Desalination 515 (2021) 115216

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Water cycle driven only by wind energy surplus: Towards 100% renewable energy islands

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HIGHLIGHTS

- How to increase the renewable energy penetration through water cycle.
- Wind energy surplus supplies water cycle in an isolated (island) energy system.
- Coupling wind energy to decentralised versus centralised water cycle is analyzed.
- Modular desalination plant is used to adapt better to intermittent energy sources.

ARTICLE INFO

Keywords:
Renewable energy
Energy-water nexus
Desalination
100% RES
Wind energy surplus
Decentralised vs. centralised water cycle

ABSTRACT

This paper studies how to increase the share of renewable energy by using solely stand-alone renewable energies to drive the water cycle. A case study is undertaken of El Hierro (Canary Islands, Spain), an island already on the path to becoming a 100% renewable energy island thanks principally to a wind-hydro power plant that covered around 60% of the annual electricity demand in 2018. The island's water cycle includes groundwater extraction, seawater desalination and water pumping and distribution, representing altogether around 35% of the annual electricity demand of the island. The idea is to investigate the possibility of driving the entire water cycle solely with the wind energy surplus. For this purpose, two scenarios are considered and developed: one based on the existing decentralised water cycle, and the second on an alternative centralised one, with just one modular reverse osmosis desalination plant and a centralised water storage system. The aim is to establish which model adapts best to an intermittent energy source such as wind energy without conventional backup systems. Results show that both scenarios lead to an increase in the overall renewable energy contribution in the island. Moreover, the centralised water model, specially due to its centralised water storage system, allows a higher contribution from renewable energy sources, increasing their overall annual penetration.

1. Introduction

1.1. Water-energy nexus in the water cycle

The exponential growth of the world's population, the effects of climate change and the rising trend of water and energy consumption underline the huge pressure on the available water and energy resources [1,2]. Energy is required in each stage of the water cycle - from its extraction, treatment, distribution and use to its disposal [3,4]. Alternative water resources like water desalination are commonly applied to mitigate the stress on conventional water resources in many islands and water-scarce regions [5]. Desalination has become an important alternative to ensure the availability and quality of the water supply [6], however this process is an intensive energy consumer. Reverse osmosis (RO) is the leading desalination technology with 66% of the world market and is the most optimized pressure membrane-based desalination process [7,8].

In order to ensure the sustainability of the water cycle a paradigm shift is required from the use of fossil fuels to renewable energy sources (RES) to power the operation of water supply systems (specially RO desalinations plants).

N. Vakilifard et al. [9] provided an overview of the role of the water-energy nexus in optimizing water supply systems and summarized recent research developments of centralised/decentralised water

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https://doi.org/10.1016/j.desal.2021.115216
Received 25 March 2021; Received in revised form 18 May 2021; Accepted 7 June 2021
Available online 1 July 2021

systems according to the energy source type (e.g. renewables). They found that the focus of most of the studies was from either a water or an energy perspective and that the necessary interlink to jointly manage water and energy was missing.

1.2. Approaches for the penetration of renewable energy sources in the water cycle

Usually, two different approaches are used to cover (totally or partially) the electricity demand of water cycles or desalination plants with RES: autonomous systems and systems connected to the grid. In the first case, the electricity produced by RES is directly consumed by the desalination plant and does not require a grid connection.

A considerable amount of research work on this topic has been undertaken (and several prototypes developed), mostly in relation to small and medium-scale RO desalination plants [10–17]. This approach presents a number of challenges related to the use of solar photovoltaic (PV) and wind energy in desalination systems due to the inherent intermittent nature of both energy sources since commercial RO plants are designed to operate under constant flow, pressure and power conditions [18]. Thus, this combination involves, in the vast majority of the cases, an over-dimensioning of the system and/or the need for an energy storage system. Many studies of stand-alone wind-RO and PV-RO desalination units supported by batteries have been developed. However, the use of batteries still presents drawbacks related to their short life cycle, high-cost maintenance and environmentally unfriendly content. For these reason, batteries have been proposed only for small-scale applications [19–20].

