs. A potential reduction in CAPEX of batteries and RE generation would accelerate this tendency.

According to this evolution of diesel price, water costs would be identical when diesel price reaches a value of 3.1 €/L approximately, (3 times more than current prices) leading to a water cost of about 2.3 €/m^3.

6. Conclusions

A multi-generation model using monitored solar and wind data has been used to assess the performance of a low scale (250 m^3/d) SWRO desalination plant with four different operation modes located at Pozo Izquierdo, Canary Islands. Four cases with different operation/ configurations of the SWRO plant have been comparatively analyzed;



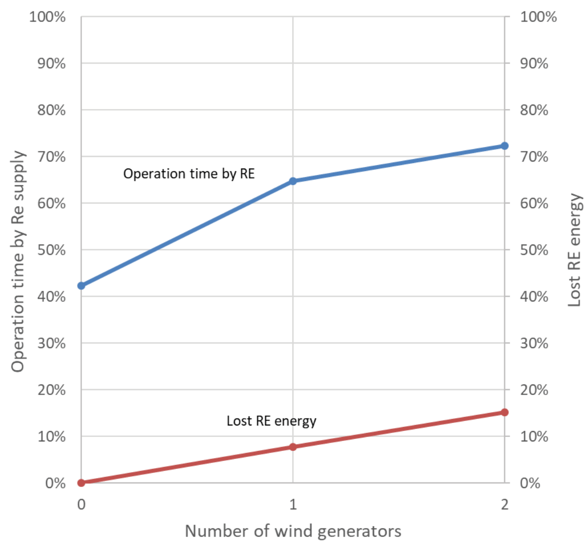


Fig. 11. Influence of a number of wind generators in the water cost, average water production, operation time *y* RE supply and lost RE energy.

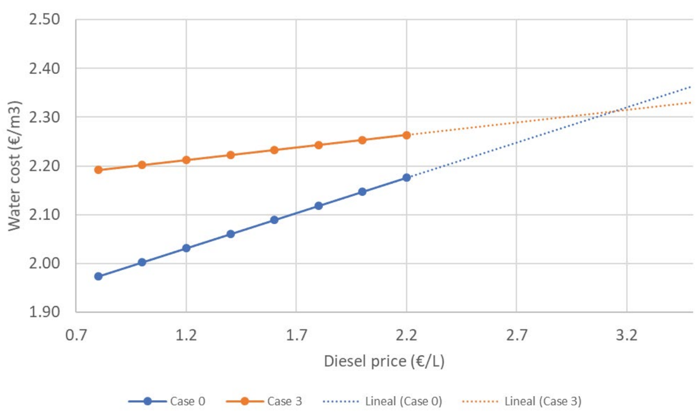


Fig. 12. Possible evolution of water cost as function of diesel cost.

namely: conventional SWRO operated at constant power (case 0), conventional SWRO with variable power load (case 1), modular SWRO skids (100 + 150 m^3/d) with and without variable operation of the large skid, (cases 3 and 4, respectively). The most remarkable conclusions are the following:

