V. J. Subiela; B. Peñate and L. García-Rodríguez. Desalination and Water Treatment, 181, 2020, pp. 80-100. DOI:10.5004/dwt.2020.25091.

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

Vicente J. Subiela*(1), Baltasar Peñate(2) and Lourdes García-Rodríguez(1)

(1) *Escuela Técnica Superior de Ingeniería. Universidad de Sevilla. ESTI, Camino de Los Descubrimientos, s/n. 41092- Sevilla. Tel. +34 95 4487231. email:* vicente.subiela@hotmail.com; *email:* mgarcia17@us.es

(2) *Water Department, Research and Development Division, Canary Islands Institute of Technology. Playa de Pozo Izquierdo, s/n. 35119 Santa Lucía, Gran Canaria, Spain. Tel. +34 928 727520; Fax +34 928 727590;* baltasarp@itccanarias.org

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; RO 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 of 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.

Keywords: PV-powered desalination, seawater desalination, reverses osmosis, PV/wind-driven desalination, design configurations, water cost.

1. Introduction

This paper deals with ~~the~~ off-grid multigeneration (Solar photovoltaic (PV) with wind + diesel energy backup) systems coupled to SeaWater Reverse Osmosis (SWRO) plants in order to increase market opportunities of PV-powered Reverse Osmosis (RO) systems. Not only the multigeneration system is analysed but also 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-powered desalination. It corresponds to about 30 % of the total Renewable Energy (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, South of Europe) [2] [3] [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 2,100 L/h ([3]). Table 1 presents a selection of PVRO units in operation.

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**	**Ref.**
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]

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 operated systems commissioned after 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 converter to AC in an inverter to supply electricity to the RO plant. Figure 1 presents a selection of pictures showing the different components of the system.

PV field on the roof of the building

RO desalination plant

Control room with the inverter

Batteries room

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

The stable operation for long periods or 24/365 - uninterruptedly along the full year - operation requires the incorporation of additional energy sources, as 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 a RO plant leads to a set of operating implications: affection to the performance due to the daily starts & stops in terms of water production and water quality.

In the case of PV driven RO systems, the average operation time is about 5 - 8 hours / day, 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, the Table 2 collects the main operation data of the PV/RO unit installed in the remote village of Ksar Ghilene (Tunisia), which has been operating since 2006 [6]. The most relevant variation is in the quality of water.

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%

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

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

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

Since electricity generation should provide from several sources (photovoltaic 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].

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	80 – 85 %	100 %	170 - 750

- Incorporation of MPPT (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 a 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 a 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:

- 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 (weighed 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 & 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 feed water 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 based on axial pistons provide better efficiencies and less 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 to isolated, inland or coastal, sites with low, but stable demand of fresh water. The main inconvenient of standalone PV or wind supply is the limitation of the operation time to 8 – 18 hours per day 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 Figure 2.

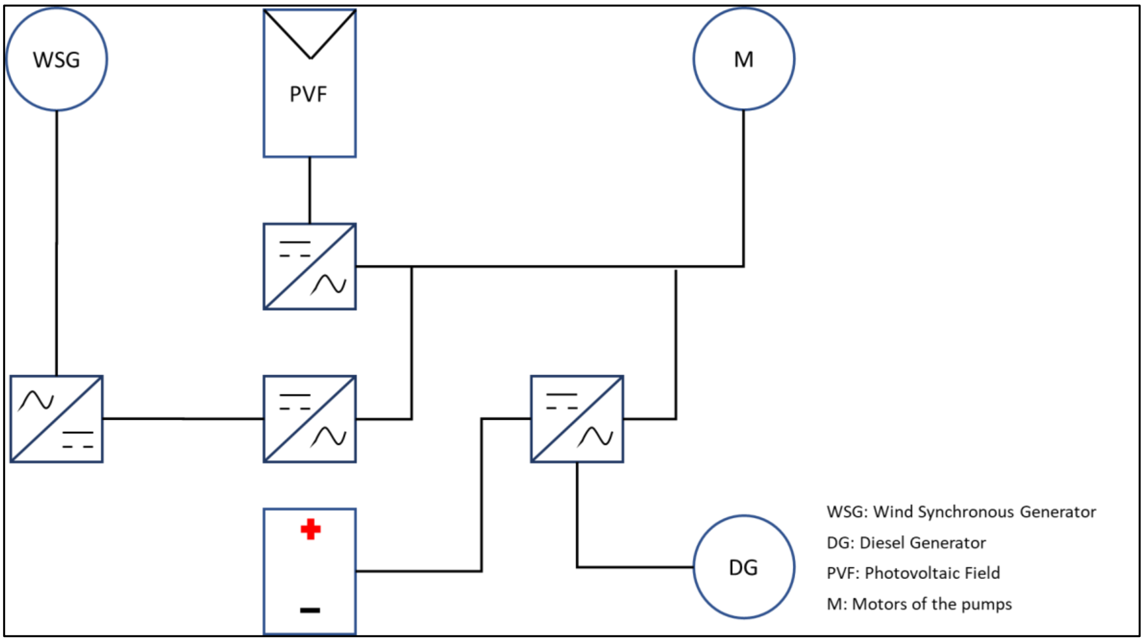


Figure 2. Electric diagram of the system (simplified version).

The objective of this section is to present and describe the technical concept of autonomous multigeneration energy 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 a maximum daily operation time (reaching 24 h/day)
    - 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 high-pressure pumps 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 high-pressure pump (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.

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)*
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

*Considering a recovery rate of 43% and desalination plant with a single SWRO train.

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 (TDS), and Silt Density Index (SDI) < 2.
- Energy consumption:
    - RO rack power demand: values given by the RO simulation software (See sections 3.5 – 3.7)
    - Feed water 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 consumptions associated to standard seawater pre-treatment and desalted water post-treatment energy requirement are included in the previous ranges.
- Solar radiation and wind speed data: from the data monitored in the facilities of the ITC (Canary Islands Institute of Technology) located in in Pozo Izquierdo, Gran Canaria Island (Spain).

The analyzed design options have been the following:

- Case 0 (Reference case): Use of high pressure pump 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 high-pressure pump 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 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.

