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Design recommendations and cost assessment for off-grid wind-powered - seawater reverse osmosis desalination with medium-size capacity

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ABSTRACT

A technical and economic assessment has been made to simulate the operation of a wind energy-driven seawater reverse osmosis (SWRO) desalination plant (10,000 m^3/d). Three different generation systems were compared: wind and batteries; wind and diesel; wind and photovoltaic (PV). In each case, two options of the SWRO plant were considered: variable operation high-pressure pump and modular plant consisting of three different trains operated independently. The ranges of power demand of said options are 81%–100% and 20%–100% of the nominal value, respectively. The energy lost, operation time, water production and water costs for each case were calculated, concluding design recommendations with the best technical and economic criteria. Water cost was identified in the range 1–1.35 €/m^3, operation time under renewable energy supply can reach 75% of the year for modular reverse osmosis plant. A sensibility study for the water cost, for different parameters (capacity of batteries, diesel price, and PV power) was carried out for the different off-grid generation systems.

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

1. Introduction

In a previous analysis [1], the authors analyzed and discussed three options of a 5,000 m^3/d seawater reverse osmosis (SWRO) wind-powered theoretical model, based on different possibilities of variable operation of the reverse osmosis (RO) desalination plant:

- RO plant operating at the nominal point;
- Variable operation point of the high-pressure pump (HPP) (2/3–3/3 of its nominal capacity);
- Modular operation by several RO racks: 2 × 1,250 m^3/d + 1 × 2,500 m^3/d;

The proposed system included a back-up system based on batteries to obtain the power balance along with the whole analysis (hourly balance for one complete year). The study identified the best back-up size to obtain the minimum water cost for each case.

The renewable energy (RE) driven desalination projects have mostly included a back-up system to supply energy during the lack of renewable resource periods. However, the inclusion of an energy storage system has a relevant implication on the total investment cost (about 12%).

The stationary battery's energy cost (€/kWh) is expected to decrease by up to 30% of 2016 values for the year 2030 [2], leading to an attractive economic scenario of autonomous renewable-powered desalination. Nonetheless, battery-less systems have already been considered: previous wind-powered SWRO systems have been tested and studied without the inclusion of electricity storage [3], by adapting the load to

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the generation power, second by second, with only the support of very short-term energy storage units. On the other hand, previous research has been made on wind and diesel-powered RO systems [4].

Thus, the proposal considered and analyzed in this paper is to couple a 10,000 SWRO plant to an off-grid wind-based system including new generation sources (a photovoltaic (PV) field or a diesel generator) and excluding the batteries. These configurations will be compared with the stand-alone wind and batteries powered system. The objective is to reach the operation of the SWRO plant at least 75% of the time at the minimum water cost. The cases to be analyzed are the following:

- *Case 1*: Wind and batteries (reference case).
- *Case 2*: Battery-less wind and diesel generation.
- *Case 3*: Battery-less wind and PV generation.

Two types of SWRO plants will be studied for each case:

- SWRO plant with variable operation (76%–100% of the nominal power demand).
- Modular SWRO plant to operate at 20%, 40%, 60%, 80%, and 100%: 1 × 2,000 m^3/d + 2 × 4,000 m^3/d.

The presented analysis is based on the idea that the inclusion of another energy source will allow a stable supply throughout the low or no-wind periods. The power supply in the low wind periods will be covered by the auxiliary generation system (either PV or diesel) by connecting the SWRO plant at the minimum power demand point.

2. Background

A wide variety of conceptual systems can be considered to identify the best combination of SWRO and RE generation systems: actuations in the desalination plant, inclusion of other generation systems, reduction or elimination of batteries. The decision will depend on the conditions and particularities of the location of the system.

The Canary Islands Institute of Technology (Playa de PozoIzquierdo s/n Gran Canaria (Spain)) [5] has been researching into RE driven seawater desalination systems since 1995, testing several combinations of generation systems (wind energy, solar photovoltaic energy, low temperature solar thermal energy) with desalination units (RO, electrodialysis, vapor compression, humidification-dehumidification, membrane distillation) [6].

Three of the tested systems were focused on battery-less configuration for low capacities:

- A 100% PV powered SWRO system with a nominal capacity of 20 m^3/d;
- A 100% wind-powered SWRO system with a nominal capacity of 200 m^3/d [3];
- A 100% wind-powered SWRO system 18 m^3/d [7];

The lack of batteries leads necessarily to a variable or continuous operation of the RO plant; different strategies were used in each case. In the PV case, it was possible by a piping installation that allowed the connection of 1, 2 or 3 of the total pressure vessels of the RO unit. In the second case, it was possible because there were 8 SWRO units (25 m^3/d each) that could be connected separately according to the available power. And in the last case, the SWRO plant was capable of operating at different modes: 50% or 100% of the nominal capacity by using 2 or 4 of the pressure vessels respectively, variable pressure and flow rates by modifying the operating point of the HPP and the position of the reject water valve.

The main common conclusions identified from the research work on these systems were the following:

- the necessity of sophisticated monitoring and control system for appropriate regulation and operation;
- the operation out of the nominal conditions reduces the quality of water and increases the specific energy consumption (SEC);
- the variable operating range is determined by the characteristics of the SWRO plant: in the case of several modules in parallel or the case of variable flow operation;
- the maximum possible time of uninterrupted operation can be achieved by stopping one or more modules or reducing the operation flow; and also in the generating system: sending a power reduction signal from the main control system to the wind generating system, which will alter the position of the blades (pitch control);

3. Description of the proposed system

3.1. Generalities

A battery-less hybrid RE powered SWRO system is described according to the following components:

- *Desalination unit*: A 10,000 m^3/d SWRO plant (extendable to higher capacities) adapted to a variable power supply by considering 2 options:
  - Conventional plant operating at variable power by modifying the working point of the head booster pump;
  - *Modular plant*: 2 units of 4,000 m^3/d and 1 unit of 2,000 m^3/d, allowing a variable connection (Table 1);
- *Power system*:
  - *Wind generation system*: 2 × E44 model [8]. Total nominal power: 2 × 900 kW = 1,800 kW;
  - Auxiliary power supply (power to cover 75% of annual demand). Two options:
  - PV system
  - Diesel generator
- Short-term energy storage system: unit to cover the power supply gaps (periods of up to 30 s) plus buffer the associated frequency fluctuations: Flywheels, Supercapacitors or superconducting magnets.
- *Location of wind data*: Facilities of the ITC in Pozo Izquierdo. Pozo Izquierdo is a windy coastal area located in the Gran Canaria Island (Spain) where the ITC [5] has specific facilities to test RE powered desalination systems. Wind data collection has been done covering more than one year (sampling time: 1 h).

The capacity of the system can be extended by adding new 10,000 cmd modules, with the associated generating system.

The basic characteristics of the system are presented in Table 2.

3.2. Desalination system

The decision on the technical characteristics of the SWRO plant has been made according to the following criteria (Table 3). The selection of the membrane

Table 1
Possible operation modes of the modular SWRO plant

Units of 2,000 m^3/d	Units of 4,000 m^3/d	% of total capacity	Production (m^3/d)
ON	OFF	20%	2,000
OFF	1 ON	40%	4,000
ON	1 ON	60%	6,000
OFF	2 ON	80%	8,000
ON	2 ON	100%	10,000

Table 2
List of main data of the proposed installation

Data	Value (unit)	Observations
Water capacity	10,000 m^3/d	
RO power (case of variable HPP operation)	717–941 kW	Variable pressure and product flow
RO power (case of modular plant)	187–933 kW	
Feedwater pumping power	265 kW	Operating at the maximum feed flow, head = 5 bar, and 50% of efficiency
Average wind speed at the location	8 m/s	Annual value at 20 m of height
Average daily solar radiation	5.77 kWh/m^2	Global value on a horizontal surface
Annual operating hours (target value)	6,570 h	75% of the time

Table 3
List of main characteristics of the SWRO plant

Characteristics	Value (case of conventional plant)	Value (case of modular plant)	Observations
Product water flow	350–420 m^3/h	83–417 m^3/h	
Recovery	38%–42%	42%	
SEC	2.05–2.24 kWh/m^3	2.24 kWh/m^3	Assumptions in the pressure exchanger: 1 bar of differential pressure, volumetric mix of 15% and a leakage of 5%, and high-pressure pump efficiency: 82%.
Membranes/tube	7	7	According to the last decade tendency to optimize the production per tube.
Flux	13.6–17 L/m^2 h	17 L/m^2 h	Parameter to select the number of tubes.
Type of element	Ultra-low energy (LG Water Solutions, Seoul, Rep. of South Korea)	Ultra-low energy (LG Water Solutions, Seoul, Rep. of South Korea)	Lowest SEC for the same operating parameters. Comparison in section 4, ultra-low energy (ULE) elements from the manufacturer LG Water Solutions (Seoul, Rep. of South Korea) (thin-film nanocomposite technology).
Input/output pressure in the head booster pump	2–4/8–10 bar		
High pressure pump (HPP)	5 units Axial Piston Pump 86 (unitary flow: 35–88 m^3/h)	1 + 2 + 2 Axial Piston Pump 86	In the case of the modular plant, 1 unit for the small module (2,000 m^3/d) and 2 units for every large module (4,000 m^3/d).
Energy recovery system and booster pump	10 × iSave 70	2 + 4 + 4 iSave 70	In the case of the modular plant, 2 units for the small module (2,000 m^3/d) and 4 units for every large module (4,000 m^3/d).

elements has been made considering the lowest energy consumption option - "ultra-low energy" elements from the manufacturer LG Water Solutions (Seoul, Rep. of South Korea) (thin-film nanocomposite technology).

Fig. 1 illustrates the basic diagrams of the two SWRO configurations with the main components. The model DANFOSS Axial Piston Pump 86/1,700 pump has been selected as the HPP due to its high efficiency (over 85% at the nominal point) and wide operating range (30–70 bar; 35–88 m^3/h). Since the flow to be pumped is up to 416 m^3/h, 5 units of this pump in parallel are required. The variable operation point will be achieved by installing a frequency converter in just 2 units and maintain the other 3 at the nominal point. Thus, the minimum flow operation point would be obtained by this combination: 3 × 88 m^3/h + 2 × 46 m^3/h = 350 m^3/h. This option allows the reduction of the cost of investment (just 2 frequency converters are necessary) and in the global performance of the system (just 2 pumps are operating outside of the nominal point, that is, under the maximum efficiency; the average value of 80% has been considered).