Stand-alone water pumping powered by wind and/or solar energy is another example of the application of RES in water supply systems [9]. Such systems have been typically designed to supply small-scale water pumping systems for domestic and irrigation purposes [21–22].

In the second approach, the desalination plant is connected to the grid and there is a trade-off between the energy consumed by the water cycle or desalination unit and the RES-generated electricity [23]. Thus, the RES in place compensate the electricity demand, partially or totally. This approach has been studied in many grid-connected large-scale desalination plants that use solar, wind or wind-solar hybrid energy systems [24–27].

I.D. Spyrou and J.S. Anagnostopoulos [28] simulated the optimum design and operation strategy of a centralised stand-alone seawater reverse osmosis (SWRO) desalination system powered by a hybrid RES (wind and solar) and a pump-hydro storage (PHS) system, capable of meeting the fresh water demand of a Greek island. The PHS is used as an alternative to batteries to drive the desalination plant during unfavourable weather conditions. The system was designed to cover the yearly fresh water demand (3840 m^3/day) of the island's 5000 inhabitants. The system includes an SWRO (3 kWh/m^3 specific energy consumption) and a water tank with an 8500 m^3 capacity (2 days of autonomy). The cumulative installed power includes 800 kW wind power, 200 kW PV power, 480 kW hydroturbine power and 600 kW pump power. The PHS includes a reservoir with a net capacity of 40,000 m^3. In this study, as in other researches [29–31], the SWRO plant operates with variable production and the recovery rate (percentage ratio of freshwater produced divided by feed flow rate) adapts to the available power within the allowable membrane operating limits. The authors concluded that the capability of exploiting the pumped storage unit to produce electricity for other parallel usages was the only effective way to improve the capacity factor of all the subsystems [28]. This would also minimize the amount of rejected energy and improve the economic results of the entire desalination plant.

1.3. Present contribution

In this paper, the approach taken is completely different and is in line with the improvements proposed by [28] with the starting point being the electricity supply to the island and the remaining RES being used to produce water. There is no rejection of RES production and no water shortage (water storage systems are sized to avoid this situation). This intermittent way of operation resembles a stand-alone system since it uses only the wind energy surplus (WES) after covering all the island electricity demand except for the water cycle.

A similar approach was followed by R. Segurado et al. who proposed an integrated approach through a RES-desalinated water system for the island of San Vicente in Cape Verde [26,27,32]. The authors proposed to use the excess wind production of a wind-pumped hydro storage system, connected to the grid, to supply an SWRO desalination plant with a capacity of 6400 m^3/day, minimizing the wind power curtailed. The freshwater produced is stored in the lower reservoir of the PHS system. The remaining wind power is used to pumped the desalinated water to the upper reservoir and when it is necessary the water is turbinated to the lower reservoir. In this case, the SWRO desalination plant, which operates as a centralised water production system for the whole island, was connected to a conventional fossil fuel unit to ensure plant operation under constant conditions (pressure and flow). The cumulative installed power includes 21.30 MW wind power, 14.5 MW pump power and 8.5 MW hydropower. They concluded that RES penetration could reach 84%, with 99.6% of freshwater production powered by wind energy [27]. That is, their paper examines the case of a RO desalination plant supplied with the WES but connected also to a conventional power plant as backup. Thus, the SWRO desalination plant operates in a continuous regime using both wind and conventional energy. In addition, these last two papers [27,28] deal only with one (centralised) desalination unit.

In the study presented here, the intention is to investigate the possibility of using only the WES to drive the entire water cycle without any conventional backup system. For this purpose, the island of El Hierro (Canary Islands, Spain) was selected as case study.