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

Case	**Minimum water production (m^3/day)**	**Maximum water production (m^3/day)**	**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

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

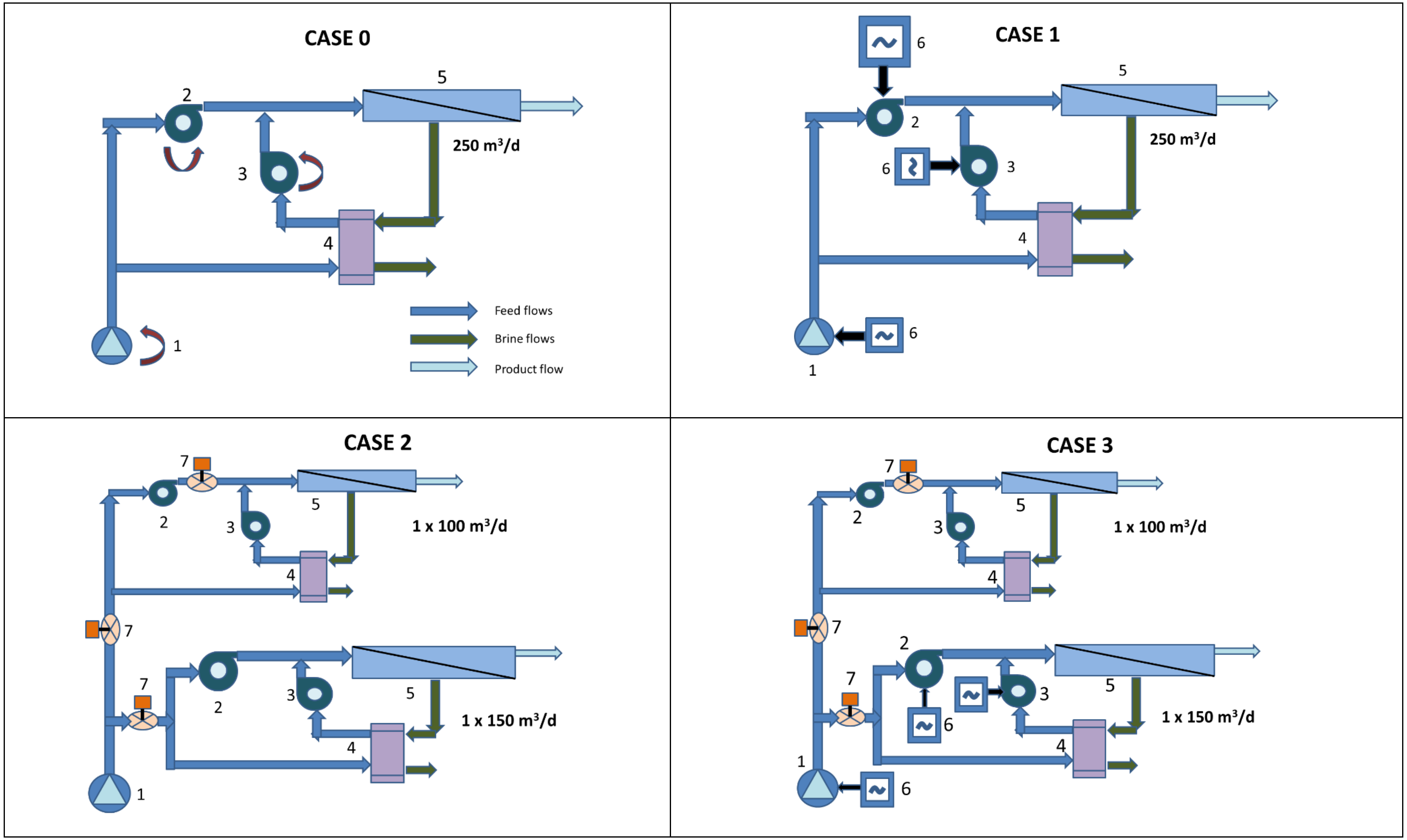


Figure 3. Basic hydraulic diagrams. Case0 (Reference case): RO unit of 250 m^3/d operating at nominal point. Case 1: RO unit of 250 m^3/d with variable operation. Case 2. Modular RO unit (100 + 150 m^3/d) at nominal point. Case 3: Modular RO unit (100 + 150 m^3/d) at variable operation. List of equipment: 1. Feed pump, 2. High-pressure pump, 3. Booster pump, 4. Energy recovery system, 5.Pressure vessels, 6. Frequency converter, 7. Automatic valves.

3. Methodology

3.1. Calculation procedure. Generalities

As the objective is to run the SWRO plant uninterruptedly throughout the 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 or 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 renewable energy 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 Figure 4 indicates the calculation flows mentioning the main variables. An example of energy flows for one-year balance is illustrated in Figure 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 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.