3.3. Generating system

The generation system is a combination of 2 power supplies: the wind generator and the auxiliary supply (see options in section 1). Fig. 2 illustrates an elemental general diagram with all the generating options.

A vision of the main pros and cons of the different auxiliary energy sources is collected in Table 4.

3.4. Energy storage system

Since the selection of the best energy storage system is outside of the aim of this work, just basic information is included in this section.

Despite the described system being a battery-less concept, the inclusion of a short – term energy storage element is unavoidable for a stable power supply (maintenance of voltage in a restricted range of oscillations of frequency). There is a wide set of systems to be used with different grades of development; according to the technology used, a basic classification would be the following:

- *Mechanical energy*: flywheels, compressed air, pumped hydro storage;
- *Direct current electricity*: fast response batteries as NaS, Ni-Cd lithium, vanadium redox, ZnBr;
- *Developing technologies*: supercapacitors, superconducting magnets, fuel cells;

The main differences in the systems are the specific cost (up to 72 $/Wh in the case of superconducting magnets), the grade of development and the storage capacity [10].

The energy storage options selected for this study have been the flywheel, for short periods (seconds) and batteries, for longer time supply (minutes, up to a few hours). The use of high-performance batteries has been increasing during the last few years and there is progressive associated market availability. The total battery electricity storage capacity in stationary applications is expected to grow to 100–167 GWh for 2030 [2], mainly used in PV installations. Some few complimentary details for each technology are the following:

- Li-ion batteries are under an increasing deployment due to its application in electro-vehicles, mostly concentrated in the Asian market. Nonetheless, there are options for stationary applications, as off-grid RE generation.

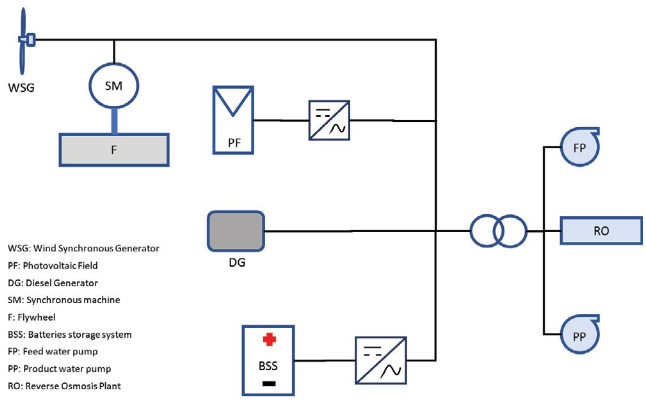

Fig. 2. Basic diagram of the multi-generation system.

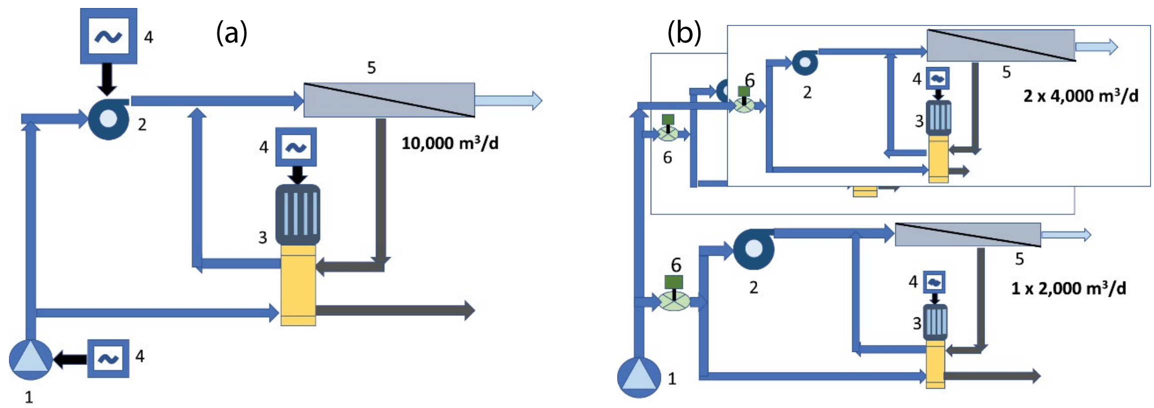

Fig. 1. Basic hydraulic diagram of the SWRO plant (a) case of variable operation and (b) case of the modular operation. 1. Feed pump; 2. High-pressure pump; 3. iSave70; 4. Frequency converter; 5. RO pressure vessels; 6. Automatic valve.

- Flow batteries, such as vanadium redox and Zn-Br, have lower efficiency than Li-ion, but can reach a lifetime of up to 10,000 full cycles and can be used in large-scale applications, among other advantages.
- NaS batteries have been extensively used for grid services in Japan since the 90 s. The main advantages of this option are the relatively high energy density (140–300 Wh/L) and a very low self-discharge.

4. Technical analysis

4.1. Desalination unit

4.1.1. Membranes performance

Two types of membranes from two different manufacturers were simulated to assess their performance in terms of SEC and water product quality. The simulations were made under the same theoretical conditions: water feed salinity: 38 g/L, no volume mixture and no losses in the energy recovery unit, efficiency of pumps: 82%. The results are collected in Table 5.

The range of recovery is 37%–44% in the option (i), and 35.3%–43.3% in option (ii); on the other hand, the range of average flow is 13.6–16.3 L/h m^2 for the first case, and 13–15.9 L/h m^2 for the second. To sum up, the first option allows for more production and quality with less energy.

4.1.2. Power demand profile: case of variable operation of the HPP

From the previous simulation data (NanoH_2O option), the operating power demand profile can be estimated with more accuracy according to these aspects:

Table 4
Comparison of main characteristics of auxiliary systems

Auxiliary generation system	Pros	Cons
PV power	• Low CAPEX technology (less than 2.5 €/Wp) [9] • Low environmental impact • High amortization period	• Large surface required (about 5.5/kWp) • Location not very close to shore to find the best solar conditions and avoid corrosion • Inclusion of direct current (DC)/alternating current (AC) converter • Connection to the grid to evacuate the excess of power and/or interrupted supply to a deferrable load
Diesel generation	• Low CAPEX technology (0.8 €/W) • Low maintenance • Fast response • Easy regulation • Long experience • Potential use of biofuels	• Cost of fuel (quite variable depending on the location). It is expected to increase in the short/medium-term future • Environmental impact (about 1 kg CO_2/kWh)
Hybrid option (combination of diesel + solar technology)	• Open the possibility of taking the advantage of the favorable elements of both technologies	• Most complex installation • Most complex control system • More expected MandO specific costs since two types of trained staff are required

Table 5
List of simulation results comparing two types of software and membranes

LG membranes Nano H_2O				DOW Chemical (Midland Michigan, USA)			
Feed pressure (bar)	Product flow (m^3/h)	SEC (kWh/m^3)	TDS product (ppm)	Feed pressure (bar)	Product flow (m^3/h)	SEC (kWh/m^3)	TDS product (ppm)
51.93	420	1.92	318	54	410.24	2.00	359
51.08	410	1.90	321	53	400.39	1.98	362
50.19	400	1.87	324	52	390.35	1.95	366
49.40	390	1.86	328	51	379.94	1.93	370
48.63	380	1.84	331	50	369.14	1.90	375
47.82	370	1.82	336	49	357.97	1.88	380
47.10	360	1.81	340	48	345.84	1.86	387
46.34	350	1.79	345	47	333.82	1.84	394

- *Performance of the energy recovery system*: 1.0 bar of pressure drop, 15% of volume mixing, and 5% of leakage (SEC = 2.05–2.24 kWh/m^3);
- *Inclusion of power demand of the feedwater pump*: considering an efficiency of 50% and an outlet head of 5 bar implies an increment of 0.64–0.75 kWh/m^3 in the SEC value, depending on the recovery;

Thus, the total specific energy demand for each point of operation is summarized in Table 6.

Consequently, the system can operate in a range of power of 980–1,206 kW (81%–100%).

4.1.3. Power demand profile: the case of the modular unit

As was already analyzed [1], the operating time over one year can be significantly extended by a modular SWRO installation. A total water production of 10,000 m^3/d SWRO plants could be considered as a modular plant composed by a rack divided into different operational capacities: one of 2,000 mcd and 2 sections of 4,000 mcd. This plant could operate in 5 different modes with 5 different water production values (Table 7). Furthermore, this option allows the high pressure pumps to operate very close to its nominal operation point (88 m^3/h), maximizing the efficiency of the operation. The operating range (20%–100%) is much higher than the previous case.

In this case, it has been considered that there is one specific feed water system (to pump the seawater from the intake to the plant) for each RO unit that operates simultaneously.

4.2. Energy balance

4.2.1. Generalities

The energy balance is made throughout the 8,760 h of the year. The possible situations of power balance are the following:

- *Wind power is higher than demanded power*: excess of generated power is either lost by altering the blade angle (pitch point).
- *Wind power is lower than demanded power*: in this case, there are two possible actions:
  - Use of auxiliary generating (diesel or PV) to produce the missing power demand.
  - Reduce the RO power demand by operating the RO plant under the nominal point or adapting the modular plant by connecting fewer modules or switching one of the large units to the small one.

According to the above-described options, the different situations are analyzed in this study (Table 8).

The energy storage in batteries is included only in cases 1.a and 1.b.

The values of the parameters used in the technical analysis are listed in Table 9.