- The multigeneration concept, combining solar power, wind power, and diesel generator can guarantee the operation throughout the year with a minimum participation of fossil energy between 28%–53% approximately, depending on the configuration of the SWRO plant and the associated variability of power demand. The modular concept (100 + 150 m^3/d) with or without a variable operation of the large sub-unit (115–150 m^3/d) leads to the less requirement of diesel energy. The variable modular case has a little bit more water production than the fix modular case, leading to a better water cost.
- The definition of the SEG ratio allows having a fast idea of the energy balance and water production in the same parameter. The variable operation cases lead to the best values of SEG: 3.63–3.68 kWh/m^3.
- With the considerations of a diesel price of 0.81 €/L and an additional CAPEX for modular options of 25%, the most economical cases are a conventional SWRO plant working at constant power (case 0) and the same unit operating in variable model (case 1): 1.97 and 1.93 €/m^3 respectively. It means 0.22–0.36 €/m^3 less than the modular options (cases 2 and 3).
- Two hypothetical scenarios have been contemplated to compare the water cost in each case: diesel price of 2 €/L, and non-refundable funding (Table 16). In the first situation, the gap of water cost between less diesel depending case (case 3) and the reference case (case 0) is significantly reduced: from 0.22 to 0.10 €/m^3. On the other hand, scenario 2 makes the case 3 to be the best option, since the expense in diesel is minimum and investment is excluded, obtaining a very attractive cost of 1.25 €/m^3.
- Considering only the modular options, 78% of water is produced by RE generation, and the average production could cover a daily demand of 120 m^3/d.
- A batteries capacity able to supply the load power demand along 3–5 h is the most appropriate selection in terms of reaching an optimal combination of water cost and RE supply.
- The inclusion of more wind power – from 1 × 17.5 kW to 2 × 17.5 kW (Fig. 11) - has the following positive consequences: 7% of increment in the water production, reduction of 0.2 €/m^3 in the water cost, increase from 65% to 72% in the RE operation time. On the contrary, it implies more RE energy (about twice) that cannot be consumed by the SWRO plant. Other uses of surplus electricity could increase the benefit of oversizing the wind power system.
- The forecast in the evolution of oil prices can lead to a scenario where the minimum water cost is obtained in the cases with maximum RE generation. From an estimated value of diesel price about 3 €/L, water cost increases up to 2.3 €/m^3, being the best option to install a modular and variable operation SWRO plant.

To sum up, autonomous RE-powered SWRO low scale systems are, for the moment, uncompetitive in comparison with conventional energy supply. Nonetheless, the prospects of higher diesel costs and lower RE CAPEX will lead to attractive RE-desalinated water costs. Besides that, considering the objective of maximizing production with minimum diesel consumption, case 3 design is recommended with batteries capacity enough for 3–5 h of operation. The recommended sizes for desalination capacity of 250 m^3/d are the following: PV, 75 kWp; batteries capacity, 4 h; wind power, 2 × 17.5 kW; thus achieving a water cost around 2.0 €/m^3 and 70% of the time powered by RE only at Pozo Izquierdo, Gran Canaria. On the contrary, considering the objective of minimizing water cost with current diesel prices, case 1 is the best option. Recommended sizing of subsystems considering 250 m^3/d are 45 kWp PV system installed, 3–5 h of a batteries capacity and 17.5 kW of wind power installed. This case achieves about 1.93 €/m^3 and 70% of the time powered by RE only at Pozo Izquierdo, Gran Canaria.

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Annex A. Calculation procedure

A1. Energy balance

A1.1. Generalities

The power balances of the system are calculated for each component according to the following process:

$$F_j = P_j + L_j \tag{1}$$

$$\eta_j = \frac{P_j}{F_j} \tag{2}$$

Combining Eqs. (1) and (2):

$$L_j = (1 - \eta_j) \times F_j \tag{3}$$

where F_j is the ingoing power flow to the component j; P_j is the outgoing power flow from the component j; L_j is the lost power flow from the component j; η_j is the energy efficiency of the component j.

The values considered for the efficiencies are the following:

- DC/AC and AC/DC converters: 90%
- Transformer: 98%
- Batteries: 85%
- Diesel engine: 30%
- Diesel generator: 95%
- High-pressure pumps: 80%
- Low-pressure pumps: 50%
- Photovoltaic (PV) panels: 15%

It is assumed that all the efficiencies are constant along the time; in the case of pumps, there are not strong flow variations from the operation time; and in the case of PV field, the selected value is quite lower than the commercial values (20%–21%) to consider the temperature, dirtiness and other reduction efficiency effects, moreover, the variations of temperature along the year are in the range 8°C–31°C (Fig. A1).