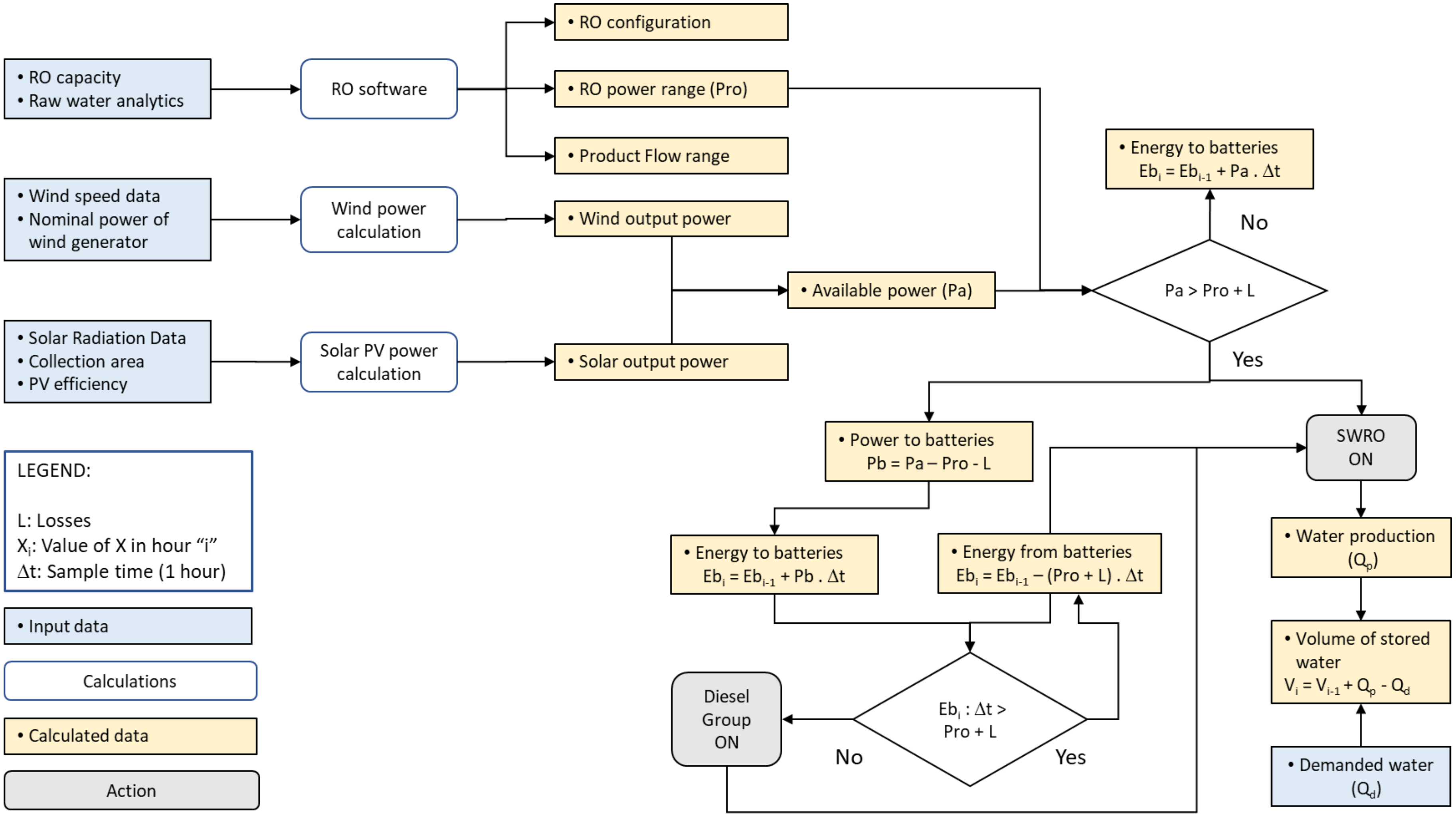


Figure 4. Graphic representation of the calculation and power / energy flows

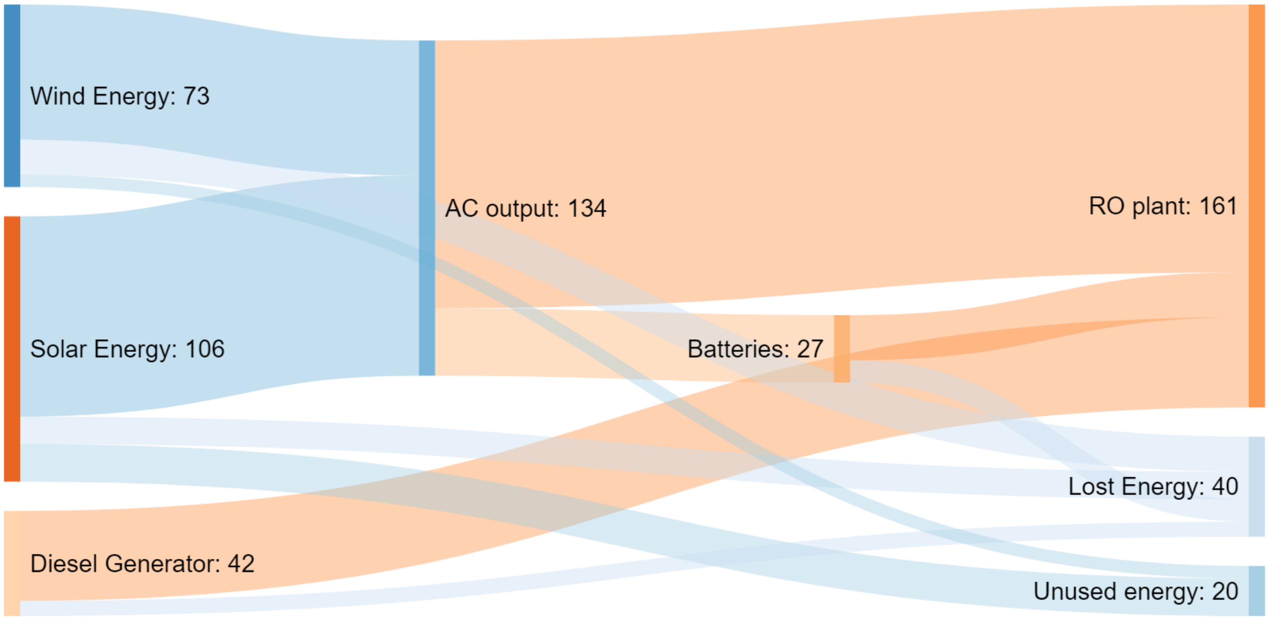


Figure 5. Illustrations of power flows. Case of Generation > Demand (Figures in MWh / a)

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, 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/(m^2·h).
- Predicted water product quality (under 400 ppm in all the cases).
- Specific energy consumption to calculate the total demanded power.
- Identification of other operation 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, high-pressure pump, booster pump, product water pump.

3.3. *Generated power*

Calculations of renewable power output has 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 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 tilted plane 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 & inverter series with wide range of output AC power (20 – 120 kW) and integration of input power from diesel generation
- Converters: Efficiency of 90% has been considered for AC/DC and DC/AC conversions.
- Batteries: Efficiency: 85 %; 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 & 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 the 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 to a reduction in the power demand and a modification of the operation parameters. Table 7 presents the values of the main operation variables for a selection of operation pressure values:

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

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

$$P\ [kW] = a \cdot Q\ [m^3/h] + b \qquad (Eq.\ 1)$$

Where “a” and “b” have 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.

Table 8. Range of operation parameters for the 100 + 150 m^3/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/m^3	L/(m^2 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

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

The case 3 is the combination of cases 1 and 3, i.e., the 150 m^3/d unit of the modular plant operates at variable point (from 115 to 150 m^3/d), and the 100 m^3/d operates at nominal point. The different combinations and the values of the operation parameters are summarized in Tables 9 and 10 respectively.

Table 9. Connection of SWRO units in the case 3

Daily production	Unit of 100 m^3/d	Unit of 150 m^3/d
100 m^3/d	On	Off
From 115 m^3/d	Off	On (partial operation)
150 m^3/d	Off	On (nominal operation)
From 215 m^3/d	On	On (partial operation)
250 m^3/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/m^3	$L/(m^2\ h)$	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

As the Case 1, a linear equation has been used to simulate the variable operation range of the large unit (115 – 150 m^3/d) (See 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 Figure 6.