A comparison between a decentralised and a centralised water system powered solely by an intermittent RES (without a conventional backup system) is carried out in order to establish the most efficient system that enables a higher penetration of RES. For this purpose, two scenarios are developed: one based on a decentralised water cycle (which is the existing one) and a second based on a centralised one (with a single modular RO desalination plant). The aim is to increase the penetration of RES by powering the water cycle solely with the WES.

The novel contributions of this paper include the approach that is taken and the system configuration itself. Another contribution of particular interest is the optimization of the use of the WES, as well as the decision mechanism of decentralised vs. centralised systems, in order to guarantee that the water needs of the island/region for both human consumption and irrigation are met while at the same time increasing the share of RES penetration.

2. Methodology

The ultimate goal of this study is to increase the RES contribution of an island or isolated region which already has wind energy facilities in place. For this purpose, the water cycle will no longer be powered by the electricity mix that supplies the island/region but only by the WES. Two scenarios are developed to cover the hourly demand of the water cycle (human consumption and irrigation) using solely the WES (without a backup system or energy storage system). The research aim is to determine which water model, centralised or decentralised, allows a higher RES penetration. In other words, which model adjusts better to the WES.

2.1. Water demand and wind energy surplus

The first step to model the system is to calculate the hourly water demand for both human consumption and irrigation. This calculation is based on the analysis of the water infrastructure and the annual water balance.

The WES is calculated on the basis of the difference between the wind energy potential and the wind energy production. This difference between the wind energy (WE) potential and the WE actually generated represents the WE that could have been potentially produced but was curtailed due to the lack of instant electricity demand or due to electricity grid stability limitations.

In the case study developed in Section 3, the hourly WES for 2018 is known data. However, the 2018 electricity demand data includes the demand for the water cycle. Thus, a new WES, that does not include the electricity demand for the water cycle, has to be estimated. In order to perform this estimation, it has to be taken into account that the water cycle represented 35% of the 2018 electricity demand. Due to various proposed improvements in the water cycle, described in the Results section, it is estimated that about 30% of the island's electricity demand will correspond to the water cycle demand. Thus, the new WES in the case study will be the result of adding 30% of wind energy production to the WES.

The hourly WES available for the water cycle is thus calculated through Eq. (1).

$$\text{WES} = WE_{\text{potential}} - WE_{\text{production}} + WE_{water\ cycle}\ (\text{kWh}) \tag{1}$$

2.2. Scenario 1 - decentralised water system

The first scenario that is considered is based on a decentralised water system (see Fig. 1). In this scenario, the aim is to cover the water demand using the current water supply network, which is decentralised. The water used comes from two different sources: groundwater and seawater. The water cycle includes collection, treatment, storage facilities, pumping stations and a pipe network for its distribution to the consumers. The driving of the water cycle using the WES is based on a strategic distribution of the WES through the different lines of the water supply network described below.

Since this scenario uses the island's current water infrastructure, an exhaustive analysis of this infrastructure was carried out. The data collection and analysis included: (a) number, capacity and altitude of the water deposits, (b) number and technical characteristics of the pumps, (c) number and capacity of the SWRO plants, (d) number of wells, (e) hourly water demand per pumping line and per water deposit and (f) hourly specific electricity consumption for desalination and pumping purposes. Under this scenario, the water supply networks are divided into water lines according to their use (human consumption or irrigation), their production source (well or SWRO plant), pumping volume and the elevation height of intermediate storage deposits.

A simulation tool was developed in Matlab to model the system and optimize the joint operation of the current water system with the WES. The simulation aims to optimize the distribution of the hourly WES between the different water lines to satisfy the hourly water demand according to pre-set priorities. Fig. 2 shows the logic diagram of the decentralised water system. Four types of water line were defined according to use and production source: desalination for human consumption (RO_HC), desalination for irrigation (RO_IR), wells for human consumption (We_HC), and wells for irrigation (We_IR). This scenario includes two possible cases:

Case 1 (right side of Fig. 2): the WES is equal to or higher than the electricity required supplying the whole water cycle. In this case, the energy demand of all four water lines (RO_HC, RO_IR, We_HC, and We_IR) is supplied by the WES. The water is produced and pumped as long as the water deposits are not full. That is, the difference between the water pumped and the water demand volume should be equal to or less than the deposit volume otherwise the volume of the deposit could be exceeded. If that is the case, the line has to be stopped until the water volume in the deposit diminishes. Thus, the excess WES is discarded.