A1.2. Wind power output

The output power from the wind generator is calculated according to the following equations:

When $v < v_1$

$$P(v) = \sum_{k=0}^{k=m} a_k \times v^k \tag{4}$$

where "m" is the number of coefficients and depends on each wind turbine.

When $v \geq v_1$

$$P(v) = \frac{P_n}{\left(1 + \dfrac{P_n}{P_0 \times e^{-rv}}\right)} \tag{5}$$

where v is the wind speed in any time; v_1 is a wind speed value from which Eq. (4) is acceptable; v_0 is the minimum wind speed to produce power; $P(v)$ is the wind power associated to v; P_n is the nominal power of the wind generator; P_0 is the power of the wind generator at v_0; a_k is the parameters obtained by a polynomic correlation from the power curve values; r is the parameter obtained by checking Eq. (4) with the power curve from the manufacturer to maximize the correlation.

The wind speed at 10 m is corrected to consider the variation along the height:

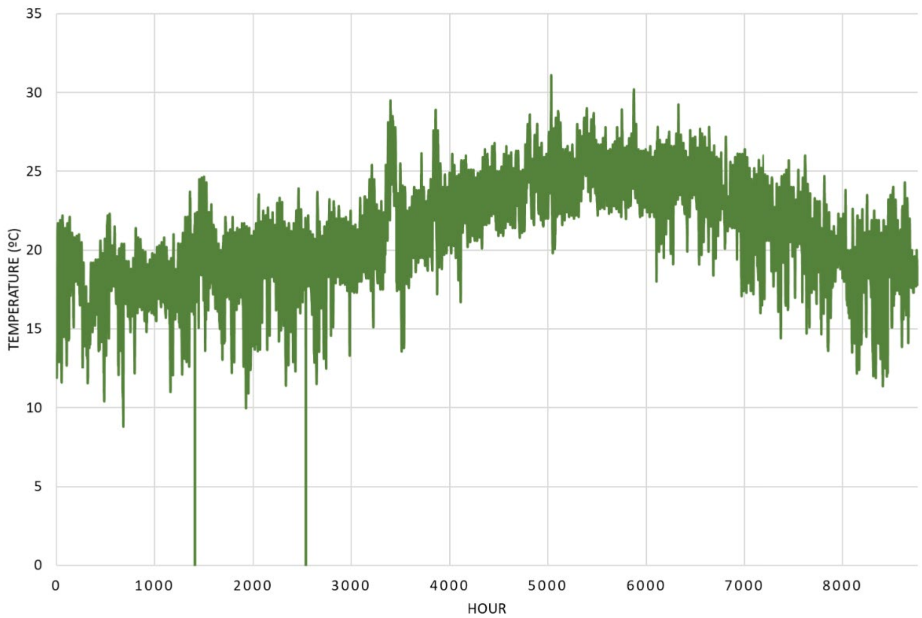


Fig. A1. Evolution of hourly temperature throughout the year.
Source: Canary Islands Institute of Technology.

$$\frac{V_h}{V_{\text{ref}}} = \left(\frac{H_h}{H_{\text{ref}}}\right)^{\lambda} \tag{6}$$

where V_h is the wind speed at the hub height; V_{ref} is the wind speed at the reference height (raw wind data at 10 m); H_h is the height at the hub; H_{ref} is the height at the reference height: 10 m; λ is the parameter to consider the soil roughness: 1/7.

The values of the parameters are given in Table A1, which is complemented with the chart of the power curves.