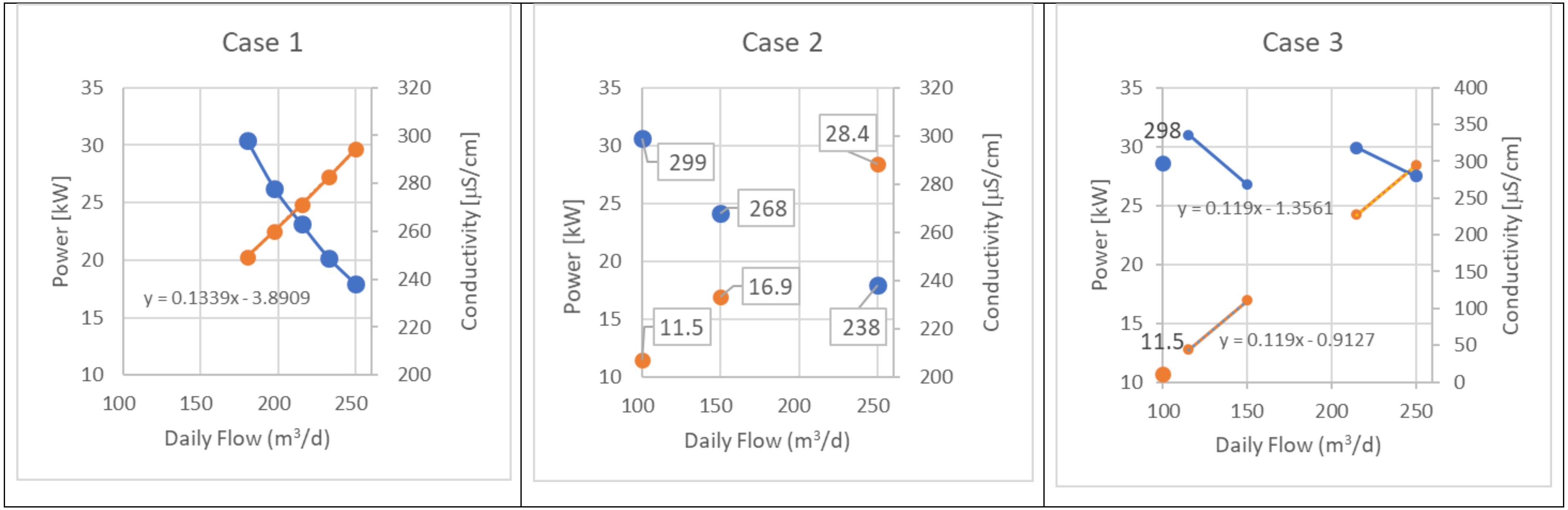


Figure 6. Charts illustrating the operation points of the SWRO plant for each case (Power: orange points; Conductivity: blue points)

3.8. Economic considerations

As there are many factors that 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 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 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 (See Table 11).
- Other costs (transport, customs, taxes, administrative management, engineering, control & 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.

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				

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 (see Table 12) incorporates the information collected from several O&M staff working in different installations and own data from ITC autonomous desalination systems.

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 LCOE (Levelized Cost Of Electricity)
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	

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 (see 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 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 the 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 generation is calculated to supply the minimum possible demand within 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 Figure 7 illustrate the input and output energy flows for the different cases, and main figures are indicated in Table 13 (units: MWh/yr).

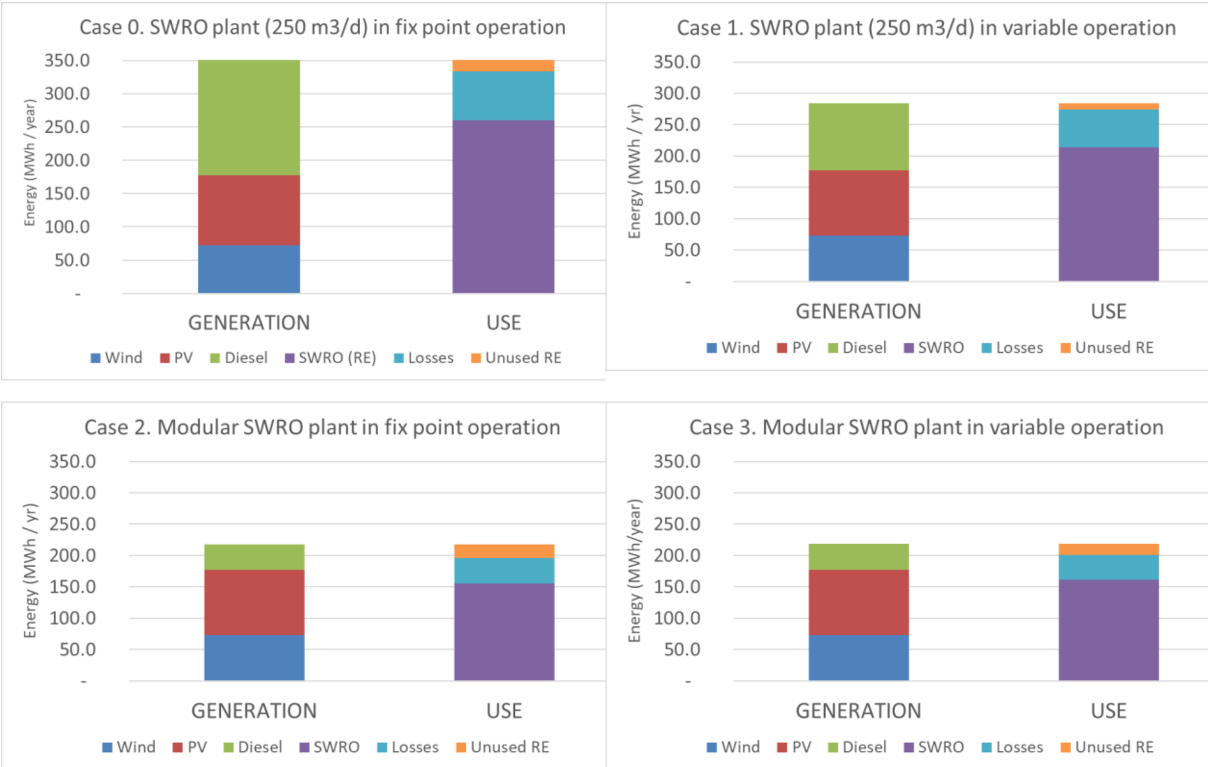


Figure 7. Charts of the annual energy balance for each case (units: MWh / yr)

Table 13. Values of the annual energy flows for each case (unit: MWh/yr)

	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**

The renewable energy 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 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 generation, 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 Figure 8, which exemplifies the evolution along 96 hours (four winter days) for the case 3. Values of wind and solar power 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.