4.2.2. Calculation of the auxiliary system

The auxiliary system will be connected when the available power from the wind system cannot cover the minimum power to operate the SWRO unit; this value will be calculated to maximize the operating time (target value: 75%) for the

Table 6
List of operation parameters and power demand values for the case of variable operation high-pressure pump

Product flow (m^3/h)	Recovery (%)	Feed flow (m^3/h)	Feed pump power (kW)	Pressure (bar)	SEC (RO) (kWh/m^3)	Power demanded in SWRO (kW)	Total power demanded (kW)
350	37%	945.95	262.76	50.20	2.05	717.50	980.26
360	38%	947.37	263.16	51.30	2.07	745.20	1,008.36
380	40%	950.00	263.89	53.15	2.12	805.60	1,069.49
400	42%	952.38	264.55	55.30	2.18	872.00	1,136.55
420	44%	954.55	265.15	57.70	2.24	940.80	1,205.95

Table 7
List of operation parameters and power demand values for the case of modular SWRO plant

Daily flow (m^3/d)	Hourly flow (m^3/h)	Units of 2,000 m^3/d in operation	Units of 4,000 m^3/d in operation	Presssure vessels (uds)	Pressure (bar)	SEC (RO) kWh/m^3	RO power (kW)	Feed pump power (kW)	Total power (kW)
2,000	83.3	ON	OFF	18	57.64	2.24	187	53	239
4,000	166.7	OFF	1 ON	36	57.71	2.24	373	105	479
6,000	250.0	ON	1 ON	54	57.71	2.24	560	158	718
8,000	333.3	OFF	2 ON	72	57.71	2.24	747	210	957
10,000	416.7	ON	2 ON	90	57.71	2.24	933	263	1,196

Table 8
Analyzed combinations

Cases	Generation system		
	Wind farm	Diesel generator	Solar PV field
1.a. Variable RO plant	■		
1.b. Modular RO plant	■		
2.a. Variable RO plant	■	■	
2.b. Modular RO plant	■	■	
3.a. Variable RO plant	■		■
3.b. Modular RO plant	■		■

Table 9
Values of technical parameters

Concept	Value
Nominal capacity of batteries, Ah	10,000
Useful capacity of batteries, Ah	8,200
Nominal power of wind generator, kW	900
Number of wind generators	2
Efficiency of converters (AC/DC, DC/AC), %	90
Efficiency of 1:1 transformer, %	98
Efficiency of diesel generator, %	30
Efficiency of PV field, %	15
PV field tilt angle, °	28
Nominal power of diesel generator, kW	1,270
PV panels area (conventional SWRO plant), m^2	10,000
PV panels area (modular SWRO plant), m^2	5,000
PV peak power (conventional SWRO plant), MW	1.7
PV peak power (modular SWRO plant), MW	0.85
Rugosity coefficient of land for wind speed profile adjustment	1/7
Efficiency of high-pressure pumps (feed and booster units), %	80
Efficiency of feed and product water pumps, %	50
Efficiency of batteries, %	85
Discharge depth, %	100

full year; other values of operating time can be tested. This evaluation will be made for every hour of the year to identify the different periods:

- *High wind periods*: operating with only wind power;
- *Medium wind periods*: operating in hybrid mode (wind + auxiliary power);
- *Low or no-wind periods*: operating only with the auxiliary system;

The option of including more than one auxiliary system has not been considered due to the high investment and operation and maintenance (O&M) costs associated.

The energy from the auxiliary system and additional installed power are calculated as follows:

- *Diesel generation*: This auxiliary generation is connected just when wind power can cover a small percentage of the maximum RO demand; with a value of 5%, an annual operating time of 75% is guaranteed. The nominal power is calculated from the nominal RO power and the efficiency of diesel generation (95%).
- *PV generation*: Power in each hour is calculated from the horizontal solar radiation (direct and diffused components), the tilt angle of panels and the efficiency (15%) and added to the available wind power to evaluate the total RE power and then check the maximum RO power that can be connected. The PV power is decided according to this:
  - *Case 3.a. (variable operation)*: A peak power value close to the nominal wind power is selected (1,724 kW).
  - *Case 3.b. (modular operation)*: The peak power (862 kW) is estimated as 50% of the power decided for case 3.a to reduce the investment as the modular RO plant can operate with lower available power.

Variations of the installed peak PV power are analyzed in Section 6.3.

Table 10
Values of economic parameters

Concept	Value	References	Comments
Specific CAPEX of wind generator	1,200–1,700 €/kW	[9,11]	Lowest value is used for the wind and diesel option and the highest value for the wind and batteries and the wind and PV cases since the diesel and wind case does not require so much investment.
Specific CAPEX of SWRO plant	875 €/(m^3/d)	[12]	
Specific CAPEX of diesel generator	760 €/kW		
Extra cost of the modular SWRO plant	35%		Estimation
Specific CAPEX of batteries	540 €/kWh	[13]	Estimated from average data
Specific CAPEX of converters	130–850 €/kW	[14]	A value of 1,000 €/kW is used to include the cabling installation and auxiliary equipment.
Specific CAPEX of solar PV field	1,100 €/kWp	[15]	
O&M costs of wind power (Fix part)	66 €/kW/y	[15]	Case of Germany, 2016
O&M costs of wind power (Variable part)	0.03 €/kWh	[15]	Case of Germany, 2016
O&M costs of PV power	0.02–0.125 €/kWh	[15]	Calculated as 25% of levelized costs of electricity (LCOE).
O&M costs of desalination plant	33 c€/m^3	[16]	Amortization and electricity costs excluded, cost of the rest of the items (labor, chemical products, membrane replacement, and others) have been doubled, since the SWRO plant will operate with interruptions.
O&M costs of diesel generation	0.001 €/kWh	[17]	Calculated considering 2% of total running costs (fuel is 98%).
O&M costs of batteries and converter	1.96 €/(kW year) + 0.56 c€/kWh	[18]	Fix part plus variable part
Diesel price	0.808 €/L		Local price of fuel
Interest rate	2%		
Amortization period	15 years		

4.2.3. Economic study

The economic data assumed in the calculation of costs are listed in Table 10.

Annex A describes the technical and economic calculation procedures in detail.

5. Results

Given the large amount of data and results, a selection of the most relevant outcomes is presented in this section for all the cases:

- *Technical results*: energy balance, water production and operating time;
- *Economic results*: specific cost of system (euros per installed daily cubic meter) and cost of water (€/m^3);

5.1. Technical results

5.1.1. Operating time

The distribution of time in the different periods can be seen in Fig. 3.

The wide variability of power demand for the modular option allows more time in operation outside of the nominal point (see blue area for cases b), that is, it is possible for the connection of the SWRO plant under low wind power periods; it implies that there is less generation from the auxiliary system in the cases b); consequently, the percentage of no operation periods (see orange areas), except the case of using diesel as auxiliary system, are smaller.

The minimum operating time of 75% is not achieved for cases 1.a and 3.a because the variable operation of the RO plant is too narrow (80%–100%) in comparison with cases 1.b

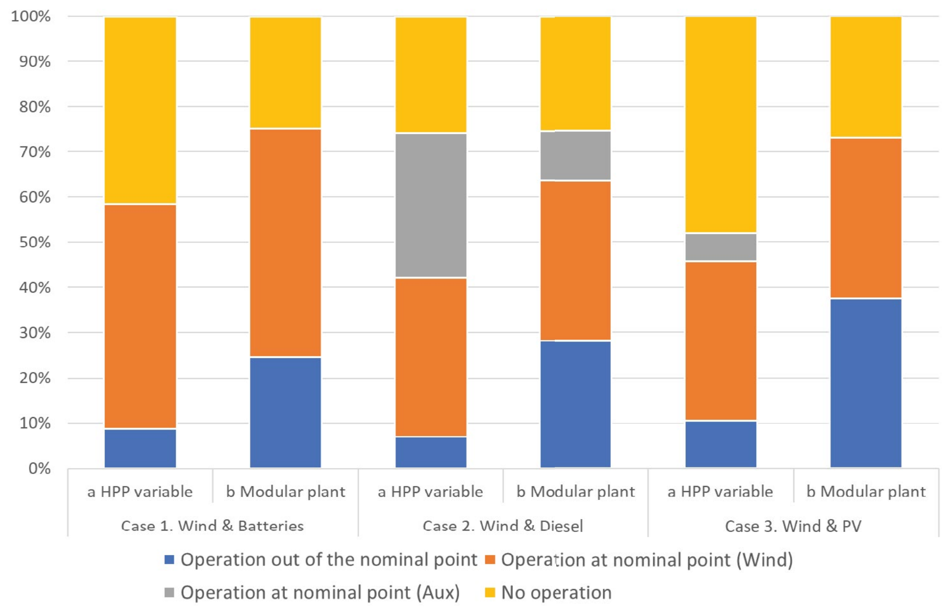

Fig. 3. Chart presenting the operation times throughout the year.

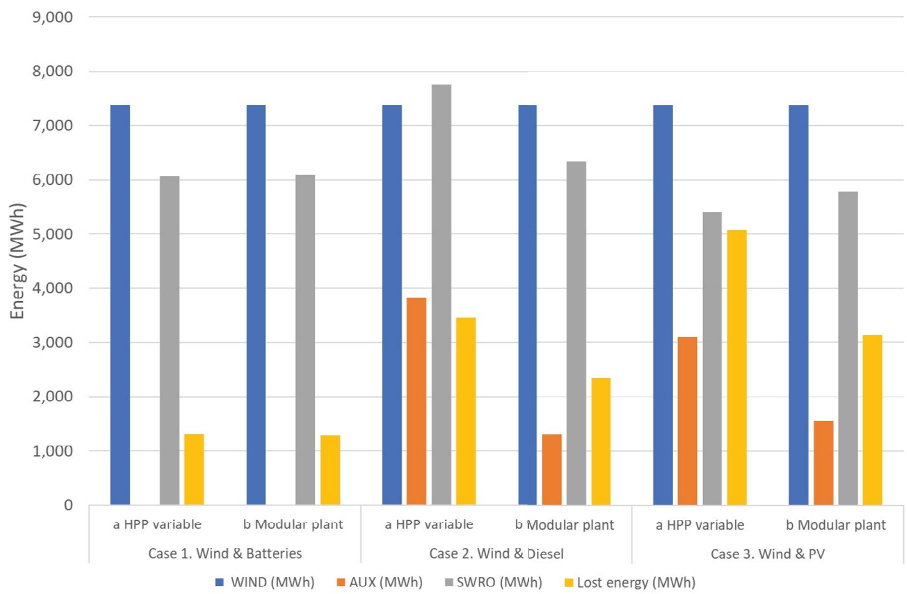

Fig. 4. Energy balance of the different studied cases.

and 3.b; nevertheless, it is possible for case 2.a by consuming more diesel.