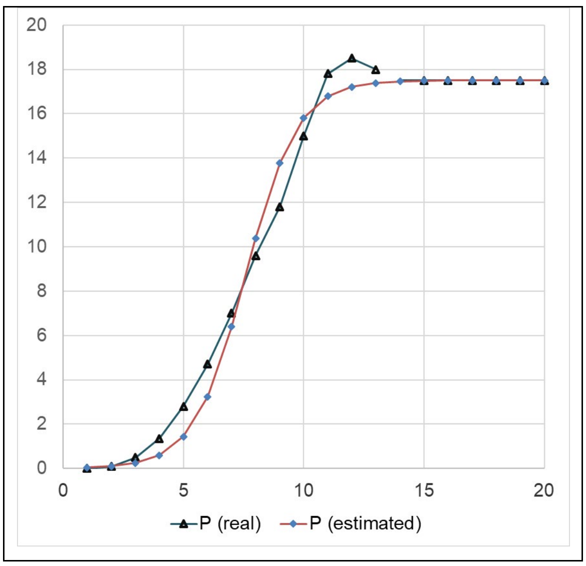
A1.3. Reverse osmosis power

The reverse osmosis (RO) power demand is obtained from the head and flow of the different pumps of the desalination plant; the power of a pump is calculated according to Eq. (7):

$$P_p = \frac{H \times Q}{\eta_p} \tag{7}$$

Table A1
List of values to calculate the output power of the wind generator and chart of power curves: real from manufacturer data and estimated from the Eqs. (4) and (5)

Parameter	e200l (17 kW)
H_h (m)	10
v_1 (m/s)	10
P_0 (kW)	0.015
P_n (kW)	17.5
r (s/m)	0.93
a_0	0.7779
a_1	–1.6322
a_2	0.6159
a_3	–0.0399
a_4	0.0008



where H is the operation head; Q is the volumetric flow; η_p is the efficiency of the pump.

The total power demand in the RO unit is the sum of the power values of every pump.

A1.4. PV power

The power from the PV field is calculated from the installed area, the incident radiation on the PV panels and the efficiency (Eq. (6)). The incident radiation is calculated from the latitude (28°), albedo value (0.15), inclination angle (same than latitude) of PV panels and the global horizontal radiation by the software METONORM.

$$P_{\text{pv}} = \frac{I_n \times A}{\eta_{\text{pv}}} \tag{8}$$

where I_n is the normal radiation on the PV panels; A is the installed PV area; η_{pv} is the efficiency of the PV panel.

A1.5. diesel generator in the batteries

The batteries store energy, receiving and supplying power along with the charging and discharging processes respectively. These balances are calculated as follows:

Charge:

$$E_i = E_{i-1} + F_{\text{bi}} \times \Delta t \tag{9}$$

Discharge:

$$E_i = E_{i-1} - P_{\text{bi}} \times \Delta t - L_{\text{bi}} \tag{10}$$

Output power from batteries:

$$P_{\text{bi}} = \frac{E_{i-1} - E_i}{\Delta t} \times \eta_b \tag{11}$$

where E_i is the energy in the hour "i"; E_{i-1} is the energy in the hour "i–1"; F_{bi} is the ingoing power flow to the batteries in the hour "i"; P_{bi} is the outgoing power flow from the batteries in the hour "i"; Δt is the period of charging or discharging: 1 h; L_{bi} is the energy loss in the batteries; it can be calculated from Eqs (10) and (11):

$$L_{\text{bi}} = (1 - \eta_b) \times \left(E_{i-1} - E_i\right) \tag{12}$$

A1.6. Diesel generation power

Energy from diesel generator is used as a complementary energy source to reach the minimum operation time. The power is calculated to cover the minimum power demand of the desalination unit for each case of RO plant:

$$P_{\text{dg}} = \frac{P_{\text{ro}}}{\eta_{\text{dg}}} \tag{13}$$

where P_{ro} is the power demand of the RO plant; η_{dg} is the efficiency of the diesel generator.