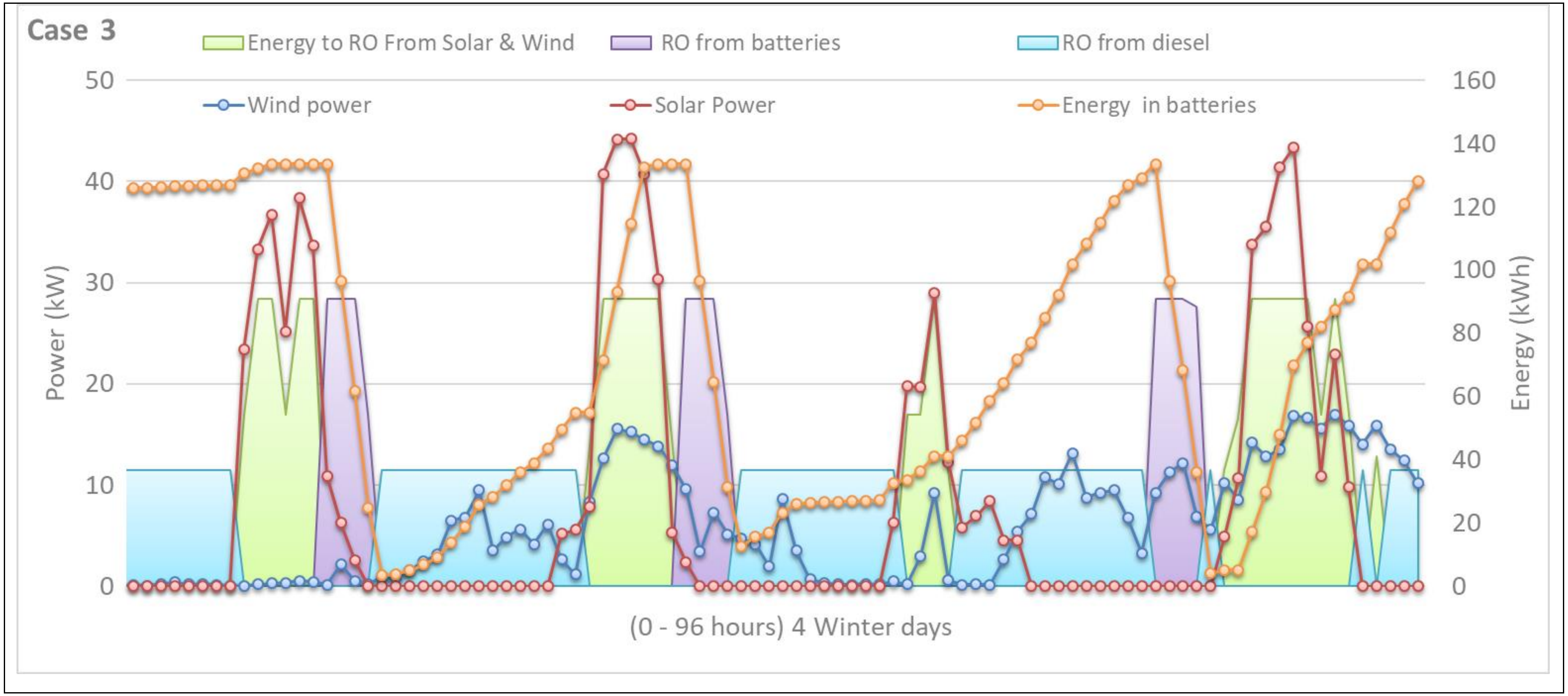
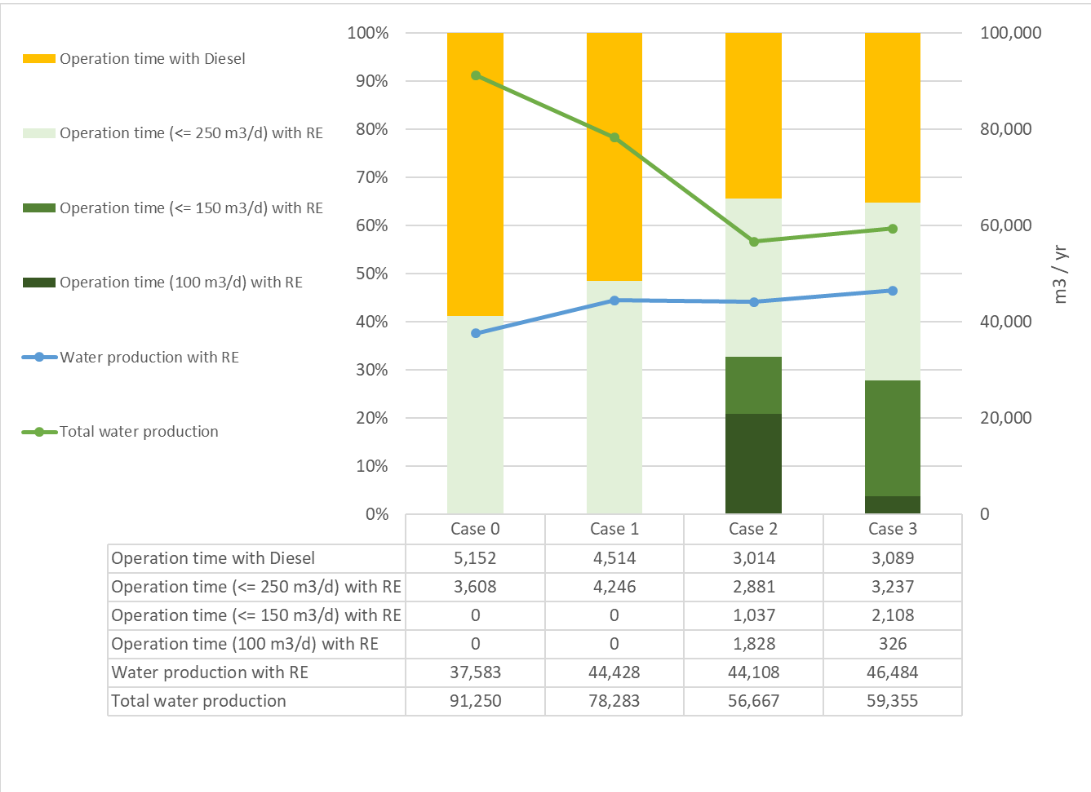


Figure 8. Chart with the generated power (wind, solar PV), connection of RO, and energy in batteries (4 Winter days) for the Case 3 (variable modular operation)

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 generation periods. Figure 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 production. In terms of water production from RE, it is very similar 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.



	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

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

The daily average water production is presented in Table 14:

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/day)	250	214	155	163
Water production by RE (m^3/day)	103	122	121	127
Water production by RE (%)	41%	57%	78%	78%
Water production by diesel (m^3/day)	147	93	34	35

The modular option is associated to the diesel generation 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) 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.

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

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; i.e., 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 the Cases 2 and 3 is higher due to the extra cost associated to the modular SWRO plant. The most economical option is the Case 1, since it is not modular and the required diesel generation power to be installed is less than Case 0.