The longest periods of operation at a nominal point are for cases 1.a and 1.b; the inclusion of batteries to fill the power generation gaps to connect the SWRO plant with the maximum power demand.

5.1.2. Energy balance

Fig. 4 illustrates the energy balances for the different cases, including the energy from the generation system (wind, diesel, and PV), the energy consumed in the SWRO plant and the energy losses, either in the internal conversions of the system or the produced energy unused by the load. Under an on-grid configuration, this part of generated energy could be supplied and potentially sold to a closed grid.

In cases 1, the modular option does not affect the total amount of consumed energy, this is because there are fewer operational hours in case 1.a, but with higher average power demand; the balance of both facts leads to similar total energy demand as in case 1.b. In cases 2, the objective is to reach a minimum operating time of 75% of the year; as a modular option (case 2.b) allows more operating time, less diesel generation is required. The inclusion of PV as auxiliary generating source (cases 3) increases the energy supplied to the SWRO plant in the modular option (case 3.b), in comparison with the conventional plant (case 3.a).

Besides that, the evolution of the power from the generating system and power consumed in the SWRO desalination plant for a high wind month (July) and a low wind month (January) is illustrated in a set of charts for the different cases:

- *Case 1.a*: Wind and batteries coupled to a conventional SWRO plant (Fig. 5);
- *Case 1.b*: Wind and batteries coupled to a modular SWRO plant (Fig. 6);
- *Case 2.a*: Wind and diesel generator coupled to a conventional SWRO plant (Fig. 7);
- *Case 2.b*: Wind and diesel generator coupled to a modular SWRO plant (Fig. 8);
- *Case 3.a*: Wind and Solar PV coupled to a conventional SWRO plant (Fig. 9);
- *Case 3.b*: Wind and Solar PV coupled to a modular SWRO plant (Fig. 10);

Each couple of charts is commented indicating the most remarkable aspects.

Concerning the conventional SWRO plant powered by wind power with batteries - case 1.a, Fig. 5., the operation in January requires a high number of starts and stops to connect the desalination plant; some level of adaptation to the power offer can be obtained by the variable operation of the HPP when the output wind power is slightly lower than the nominal value. On the other hand, the system is much more stable through the windy month (July), the wide availability of wind power allows a constant consumption at maximum capacity of the SWRO unit throughout almost the whole month.

In the case 1.b modular SWRO plant powered by wind power with batteries - Fig. 6, a higher operating time can be observed in January due to the modular operation of the SWRO plant and the different five levels of power demand can be observed. No relevant differences can be appreciated for July in comparison with the conventional SWRO plant (case 1.a).

In the case 2.a - Fig. 7 - only a wind and diesel generating system supplies the energy to the conventional SWRO plant without the storage in batteries. The incorporation of the diesel generator (green lines) under the low wind periods allows the connection of the SWRO plant, increasing the operating time (and the water production) in comparison with the wind and batteries generation. The absence of batteries obliges point by point regulation of the desalination plant on some days of July. The modular concept of the SWRO plant – case 2.b, Fig. 8 - leads to some more operating time using the energy from the wind generator to the conventional concept in the low wind periods.

The inclusion of a solar PV generation (cases 3.a and 3.b) increases the available power and extends the periods for the connection of the desalination plant. Regarding case 3.a - Fig. 9, the chart for January illustrates clearly the moments when the conventional SWRO plant is supplied only with solar power or a combination of wind and solar sources. The high wind and high solar radiation in July lead to a large amount of generating power than cannot be consumed since the load could be connected without the solar contribution.

In case 3.b - Fig. 10, the participation of the solar power was reduced to 50% of the case 3.a because due to the modular power demand of the desalination plant. The

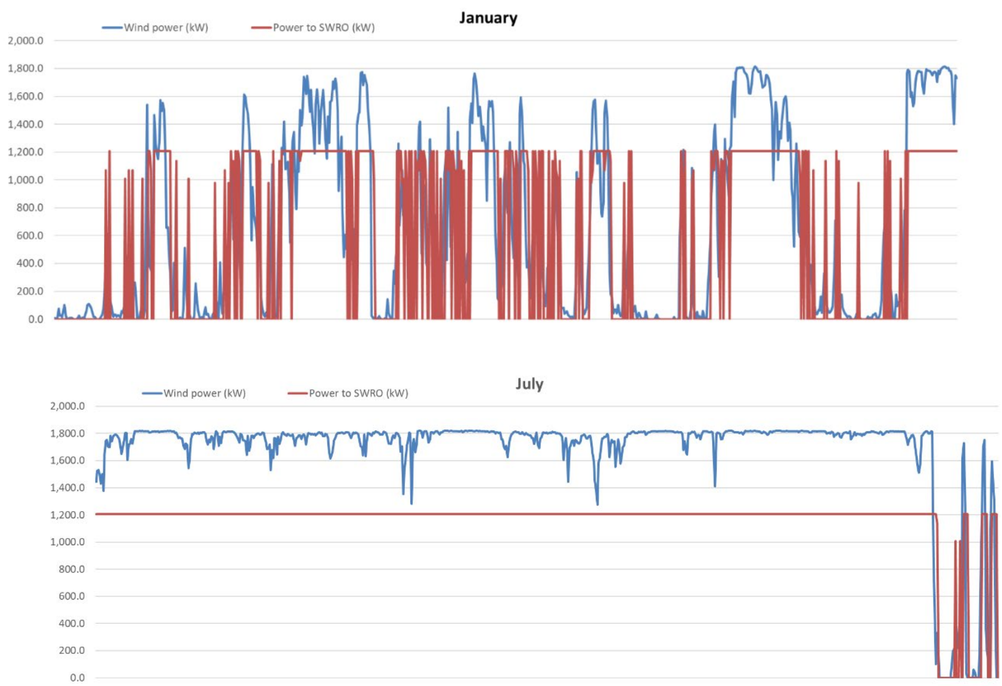

Fig. 5. Case 1.a Wind and batteries coupled to a conventional SWRO plant.

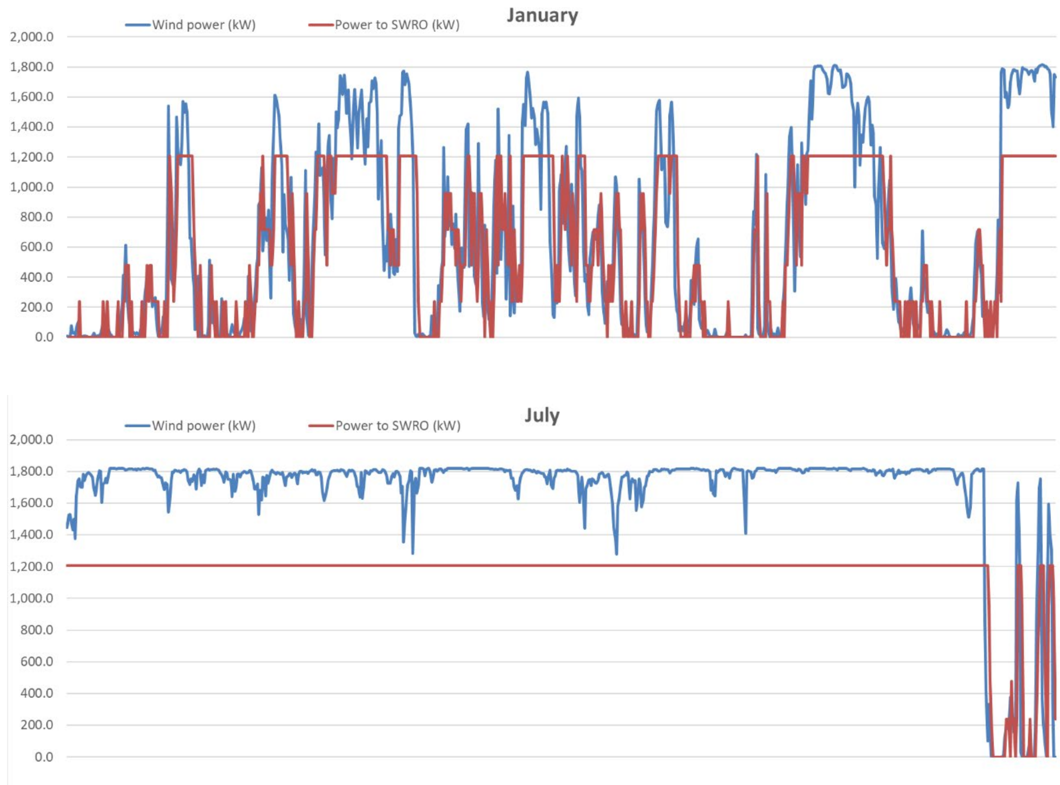

Fig. 6. Case 1.b Wind and batteries coupled to a modular SWRO plant.