A1.7. Annual energy balance

For each component, the annual consumed or generated energy is calculated from the power flows values in every hour:

Consumed energy in the RO plant:

$$E_{\text{ro}} = \sum_{k=1}^{k=8{,}760} P_{\text{ro},k} \times \Delta t \tag{14}$$

Generated energy:

$$E_g = \sum_{k=1}^{k=8{,}760} P_{g,k} \times \Delta t \tag{15}$$

Lost energy:

$$E_L = E_g - E_{\text{ro}} \tag{16}$$

A1.8. Annual water production

$$V_w = \sum_{k=1}^{k=8{,}760} Q_{\text{ro},k} \times \Delta t \tag{17}$$

$$Q_{\text{ro},k} = a \times P_{\text{ro},k} + b \tag{18}$$

where V_w is the total water volume produced along the year; $Q_{\text{ro},k}$ is the water produced in the hour "k"; $P_{\text{ro},k}$ is the total power supplied to the RO plant in the hour "k"; a and b are coefficients calculated from the maximum and minimum operation point of the RO plant; in the cases of fix flow/power point and modular RO concepts, "a" is the inverse of the specific energy consumption and "b" is equal to 0.

A1.9. Fuel consumption

Fuel consumption is calculated from the total annual energy produced by the diesel generator:

$$C_f = \frac{E_{\text{gd}}}{\eta_{\text{de}} \times \text{LHV} \times q} \tag{19}$$

where η_{de} is the efficiency of the diesel engine; LHV is the low heating value of the fuel (9,000 kcal/kg); q is a conversion factor from kcal to kWh (1.16×10^{-3} kcal/kWh).

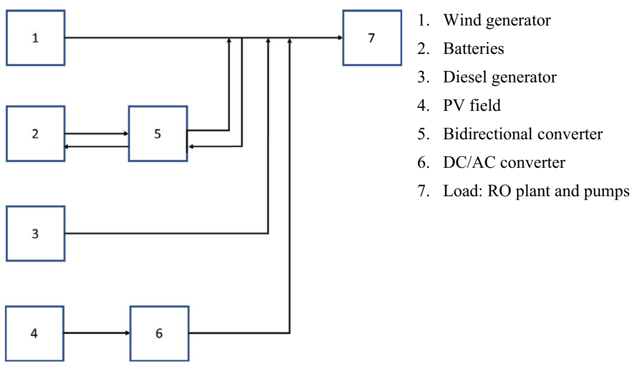


Fig. A2. Diagram of the main components of the system.

A2. Power balance

Fig. A2 illustrates the power flows among the different units or components of the system.

P_4 is obtained by Eq. (8). The surface of the PV field is calculated from the peak power (selected in 52 kW); this value is used as a parameter within the sensitivity analysis to find the optimal value.

In this case, the wind and PV power are used to run the RO plant, and then, to charge the batteries. When the power from renewable sources is not high enough to operate the RO plant, then batteries are discharged, and in case of lack of stored energy, then the RO plant is supplied by the diesel generator, so that the desalination plant operates along the whole year.

$F_6 = P_4$
$P_6 = F_6 \cdot \eta_6$
$L_6 = F_6 - P_6$

The possible situations are the following:

- When batteries are charged by renewable energy (RE) sources.

  If $P_1 + P_6 < F_7$ (RE power is lower than the minimum RO demand and flows to the batteries)
  Then:
  $F_5 = P_1 + P_6$
  The energy lost is:
  - In the PV inverter $(F_6 - P_6)\cdot\Delta t$
  - In the batteries converter $(F_5 - P_5)\cdot\Delta t$

  If $P_1 + P_6 >= F_7$ (RE power is higher than the minimum RO demand and flows to the RO plant, the surplus of power flows to batteries)
  Then:
  $F_5 = P_1 + P_6 - F_7$
  $P_5 = F_5 \cdot \eta_5$
  $F_2 = P_5$
  The energy lost is like the previous case.

When the energy stored in the batteries reaches the maximum value, then the solar and wind power either is transferred to the RO plant or lost as "unused energy" (L_{ue}) if the load cannot consume this available energy. In other words:
If $F_5 + E_{i-1} >= E_{b\max}$
Then $L_{ue} = P_1 + P_6 - F_7$

- When batteries are discharged to supply power to the RO plant.
  From Eq (11): $P_2 = \Delta E_b/\Delta t\cdot\eta_2$
  $F_5 = P_2$
  $P_5 = F_5 \cdot \eta_5$
  $F_7 = P_5$
  The energy lost is: $(P_2 - F_7)\ \Delta t$.