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 (€ / daily m^3)	2,730 €	2,645 €	2,888 €	2,888 €
Diesel fuel expense (€ / yr), from a price of 0.81 €/L	10,649 €	6,377 €	2,403 €	2,463 €
Annual water production (m^3/yr)	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

Water cost of Case 3 is lightly better than Case 2 since there is more water production with this option. Nevertheless, there are not relevant differences among 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 a previous research: 2.2 \$/m^3, for a PV & wind & diesel powered SWRO model, with a nominal capacity of 24 m^3/day [28].

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 are 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 specially to Case 0: almost 9%, with less influence in Case 1 (6%), and less than 3% for Cases 2 and 3. The Scenario 2 leads to more economical water costs, benefiting to 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 greater associated capital expenses. Water cost and operation time by RE supply are plotted in Figure 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 hours of battery capacity. On the other hand, the percent of operation by RE power generation starts to stabilize from 3 - 6 hours, 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 hours is enough to reach the 73 % of RE operation.

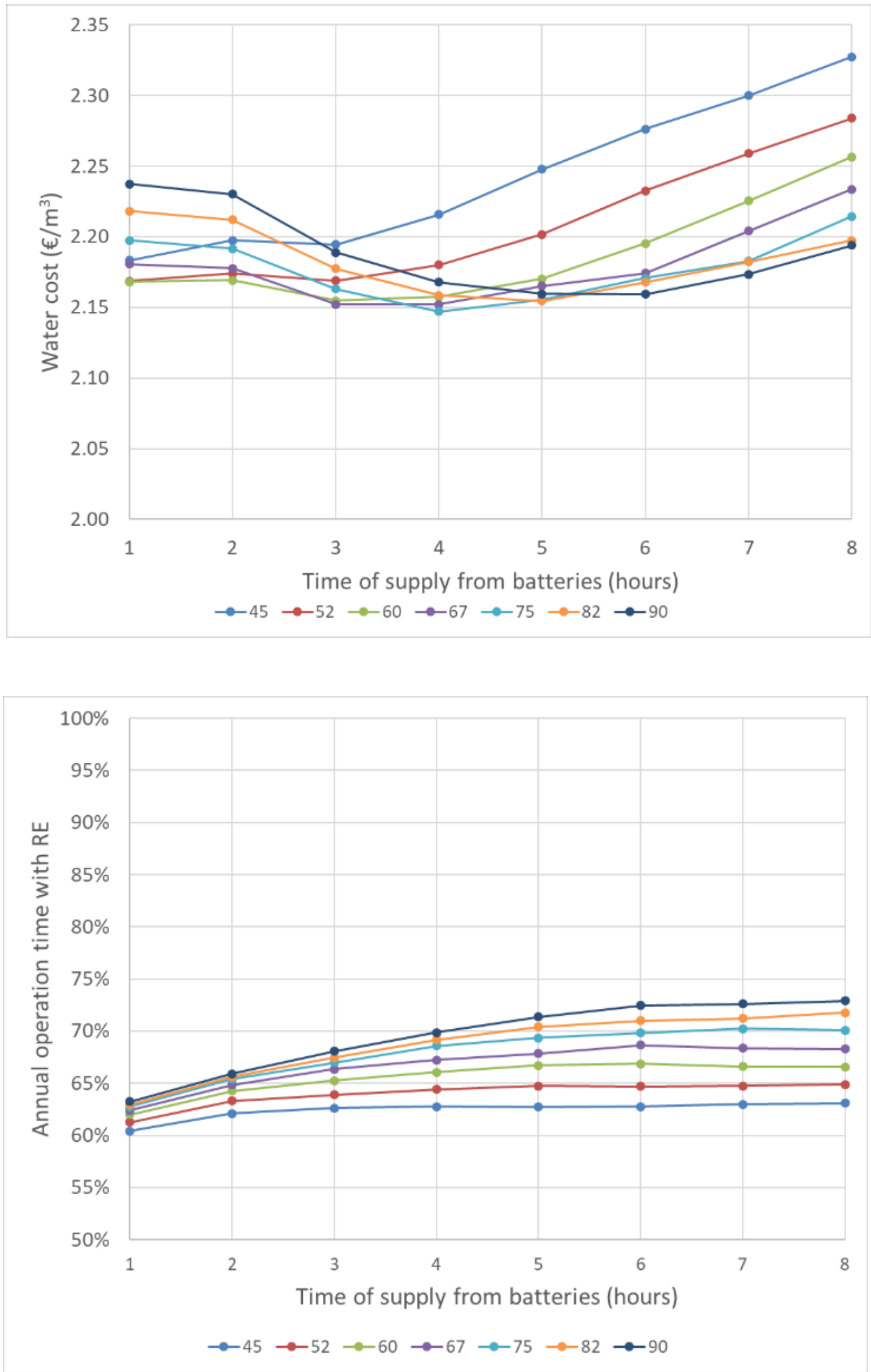


Figure 10. Variation of water cost (top chart) and operation under RE supply (bottom chart) for different values of battery capacity (in hours of supply) and PV power (in kW)

5.2. *Water cost and operation time vs. wind power*

The influence of the variation of installed wind power is indicated in Figure 11 for a fix nominal PV power of 52 kW and a battery capacity of 5 hours. 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.

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

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 of fossil fuels cost will modify the water cost, the Figure 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. Potential reduction in CAPEX of batteries and RE generation would accelerate this tendency.