Case 2 (left side of Fig. 2): the electricity demand to supply the whole water cycle is higher than the WES. In this situation, it is necessary to establish priorities. In this study, the following priorities are established:

(1) Human water consumption must be satisfied before water for irrigation
(2) Water for irrigation must be satisfied by desalination before wells

In this case, there are two possibilities: the WES is higher than the demand for human consumption (line 3 of Fig. 2) or the WES is lower than the demand for human consumption (line 7 of Fig. 2). Both possibilities are described below.

Case 2.1: the WES is higher than the demand for human consumption. In this case, the water for human consumption is supplied entirely by the WES. Additionally, the extra WES (the surplus that has not been used to produce water for human consumption) is used to produce water for irrigation. Again, there are two possibilities. Firstly, the extra WES is higher than the demand for the irrigation water produced by desalination (line 5 of Fig. 2). In this case, all the foreseen desalinated irrigation water is produced and the remaining surplus is used to pump irrigation water from the wells until the surplus is exhausted. The second possibility is that this extra WES is lower than the demand for the irrigation water produced by desalination (line 6 of Fig. 2). In this case, the

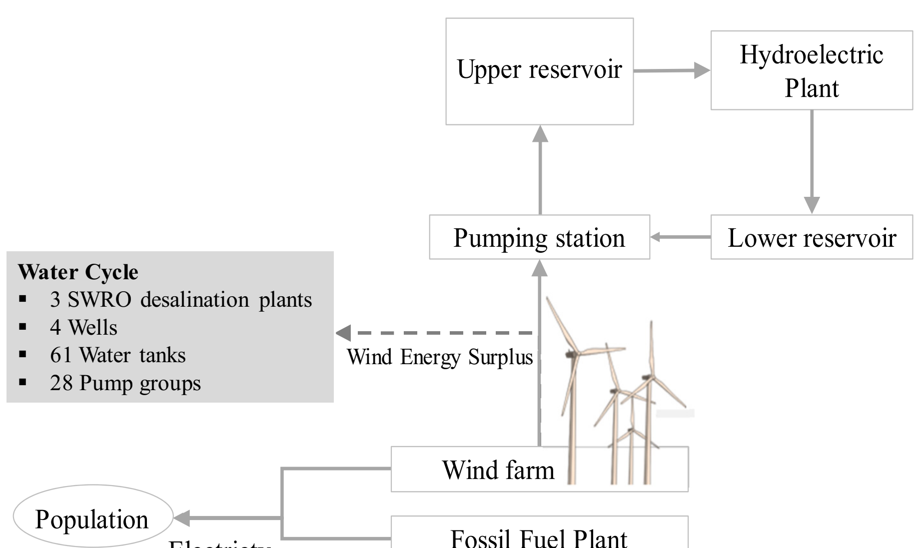
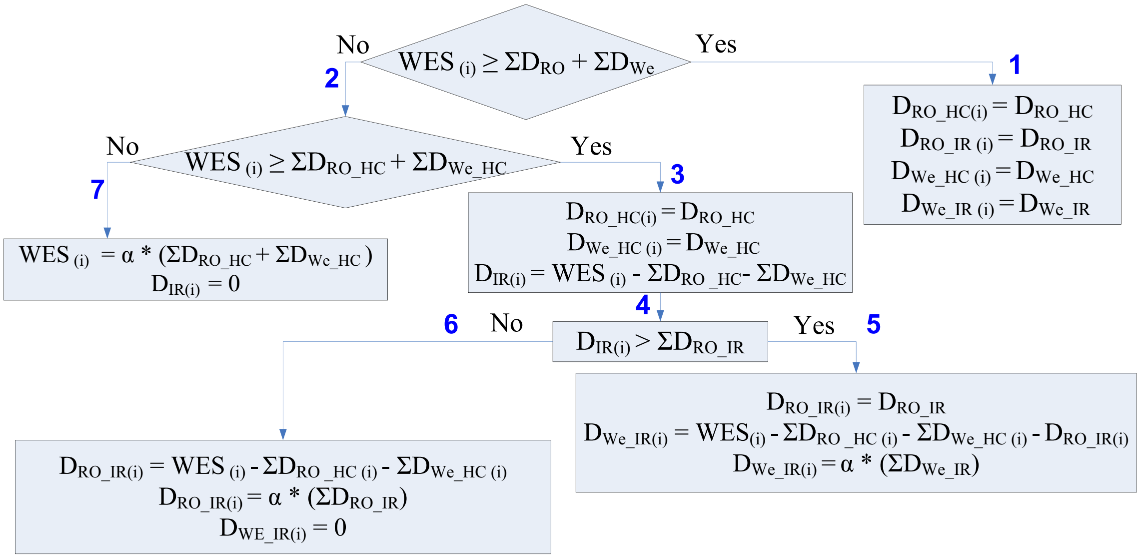