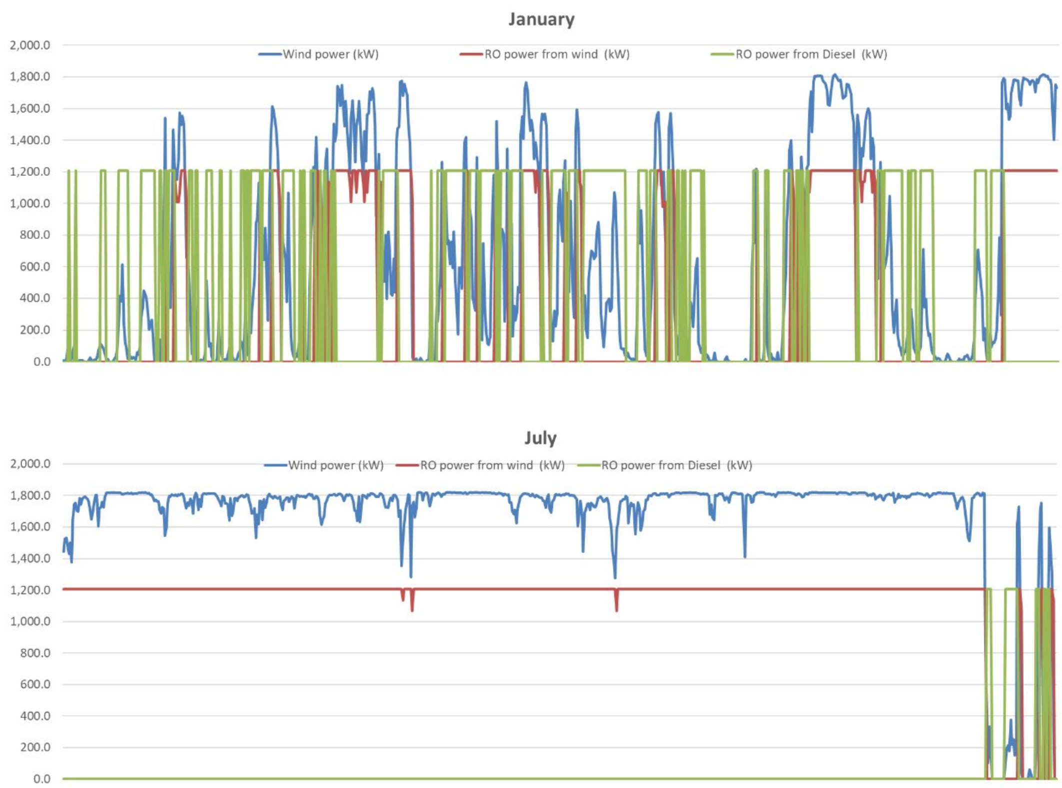

Fig. 7. Case 2.a Wind and diesel generator coupled to a conventional SWRO plant.

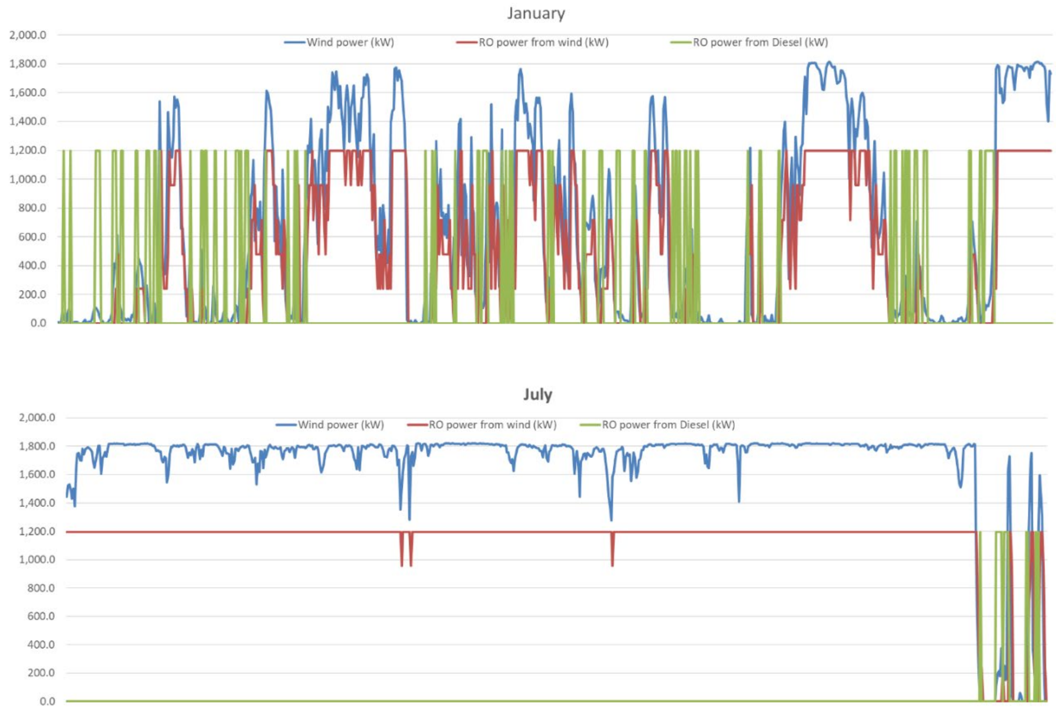

Fig. 8. Case 2.b Wind and diesel generator coupled to a modular SWRO plant.

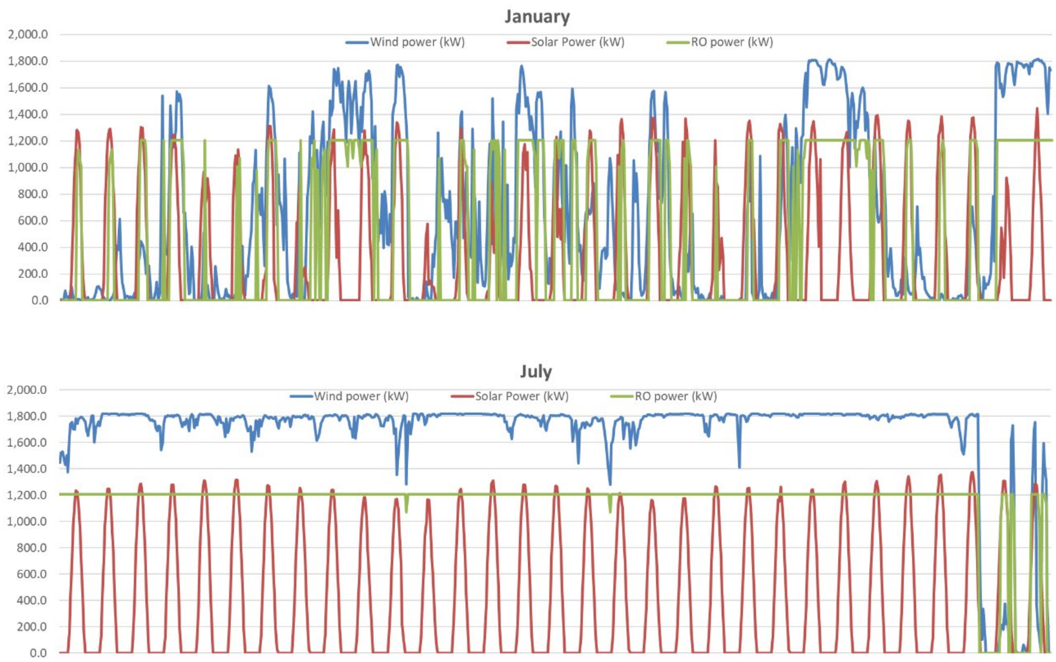

Fig. 9. Case 3.a Wind and Solar PV coupled to a conventional SWRO plant.

installation of just 5,000 m² of solar panels needed to reach 75% of the SWRO operating time over the year. The low wind chart (January) shows periods with operation with only solar power. As the case 3.a, there is no influence by the presence of solar PV power for July due to the high wind.

5.1.3. Water production

Water production for each case is represented in the chart of Fig. 11.

In cases 1a and 1b, the available energy allows the production of a similar amount of water, so the modular operation

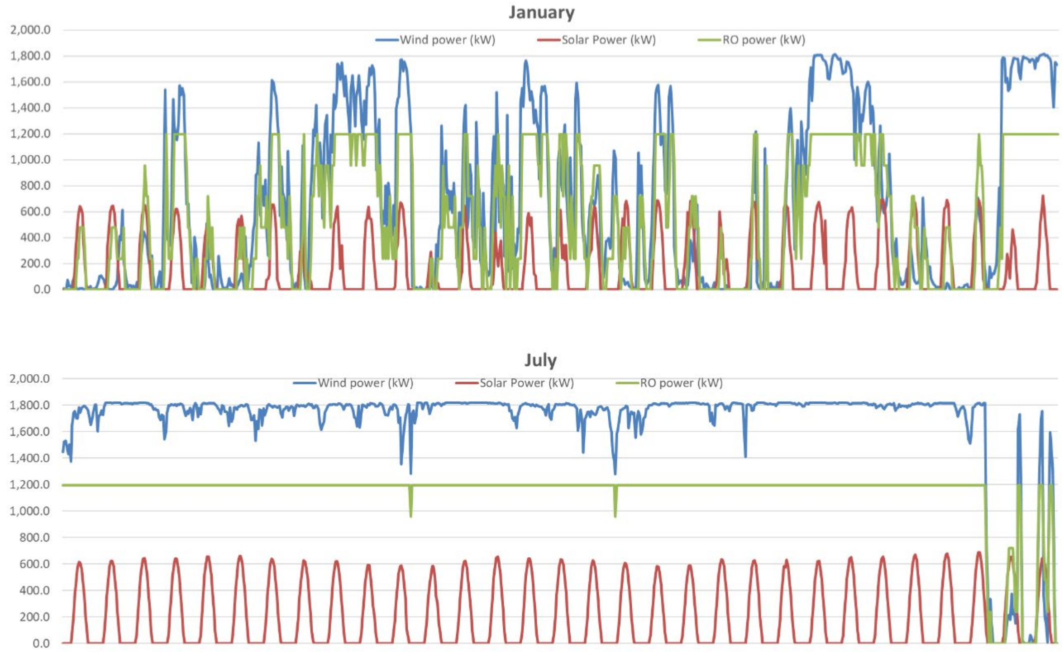

Fig. 10. Case 3.b Wind and Solar PV coupled to a modular SWRO plant.