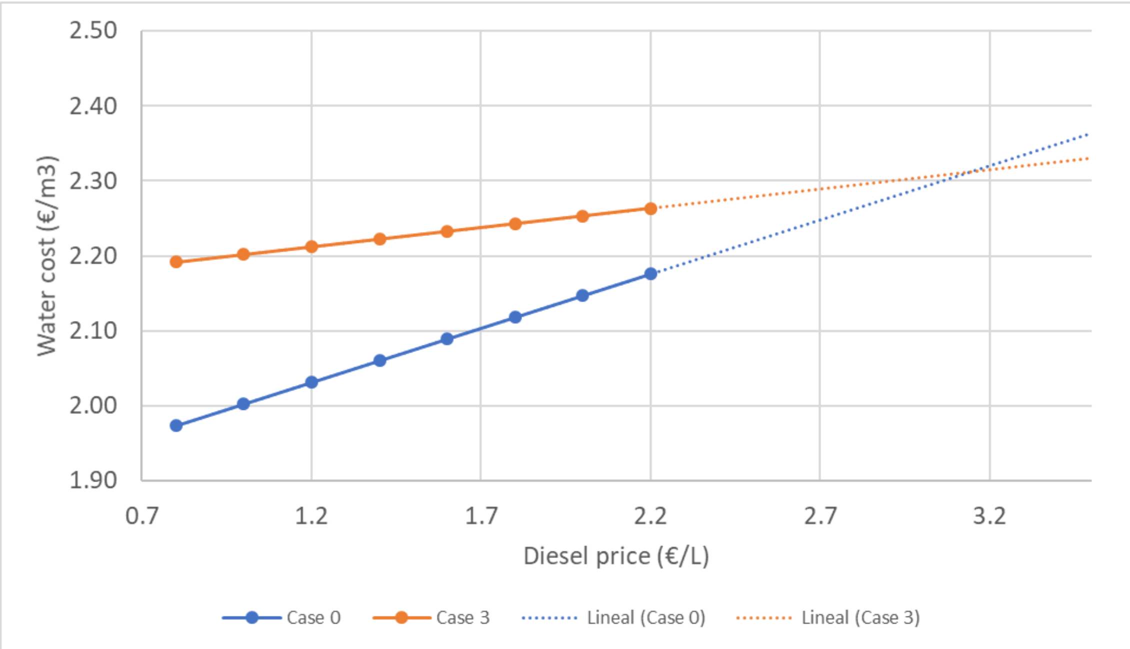


Figure 12. Possible evolution of water cost as function of diesel cost

According to this evolution of diesel price, water costs would be identical when diesel price reach 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 real 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 skids have been comparatively analyzed 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 generation 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 "Specific Energy Generation" ratio allows to have a fast idea of the energy balance and the 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 mode (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.~~ According to the results for Scenario 1, 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, the 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 €/m³.~~
- 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/day.
- A batteries capacity able to supply the load power demand along 3 – 5 hours 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 1x17.5 kW to 2x17.5 kW installed see 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 the 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 & 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 future prospective of higher diesel costs and lower RE CAPEX, will lead to attractive RE-desalinated water costs. Besides that, considering the objective of maximize production with minimum diesel consumption, case 3 design is recommended with batteries capacity enough for 3-5 h of desalination plant operation. Sizes recommended for desalination capacity of 250 m^3/d are as follows: PV, 75 kWp; batteries capacity, 4 h; 2x17.5 kW, thus achieving 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 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.

Acknowledgement

L. García-Rodríguez and B. Peñate wish to thank the European Regional Development fund, Interreg Atlantic Area, for its financial assistance within the framework of the EERES4WATER Project (EAPA_1058/2018).

7. References

[1] A. Cipollina, E. Tzen, V. Subiela, M. Papapetrou, J. Koschikowski, R. Schwantes, M. Wieghaus and G. Zaragozag, "Renewable energy desalination: performance analysis and operating data of existing RES desalination plants," *Desalination and Water Treatment,* pp. 1-21, 2014.

[2] L. Garcia-Rodriguez , "Seawater desalination driven by renewable energies: a review," *Desalination ,* no. 143, pp. 103-113, 2002.

[3] V. J. Subiela, B. Peñate, F. Castellano and F. J. Domínguez, "Chapter 8. Solar PV powered RO systems," in *Renewable Energy Applications for Freshwater Production*, J. Bundschuh and J. Hoinkis, Eds., CRC Press, 2012.

[4] A. Ghermandi and R. Messalem, "Solar-driven desalination with reverse osmosis: the state of the art," *Desalination and Water Treatment ,* no. 7, pp. 285-96, 2009.

[5] V. J. Subiela, J. A. de la Fuente, G. Piernavieja and B. Peñate, "Canary Islands Institute of Technology (ITC) experiences in desalination with renewable energies (1996–2008)," *Desalination and Water Treatment ,* vol. 7, pp. 220-235, 2009.

[6] B. Peñate, V. J. Subiela, F. Vega, F. Castellano and F. J. Domínguez, "Uninterrupted eight-year operation of the autonomous solar photovoltaic reverse osmosis system in Ksar Ghilène (Tunisia)," *Desalination and Water Treatment* , vol. 55, pp. 3141-3148, 2015.

[7] J. A. Carta, J. González and V. J. Subiela, "Operational analysis of an innovative wind powered reverse osmosis system installed in the Canary Islands," *Solar Energy,* vol. 75, no. 2, pp. 153-168, 2003.

[8] IRENA, "Electricity storage and renewables: Costs and markets to 2030," November 2017. [Online].

[9] V. J. Subiela and B. Peñate, "Autonomous desalination and cooperation. The experience in Morocco within the ADIRA Project," in *Water Security in the Mediterranean Region: An International Evaluation of Management, Control, and Governance Approaches,* A. E. M. B. Scozzari, Ed., Springer, Septiembre 2011, pp. 319 - 338.

[10] IRENA, "Renewable Power Generation Costs in 2017 (IRENA Publications)," 2018. [Online]. Available: http://www.irena.org/publications. [Accessed March 2018].

[11] IRENA, "IRENA Publications:; The power to change. Solar and wind cost reduction potential to 2025," 2015. [Online]. Available: http://www.irena.org/publications/2016/Jun/The-Power-to-Change-Solar-and-Wind-Cost-Reduction-Potential-to-2025. [Accessed November 2017].

[12] C.-S. Karavas, K. G. Arvanitis, G. Kyriakarakos, D. D. Piromalis and G. Papadakis, "A novel autonomous PV powered desalination system based on a DC microgrid concept incorporating short-term energy storage," *Solar Energy,* no. 159, pp. 947-961, 2018.

[13] M. Thompson, M. Miranda, J. Gwillim, A. Rowbottom and I. Draisey, "Battery-less photovoltaic reverse-osmosis desalination system," 2001.

[14] C. Sing-Foon, "Photovoltaic Reverse Osmosis Desalination System," U.S. Department of the Interior. Bureau of Reclamation, Denver, May 2004.

[15] IRENA, "Electricity Storage. Technology Brief," 2012. [Online]. Available: https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E18%20Electricity-Storage.pdf). [Accessed December 2017].

[16] ENAIR, "Aerogenerador Enair 200L," [Online]. Available: https://www.enair.es/es/aerogeneradores/e200l . [Accessed February 2018].

[17] LG Water Solutions;, "Tools," [Online]. Available: http://www.lgwatersolutions.com/en/tools. [Accessed February 2018].

[18] V. J. Subiela, B. Peñate and L. García-Rodríguez, "Innovative proposals for off-grid wind powered medium scale reverse osmosis plant optimization," *To be submmitted to Desalination,* 2018.

[19] ENF, "Solar Panel Directory," [Online]. Available: https://www.enfsolar.com/pv/panel?page=1. [Accessed February 2018].

[20] M. Blanco-Muriel, D. C. Alarcón-Padilla, T. López-Moratalla and M. Lara-Coira, "Computing the solar vector," *Solar Energy,* vol. 70, no. 5, pp. 431-41, 2001.

[21] Y. Dazhi , "Solar radiation on inclined surfaces: Corrections and benchmarks," *Solar Energy* , vol. 136, pp. 288-302, 2016.