Fig. 1. Schematic diagram of the decentralised water system.



WES = Wind energy surplus
D_{RO} = Energy consumption of reverse osmosis desalination plants
D_{IR} =Energy consumption for irrigation
D_{RO_HC}= Energy consumption of desalination plants for production of water for human consumption
D_{RO_IR}= Energy consumption of desalination plants for production of water for irrigation
D_{We}= Well energy consumption
D_{We_HC}= Well energy consumption for production of water for human consumption
D_{We_IR}= Well energy consumption for production of water for irrigation

Fig. 2. Logic diagram of the decentralised water system.

remaining surplus is used to desalinate water until the surplus is exhausted. In this case, there is no irrigation water coming from wells.

Case 2.2: the WES is lower than the demand for human consumption (line 7 of Fig. 2). In this case, all the WES is used to produce water for human consumption (same percentage for all lines) until the surplus is exhausted.

2.3. Scenario 2 - centralised system

The second scenario, the centralised system, explores the combination of a single large-scale SWRO desalination plant, able to supply the island's entire freshwater demand and powered by the WES, and a centralised water storage system (see Fig. 3).

The solution is based on a gradual capacity SWRO desalination plant which is able to match the load to the WES [17]. The proposed SWRO plant is designed in accordance with the following characteristics:

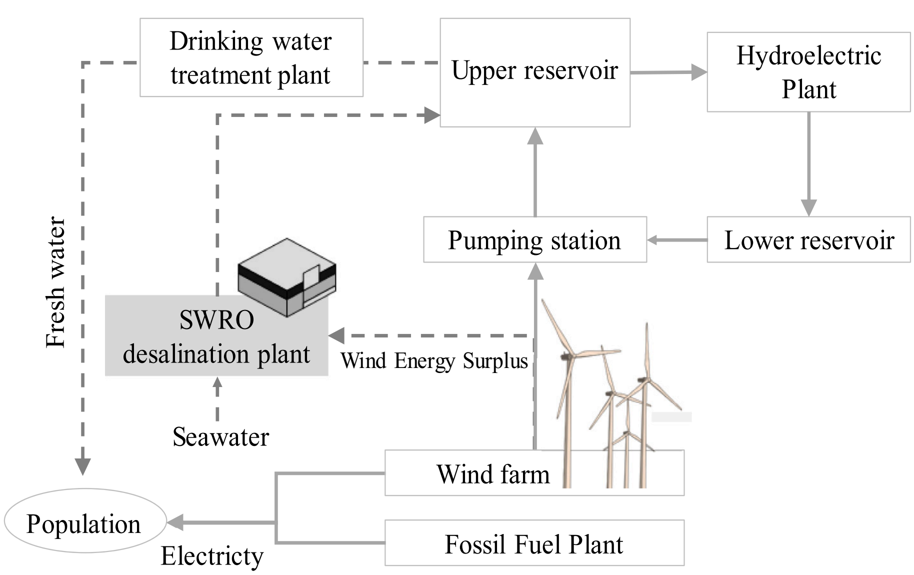


Fig. 3. Schematic diagram of the centralised water system.

- The SWRO is a modular plant with various numbers of identical and independent RO racks. The number of RO racks determines the seawater desalination capacity of the plant.
- The SWRO plant is driven exclusively by wind energy (without backup or storage system).
- Each RO train is able to operate independently, with its connection or disconnection depending on the amount of available wind energy.
- Each RO train consists of a seawater pre-treatment unit, an RO rack, an energy recovery system and a rinsing system to preserve the membrane elements in each disconnection.
- The specific energy consumption of the SWRO plant is 2.8 kWh/m^3 [33]

The total capacity of each rack (m^3 of freshwater per hour) is defined taking into account the intermittent nature of wind energy. The hourly desalinated water production is calculated based on the number of RO racks that can operate simultaneously according to the available wind energy. Fig. 4 shows a logic diagram summarizing this procedure. The SWRO plant follows the operating strategy proposed by J.A. Carta et al. [12], with the first rack to be connected being the last one to be disconnected.