- RO plant supply
  If $P_1 + P_6 >= F_7$ (RE power is higher than the minimum RO demand)
  Then: F_7 is the maximum possible value within the operation range
  If $P_1 + P_6 < F_7$ (RE power is lower than the minimum RO demand)
  Then: F_7 is the maximum possible value within the operation range

A3. Water balance

A3.1. Water demand profile

The daily water demand profile is summarized in Table A2.

Table A2
Water demand profile along the day

Time	%	Case 0 and Case 1 (m^3/h)	Case 2 and Case 3 (m^3/h)
00:00–07:00	5%	10	7.5
07:00–18:00	75%	150	112.5
18:00–00:00	20%	40	30
Total	100%	200	150

A correction factor has been used to consider the seasonal variation of the water demand: 0.7 for winter (December, January, February, and March), 1.0 for spring and autumn months (April, May, June, October, and November) and 1.3 for summer (July, August, and September).

Daily water demand is estimated from the nominal RO production (250 m^3/d): 80% for the cases 0 and 1, and 60% for cases 2 and 3, since the annual production is lower in the modular cases.

A3.2. Evolution of stored water

A simple calculation of the mass water balance is expressed in Eq. (20).

$$V(i) = V(i-1) + \mathrm{Qp}(i)\times\Delta t - \mathrm{Vd}(i) \tag{20}$$

where $V(i)$ is the volume of water at the end of hour "i"; $V(i-1)$ is the volume of water at the end of hour "i–1"; Qp(i) is the water produced in the hour "i"; Vd(i) is the volume of water demanded in the hour "i"; Δt is the time between i and i–1: 1 h.

$V(i = 0)$ is the amount of stored water at the beginning of the year; it is considered that water level is at 50%.

The maximum water level (Vmax) is calculated from the maximum daily production (Vd) and the number of water supply days without operation of the desalination plant (T):

$$V_{\max}\left[\mathrm{m}^3\right] = \mathrm{Vd}\left[\frac{\mathrm{m}^3}{\mathrm{d}}\right]\times T\left[\mathrm{d}\right] \tag{21}$$

The value of T is estimated, by testing different values, to guarantee that the water storage tank is never empty: 10 d for case 0, 15 d for cases 1, 2 and 3.

The evolution of water in the storage tank is represented in the Fig. A3.

A4. Economic calculations

Economic calculations have been made according to data listed in Tables 9 and 10.