[22] Meteonorm, [Online]. Available: http://www.meteonorm.com/. [Accessed February 2018].

[23] J.-D. Pitteloud and S. Gsänger , "Small wind world report 2016 (summary) (Av. at: small-wind.org/statistics)," World Wind Energy Association (www.wwindea.org), March 2016.

[24] ENAIR, *Commercial contact,* 2017.

[25] ENF, "Solar Inverter Directory," [Online]. Available: https://www.enfsolar.com/pv/inverter?page=1. [Accessed February 2018].

[26] H. w. tanks, "Water Tank Sizes and Capacities," [Online]. Available: https://heritagetanks.com.au/sizes-and-capacities/. [Accessed February 2018].

[27] W. w. p. products, "New and used diesel generators," [Online]. Available: http://www.wpowerproducts.com/Diesel-Generators-1-c-8.html. [Accessed Februrary 2018].

[28] M. Gökçek, "Integration of hybrid power (wind-photovoltaic-diesel-battery) and seawater reverse osmosis systems for small-scale desalination applications," *Desalination,* vol. 435, pp. 210-220, 1 6 2018.

[29] J. Carta, J. Gonzalez, V. Subiela, B. Peñate, E. Revuelta and V. Fernandez-Alonso,V, "Wind Power assisted RO System Configurations," in *9th IWA International Conference on Water Reuse. 27 – 31 October,* Windhoek, Namibia, 2013.

[30] H. Nor Shahida, M. Yusri Hassan, M. S. Majdi and H. A. Rahman, "Review of storage schemes for wind energy systems," *Renewable and Sustainable Energy Reviews,* vol. 21, pp. 237-247, May 2013.

[31] NREL, "NREL report," June 2017. [Online]. Available: http://www.nrel.gov/docs/fy16osti/64281.pdf.

[32] J. A. Carta, J. Gonzalez and C. Gomez, "Operating results of a wind–diesel system which supplies the full energy needs of an isolated village community in the Canary Islands," *Solar Energy,* vol. 74, no. 1, pp. 53-63, 2003.

[33] M. Beaudin, H. Zareipour, A. Schellenbergable and W. Rosehart, "Energy storage for mitigating the variability of renewable electricity sources: An updated review," *Energy for Sustainable Development,* vol. 14, p. 302–314, 2010.

[34] J. A. Carta, J. González, P. Cabrera and V. J. Subiela, "Preliminary experimental analysis of a small-scale prototype SWRO desalination plant, designed for continuous adjustment of its energy consumption to the widely varying power generated by a stand-alone wind turbine," *Applied Energy,* no. 137, pp. 222 - 239, 2015.

[35] J. Díaz-Caneja, M. Fariñas and R. Rubial, "Cost Estimation Briefing for Large Seawater Reverse Osmosis Facilities in Spain," January, 2004.

[36] E. Tzen, "Wind energy powered technologies for freshwater production: fundamentals and case studies (Chapter 69)," in *Renewable Energy Applications for Freshwater Production*, CRC Press, 2012.

[37] DOW Filmtec, "https://www.dow.com/en-us/markets-and-solutions/products/DOWFILMTECSeawaterReverseOsmosis8Elements/DOWFILMTECSW30ULE440i," [Online]. [Accessed December 2017].

[38] Danfoss. Energy Recovery Device, "https://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=4&cad=rja&uact=8&ved=0ahUKEwi617iTp4TYAhUInBoKHWLIDmsQFghBMAM&url=http%3A%2F%2Fhigh-pressurepumps.danfoss.com%2Fworkarea%2Fdownloadasset.aspx%3Fid%3D17179955493&usg=AOvVaw1_i80cuWDKCEGGAXB8QRur," [Online]. [Accessed December 2017].

[39] Energy Recovery. Desalination Products and Applications Catakogue 2013, 2013. [Online]. Available: https://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=9&cad=rja&uact=8&ved=0ahUKEwil98yUqITYAhVGOBoKHV5HCJcQFghUMAg&url=http%3A%2F%2Finfota.siss.cl%2Fconcesiones%2Fempresas%2FAguasdeAntofagasta%2F09%2520Estudio%2520Tarifario%2520SISS%2FAnexos%2FAne. [Accessed December 2017].

[40] Lennitech, "High-pressure pump. Type series booklet KSB," [Online]. Available: http://www.lenntech.com/Data-sheets/KSB-Multitec-L.pdf. [Accessed December 2017].

[41] ITC, Canary Islands Institutte of Technology, "Recurso Eólico de Canarias (Wind Resource in the Canary Islands)," [Online]. Available: http://www.itccanarias.org/recursoeolico. [Accessed December 2017].

[42] C. Moné, . T. Stehly, B. Maples and E. Settle , "2014 Cost of Wind Energy Review. NREL report," [Online]. Available: http://www.nrel.gov/docs/fy16osti/64281.pdf. [Accessed December 2017].

[43] ALMAR Water Solutions. , "Desalination Technologies and Economics: CAPEX, OPEX & Technological Game Changers to Come.," in *Mediterranean Regional Technical Meeting (CMI, Center for Mediterranean Integration)*, Marseille, December 12-14, 2016 .

[44] F. Bañuelos-Ruedas, C. Angeles-Camacho and S. Rios-Marcuello, "Methodologies Used in the Extrapolation of Wind Speed Data at Different Heights and Its Impact in the Wind Energy Resource Assessment in a Region," in *Wind Farm - Technical Regulations, Potential Estimation and Siting Assessment*, G. Orlando Suvire, Ed., 2011.

[45] B. Peñate, F. Castellano , A. Bello and L. García-Rodríguez, "Assessment of a stand -alone gradual capcity reverse osmosis desaliination plant to adapt to wind power avalability: A case study," *Energy*, vol. 36, no. 7, pp. 4372-4384, 2011.

[46] A. Poullikkas, "An optimization model for the production of desalinated water using," *Desalination*, vol. 258, p. 100–105, 2010).

[47] ECOFYS Netherlands B.V, "PRICES AND COSTS OF EU ENERGY. Final Report," April 2016. [Online]. Available: https://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwjmj4Oaw7nZAhUGlxQKHWB7BQkQFggqMAA&url=https%3A%2F%2Fec.europa.eu%2Fenergy%2Fsites%2Fener%2Ffiles%2Fdocuments%2Freport_ecofys2016.pdf&usg=AOvVaw0G54tfyNXoGXv83GxuTSuz.

[48] LENNTECH, "Water Treatment Solutions," [Online]. Available: https://www.lenntech.com/processes/desalination/energy/general/desalination-costs.htm. [Accessed June 2018].