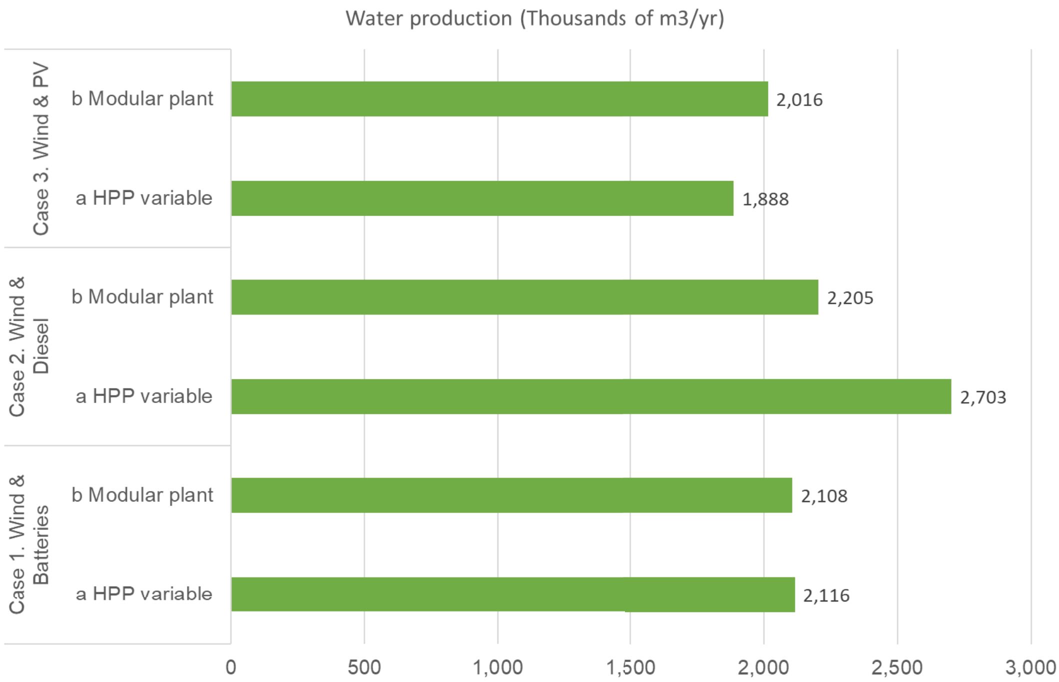

Fig. 11. Water production chart for the studied cases.

does not affect the annual water production; case 1.a operates less time than case 1b, but with higher consumption, and thus, higher water production. Case 2a produces more water than case 2.b because the time in operation with wind energy (56%) did not reach the minimum annual period of 75%; the rest of the time, energy is provided by diesel generation connected to the plant at nominal point (maximum water production). In cases 3, the variability of PV leads to more production for the modular option.

5.2. Economic results

The water production cost and the specific investment (ratio between the total investment and the nominal capacity

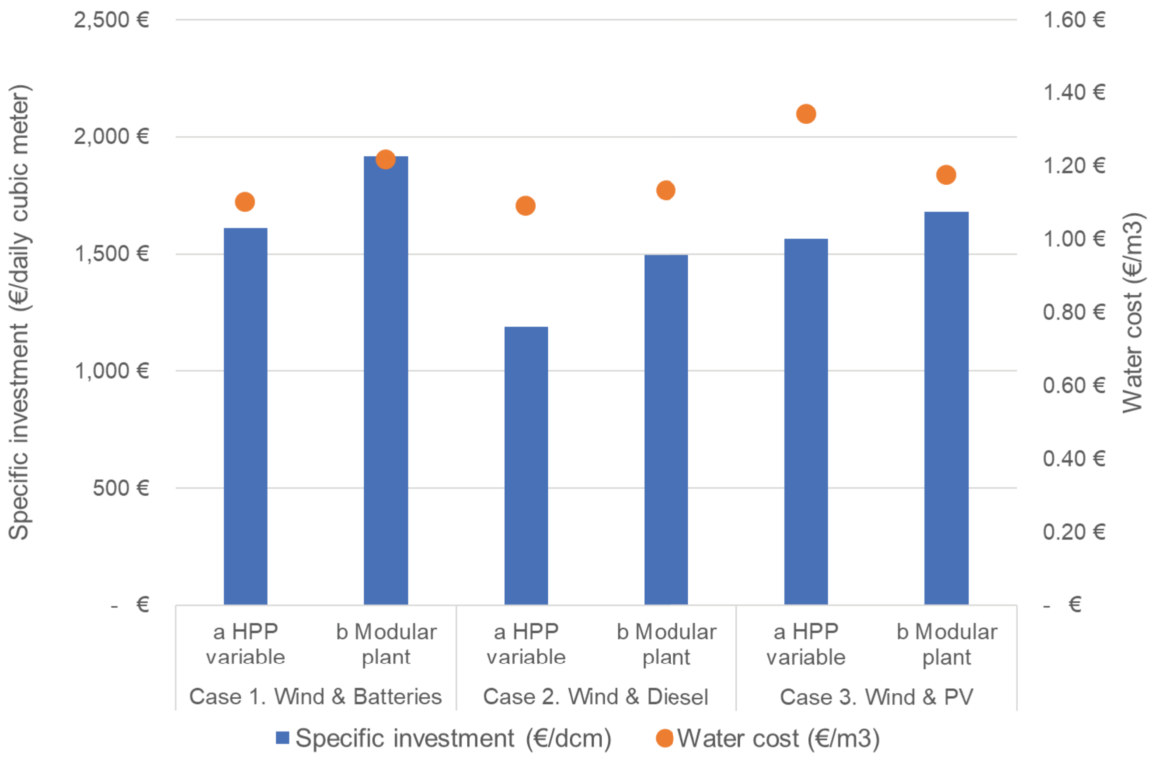

Fig. 12. Chart illustrating the costs of the possible systems.

of the SWRO unit) are presented in Fig. 12. An extra cost of 35% (estimation from capital expenses (CAPEX) data presented in reference [19] for 3 SWRO different capacities) has been considered for the CAPEX of the modular SWRO units, thus, the specific investment is higher for cases b). Data provided by [19] are the following: 1,000 US$/dcm, 600 US$/dcm, 480 US$/dcm for nominal capacities of 1,000, 10,000, and 25,000 m^3/d respectively. Other technical and economic parameters are given in Tables 9 and 10.

In all cases but the incorporation of PV as auxiliary generation (Cases 3.a and 3.b) - see Fig. 12, the cost of water is higher for cases b since the water production is quite similar than cases a), or even quite lower (case 2b) with less investment. The particularity of cases 3 is due to the water production of case 3.b is about 30% higher than case 3.a, despite the additional investment (about 7%), the first point influences more than the second one, leading to a better water cost than for case 3.b (about 20% more economical than case 3.a).

6. Sensitivity analysis

A set of simulations have been made to identify the parameters to achieve the optimized system from the technical point of view (maximum operation time along the year) and the economic point of view (minimum cost of water). For each case, the parameters selected for the analysis have been the following:

- *Wind and batteries*: Cost and size of batteries;
- *Wind and diesel*: Cost of fuel and size of diesel system;
- *Wind and PV*: Cost and size of the PV system;

6.1. Case 1: wind and batteries

The specific cost of water depending on the battery's size and specific cost (cases 1.a and 1.b) is plotted in the charts of Fig. 13.

The most appropriate nominal capacity of batteries should be within the range 6,000–8,000 Ah (about 90–120 min of power supply); when the future cost of batteries reaches the value of 200 €/kWh, as expected [2], the increase in the capacity will not affect to the water cost.

In the case of a modular plant, the system could operate reducing the batteries capacity to 4,000 Ah, but with a high increment in the water cost. However, the minimum capacity to operate the conventional plant is 6,000 Ah; for smaller values, there is not water production.

6.2. Case 2: wind and diesel

Fig. 14 illustrates the cost of water as a function of cost of diesel for a conventional and a modular SWRO plant; a projection of increment in diesel price will lead to probable foreseen water costs along the next decades, considering the wind and diesel option and a 100% diesel generation.

In the case of a conventional RO plant (left chart), the price of diesel to obtain a water cost such as the wind and batteries option (1.13 €/m^3; see dot line) can be identified: about 1 €/L; from this value it will be more economical to select a wind and batteries option.

In the case of a modular plant (right chart), the water cost of the wind and batteries option is 1.25 €/m^3; thus, as soon as the diesel price is about 1.3 €/L, the 100% wind-powered option with the battery storage will be more interesting.

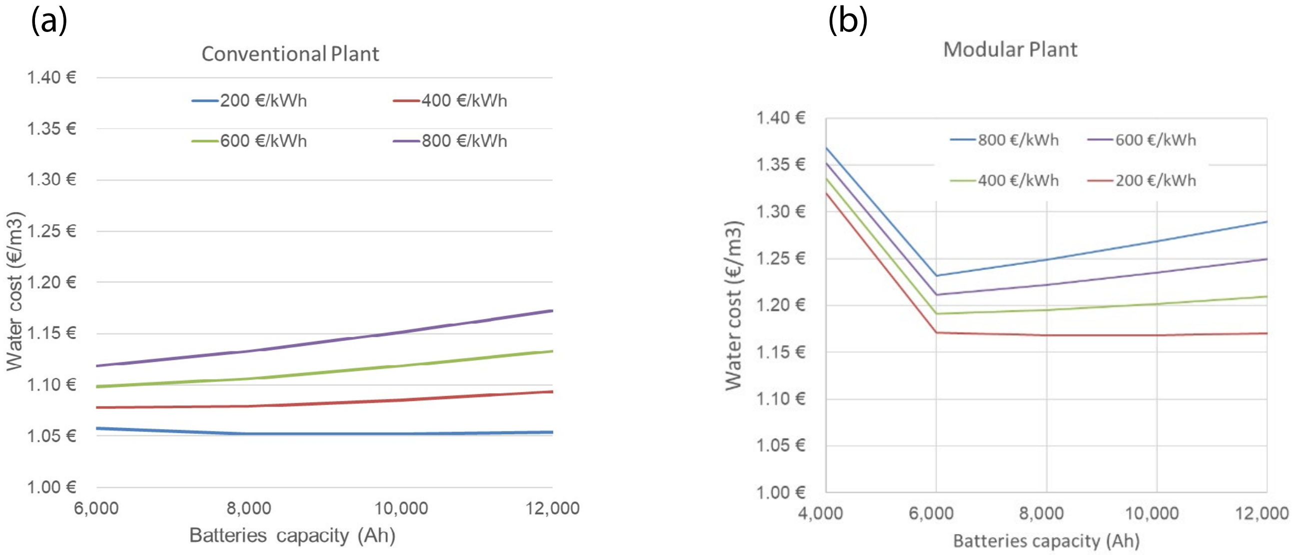

Fig. 13. Water cost as function of the batteries capacity and batteries cost (case of 100% wind power). (a) Conventional RO plant and (b) modular RO plant.