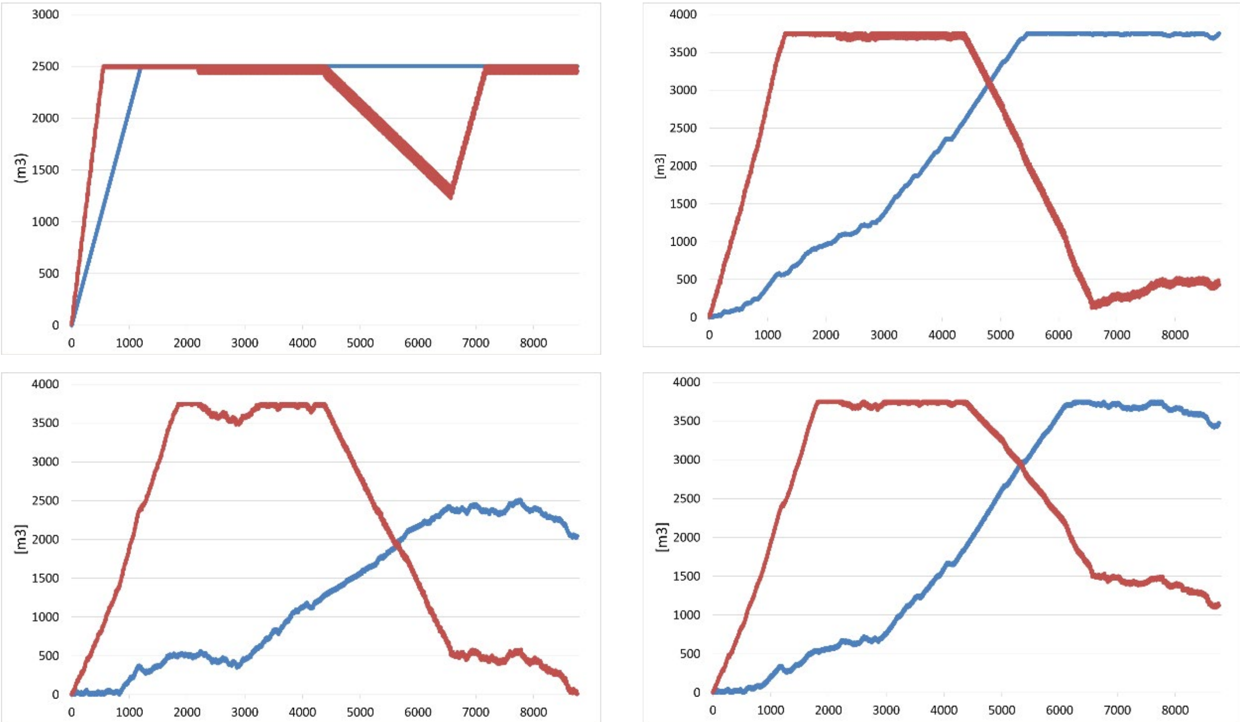


Fig. A3. Evolution of volume in the storage water tank throughout the year. The blue line indicates the volume considering a constant demand; the red line indicates the volume considering variable demand. From top to bottom and left to right: Case 0, Case 1, Case 2, and Case 3.

A4.1. Operation expenses

Fix and variable operation costs have been considered for the case of the wind farm components (wind generators, batteries, and converters). For the rest of the subsystems (RO plant, PV field, and diesel generator) only variable costs have been considered. Fix costs have been calculated from the nominal power or capacity and variable costs have been calculated from the energy or water production (Eq. (22)).

$$\mathrm{Cop} = \sum z_{\mathrm{fi}} \times X_i + \sum z_{\mathrm{vj}} \times Y_j \quad (22)$$

where Cop is the operation and maintenance (O&M) costs (€/y); z_{fi} is the ratios of fixed O&M costs; X_i is the value of a parameter associated to fixed O&M cost; z_{vj} is the ratios of variable O&M costs; Y_j is the value of a parameter associated to variable O&M cost

Diesel cost is calculated from the diesel consumption and the price of diesel and added as part of the variable operating costs.

A4.2. Capital expenses

The investment costs have been calculated from the specific investment and the associated nominal parameter (Eq. (23)), and then is included with the interest ratio and the amortization period to calculate the amortization costs (Eq. (24)).

$$I = \sum z_k \times S_k \quad (23)$$

$$C_{\mathrm{am}} = \frac{r\, I(1+r)^n}{(1+r)^{n-1}} \quad (24)$$

where I is the total investment or capital expenses (€); z_k is the specific investment of equipment "k"; S_k is the nominal size of equipment "*k*" used to calculate the investment; Cam is the amortization costs (€/y); r is the interest rate (–); n is the amortization period (y).

A4.3. Water cost

The water cost is obtained from the total annual cost and the total annual water production:

$$\mathrm{Zw} = \frac{\mathrm{Cy}}{P} \quad (25)$$

$$\mathrm{Cy} = \mathrm{Cop} + \mathrm{Cam} \quad (26)$$

where Zw is the cost of water (€/m^3); Cy is the total annual cost (€/y); P is the annual water production (m^3/y).