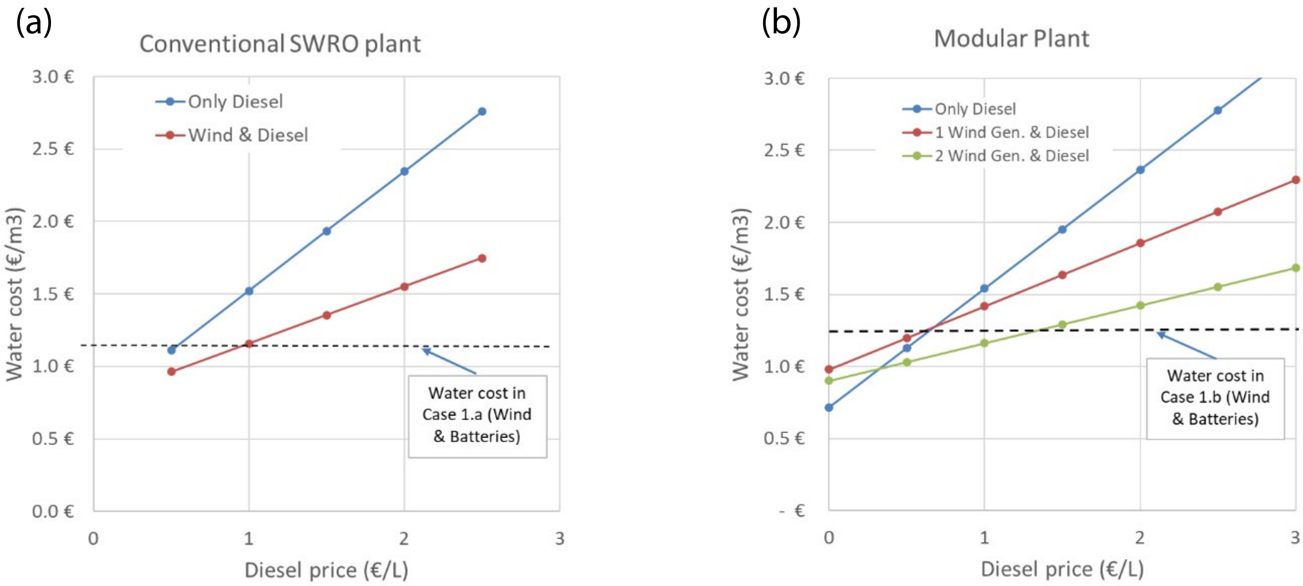

Fig. 14. Water cost as function of the diesel cost (case of wind-diesel generation) in comparison to wind and batteries (case 1).

The situations of generation with only diesel and only one wind generator (instead of two) have been plotted as well. Water cost is higher than the 100% wind generation for both cases (considering a diesel price of 0.7 €/L).

6.3. Case 3: wind and PV

The water cost for the case of the solar and wind hybrid concept is plotted in Fig. 15, presenting the variations as a function of the specific cost and size (area) of PV panels.

According to both charts, the price of the PV system hardly affects the water cost, which remains almost constant in a range of 1.2–1.3 €/m^3 (conventional plant) and 0.95–1.05 €/m^3 (modular plant). In case of modular plant (right chart), the lowest water costs are obtained with the medium size configurations; and for the case of conventional plant (left chart), the largest PV sizes lead to minimum water costs; the reason of this difference comes from the variable demand of the modular SWRO plant matches better with the PV generation, leading to higher water production (Fig. 11) and less losses of energy (Fig. 4), in other words, a modular SWRO unit can work more time connected to PV supply than a conventional unit. Despite the increment of investment associated with the modular concept, water cost is slightly lower than the conventional SWRO concept (see explanation of Fig. 12).

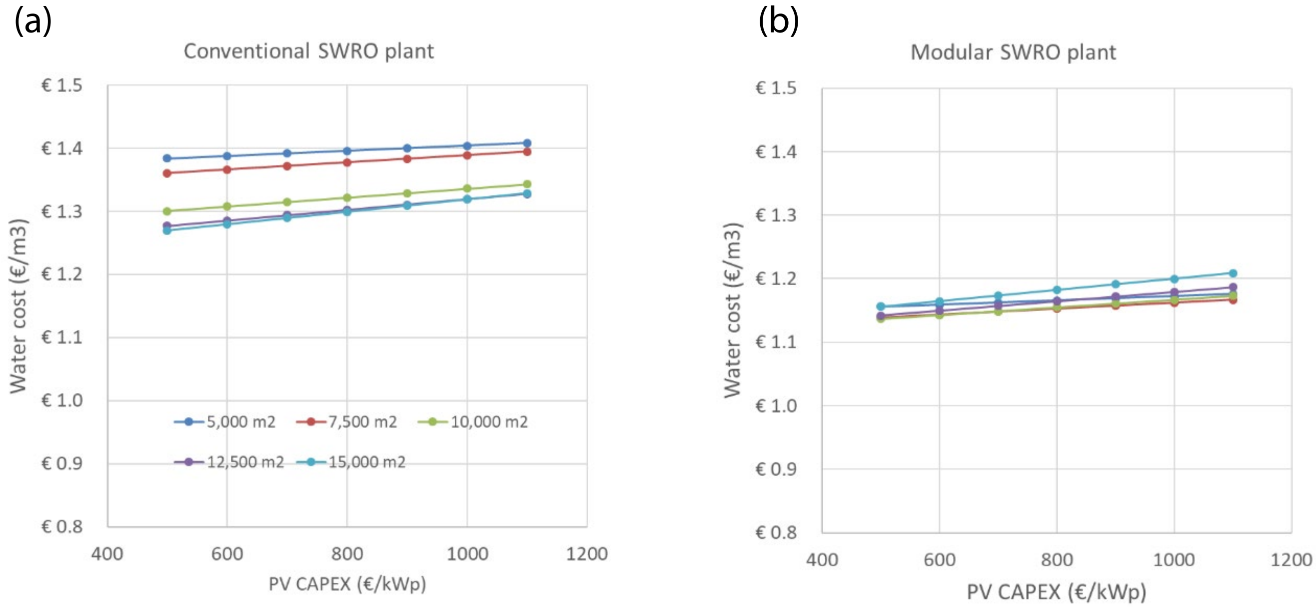

Fig. 15. Water cost as function of the PV collection area and PV CAPEX (case of wind and PV generation).

7. Conclusions

A techno-economic wind-powered SWRO model has been created and simulated from real data to identify the optimal wind-powered medium-capacity SWRO system. Three different generation systems: 100% wind with the support of NaS batteries, wind and diesel, and wind and PV, and two possible SWRO concepts: conventional plant with variable operation of the HPP, and modular plant, have been analyzed and compared. After studying the results and performing a sensibility analysis, the most remarkable conclusions are the following:

- A better energy balance (fewer energy losses) is obtained for hybrid systems (wind plus diesel or PV) when the modular option is selected. However, it is very similar when wind is the only energy source (cases 1.a and 1.b). In other words, there is no advantage (reduction in the energy lost) when the modular RO concept is selected.
- Water production is different for each case:
  - Wind and batteries cases (1.a and 1.b) have similar values; no more water is obtained for the fact of implementing an SWRO modular design.
  - Wind and diesel (subcase of the conventional SWRO concept, 2.a) is the option with the most water production since the SWRO is operated with only diesel at the nominal production point along 30% of the year to achieve an operating time of 75%. On the other hand, the modular option (2.b) requires less diesel generation to get that minimum period of operation.
  - Wind and PV production only reaches 73% of operation time by the modular subcase (3.b), whereas the no-modular option has the least production of all, even less than the no-modular wind option (subcase 3.a) because of the lack of batteries.
- The modular configuration allows achieving an operating time of more than 70% just by using PV as an auxiliary system (case 3.b) and reducing diesel consumption (case 2.b).
- Water cost is higher for modular options powered by only wind and wind-diesel systems; this is due to the additional investment required for the desalination plant. However, the opposite occurs in the case of wind and PV, thanks to the increment of water production and the lower required PV power to operate the modular RO plant. In other words, it is recommended a modular RO configuration only with the hybrid RE generation (wind and PV).
- The most economic water cost is obtained for the wind and diesel combination. However, when future fuel prices are higher (from 1.13 €/L for fix capacity plant, and 1.25 €/L for modular plant), then similar values for water cost from 100% wind-powered configurations will be achieved.
- The incorporation of solar energy is more favorable in terms of water cost than the use of batteries when a modular SWRO plant is coupled. On the one hand, the specific investment associated with wind and PV is 15% lower than the wind and batteries option, and on the other hand, the water production is quite similar in both cases.

Water costs around 1.10–1.15 €/m^3 and specific investment costs ranged between 1,200 and 1,700 €/(m^3 d) are realistic based on wind-powered SWRO desalination with nominal capacity of 10,000 m^3/d. To achieve these values, the main design recommendations are the following:

- Considering 15% of efficiency for PV panels, the effective area required to minimize water cost in wind/PV hybrid systems is 15,000 m^2 for conventional SWRO plants with variable working conditions at the HPP and 10,000 m^2 for modular SWRO plants.

- Wind-diesel energy systems are recommended for conventional SWRO plants with variable HPP in comparison to diesel-only and wind and batteries, for diesel price below 1 €/L. Wind and batteries will be the design recommended for higher diesel costs.
- Design recommendations for modular SWRO plants corresponds to diesel-only for diesel price up to 0.4 €/L; wind and diesel for diesel price between 0.4 and 1.3 €/L, and wind and batteries for higher diesel prices.
- Recommended energy storage of batteries ranged from 6,000 Ah to 8,000 Ah, depending on the price between 200 and 800 €/kWh for desalination plants based on both, variable HPP and modular designs.

Acknowledgment

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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):

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

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%
- 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 $v < v_1$:

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

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

When $v \geq v_1$:

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

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: nominal power of the wind generator; P_0: power of the wind generator at v_0; a_k: parameters obtained by a polynomic correlation from the power curve values; r: 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:

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

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

The values of the parameters are given in Table A1:

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):

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

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

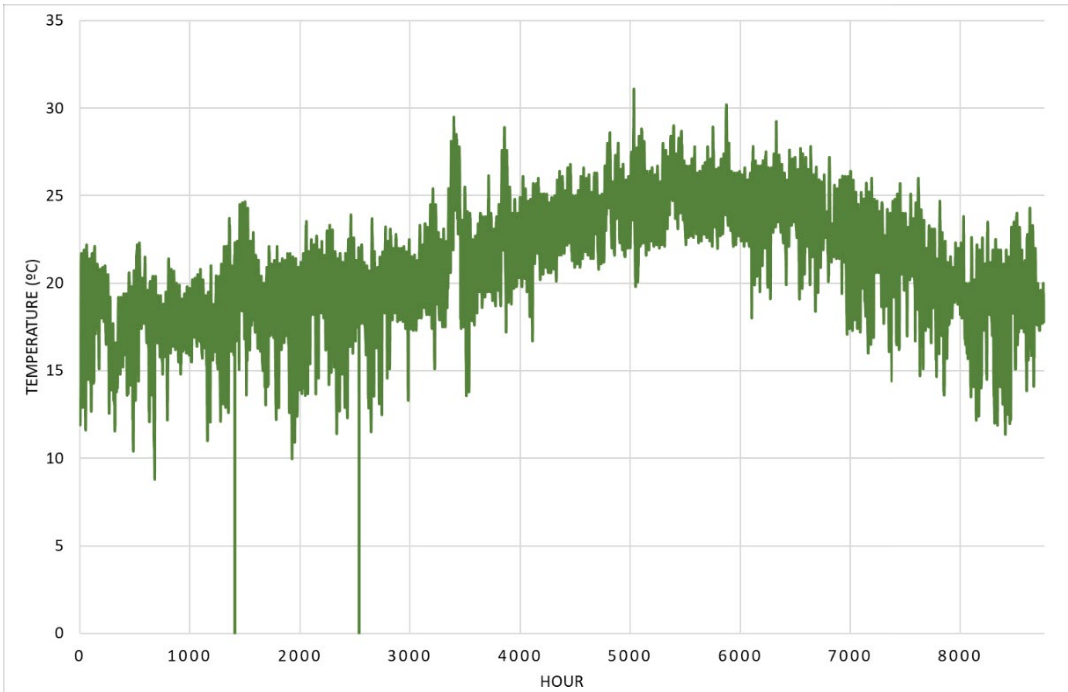


Fig. A1. Evolution of hourly temperature throughout the year (Source: ITC).

Table A1
Values of the parameters used to calculate the power curve of the wind generator

Parameter	E44 (900 kW)
H_h (m)	55
v_1 (m/s)	6
P_0 (kW)	4
P_n (kW)	900
r (s/m)	0.5528
a_0	40
a_1	–33
a_2	7
a_3	0
a_4	0

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 photovoltaic 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.

$$P_{pv} = \frac{I_n \cdot A}{\eta_{pv}} \quad (8)$$

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. Energy balance 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:

$$\text{Charge: } E_i = E_{i-1} + F_{bi} \cdot \Delta t \quad (9)$$

$$\text{Discharge: } E_i = E_{i-1} - P_{bi} \cdot \Delta t - L_{bi} \quad (10)$$

$$\text{Output power from batteries: } P_{bi} = \frac{E_{i-1} - E_i}{\Delta t} \eta_b \quad (11)$$

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):

$$L_{bi} = (1 - \eta_b) \cdot (E_{i-1} - E_i) \quad (12)$$

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:

$$P_{dg} = \frac{P_{ro}}{\eta_{dg}} \quad (13)$$

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:

$$E_{ro} = \sum_{k=1}^{k=8,760} P_{ro,k} \cdot \Delta t \quad (14)$$

- Generated energy:

$$E_g = \sum_{k=1}^{k=8,760} P_{g,k} \cdot \Delta t \quad (15)$$

- Lost energy:

$$E_L = E_g - E_{ro} \quad (16)$$

A1.8. Annual water production

$$V_w = \sum_{k=1}^{k=8,760} Q_{ro,k} \cdot \Delta t \quad (17)$$

$$Q_{ro,k} = a \cdot P_{ro,k} + b \quad (18)$$

where V_w is the total water volume produced along the year; $Q_{ro,k}$ is the water produced in the hour "k"; $P_{ro,k}$ 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/powerpoint 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:

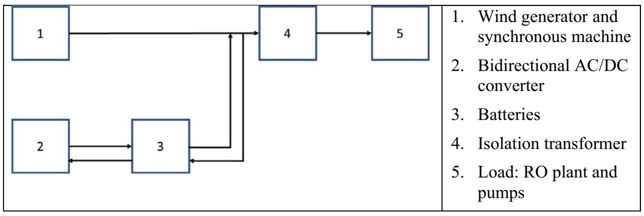
$$C_f = \frac{E_{gd}}{\eta_{de} \cdot \text{LHV} \cdot q} \quad (19)$$

where η_{de} is the efficiency of the diesel engine; LHV is de 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).

A2. Power balance in each system

Using the previous concepts and equations and calculating P_1 from Eqs. (4) and (5), a specific power balance for each system and situation is detailed in this section. The water flow is obtained from the ingoing power to the RO plant and Eq. (17). The power to RO plant is a unique value (case of a fix flow unit), is within a range (case of a variable flow plant), or takes one of the possible fix values (case of a modular plant). The value of RO power in each balance is the highest possible value for the specific available power of every hour.

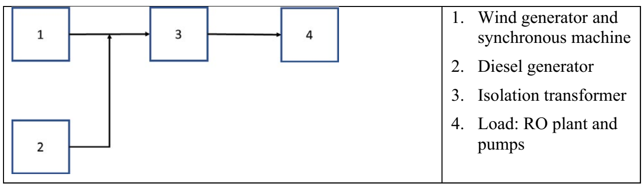
A2.1. Wind and batteries powered RO plant



- When batteries are charged by the wind generator
  $F_3 = P_1$
  $P_3 = F_3 \cdot \eta_3$
  $F_2 = P_3$
  Energy lost: $(F_3 - F_2)\ \Delta t$
- When batteries are discharged to the RO plant
  From Eqs. (10) and (11): $P_2 = \Delta E_b / \Delta t\ \eta_2$
  $F_3 = P_2$
  $P_3 = F_3 \cdot \eta_3$
  $F_4 = P_3$
  $P_4 = F_4 \cdot \eta_4$
  $F_5 = P_4$
  Energy lost:
- In the batteries: $(1 - \eta_2)\ \Delta E_b$
- In the converter: $(F_3 - P_3)\ \Delta t$
- In the transformer: $(F_4 - P_4)\ \Delta t$
- When batteries are fully charged, and the RO plant is powered directly by the wind generator

F_5 is selected as the maximum value within the power range of the RO plant, as long as it is lower than P_1 (power from wind generation system).
The energy lost is: $(P_1 - F_5)\ \Delta t$.

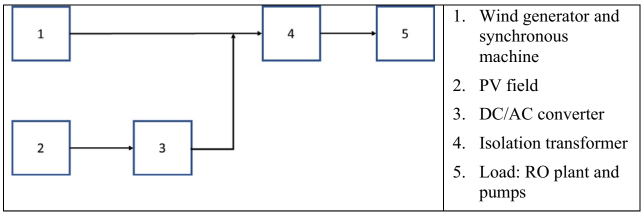
A2.2. Wind and diesel-powered RO plant



If $P_1 > F_4$
  then $P_2 = 0$,
  else, if $P_1 > F_4\ \alpha$
    then, $P_2 = F_4 - P_1$
    else, $P_2 = 0$

α is a factor to consider that there is a minimum presence of wind power to reach a total operation time of 75%; it is calculated by testing and has a value of 0.05.
The energy lost is: $(P_1 + P_2 - F_4)\ \Delta t$
The fuel consumption is calculated from P_2 and Eq. (19).

A2.3. Wind and PV-powered RO plant



P_2 is obtained by Eq. (8), and the surface of the photovoltaic field is calculated to reach a nominal power similar to the wind power for the variable flow RO plant and 50% of the wind power for the modular RO plant.
$F_3 = P_2$
$P_3 = F_3 \cdot \eta_3$
$F_4 = P_1 + P_3$
$P_4 = F_4 \cdot \eta_4$
If $P_4 > F_5$
Then, the RO unit is ON, F_4 is the maximum possible value within the operation range.
Else, the RO unit is OFF
The energy lost is:

- In the converter: $(F_3 - P_3)\ \Delta t$
- In the transformer: $(F_4 - P_4)\ \Delta t$

A3. Economic calculations

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

A3.1. 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. 20).

$$\text{Cop} = \sum z_{\text{fi}} \cdot X_i + \sum z_{\text{vj}} \cdot Y_j \quad (20)$$

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

A3.2. Capital expenses

The investment costs have been calculated from the specific investment and the associated nominal parameter (Eq. (21)), and then is included with the interest ratio and the amortization period to calculate the amortization costs (Eq. (22)).

$$I = \sum z_k \cdot S_k \tag{21}$$

$$C_{\text{am}} = \frac{rI(1+r)^n}{(1+r)^{n-1}} \tag{22}$$

where I: total investment or capital expenses (€); z_k: specific investment of equipment "k"; S_k: nominal size of equipment "k" used to calculate the investment; C_{am}: amortization costs (€/y); r: Interest rate (–); n: amortization period (y).

A3.3. Water cost

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

$$Z_w = \frac{C_y}{P} \tag{23}$$

$$C_y = C_{\text{op}} + C_{\text{am}} \tag{24}$$

where Z_w: cost of water (€/m^3); C_y: Total annual cost (€/y); P: Annual water production (m^3/y).