Unlike the studies published to date, the proposed SWRO plant operates with different trains (sets of identical modules that constitute an RO plant) at a constant production rate that can be connected or disconnected depending on the available WES. This modular operating mode is supported by other research works [11,12,17,34–36].

This scenario additionally considers the use of an upper reservoir, at high altitude, to store the desalinated water. This large water storage facility allows matching of the local water demand with the WES. Such a storage system is flexible and entails a reduction in the investment cost compared to what would be required in a decentralised system to either store energy or water.

The direct use of wind energy to supply the SWRO desalination plant requires oversizing of the desalination plant in order to take into account the use of water storage as an energy storage strategy. With this system, during periods when the wind resource is insufficient to power the desalination plant, the stored water can be used to meet the water demand.

The analysis of the most suitable SWRO desalination plant design was carried out taking into account the highest freshwater production and operating (hours of operation) rates of racks independently or jointly.

3. Results

3.1. Case study: El Hierro Island

3.1.1. The energy-water system in El Hierro

El Hierro Island (Canary Islands, Spain) is the case study selected. El Hierro is the youngest and smallest island of the Canary Islands with 10,968 inhabitants (2019) [36]. Like the other islands of the archipelago, El Hierro has an isolated electrical system with a weak grid that is not connected to another island or territory.

In order to cover the electricity demand of the island with RES and reduce the use of fossils fuels, the Gorona del Viento wind-hydro power plant was commissioned and built in 2014. The plant was designed to supply as much as possible of the island's electricity requirements through RES (wind) and, thus, reduces its dependence on fossil fuel energy sources. The system combines wind power generation, hydraulic energy and a pumping station that allows the storage of water at high altitude. In this way, the system converts an intermittent and fluctuating energy source, like wind energy, into a constant electricity supply guaranteeing grid stability. The island also has a conventional diesel thermal power plant that ensures the electricity demand is met when the Gorona de Viento plant is unable to do so.

The operation of the Gorona del Viento wind-hydro power plant has improved over time, attaining a coverage of about 55% of the annual electricity demand in 2018 [37]. During that year, the system often reached peaks of 100% RES (during 18 consecutive days the system ran exclusively with RES) [38]. However, there is still a lot to be done for it to become a 100% RES island, completely free of greenhouse gas emissions [39–40]. To date, a number of studies have been made by the

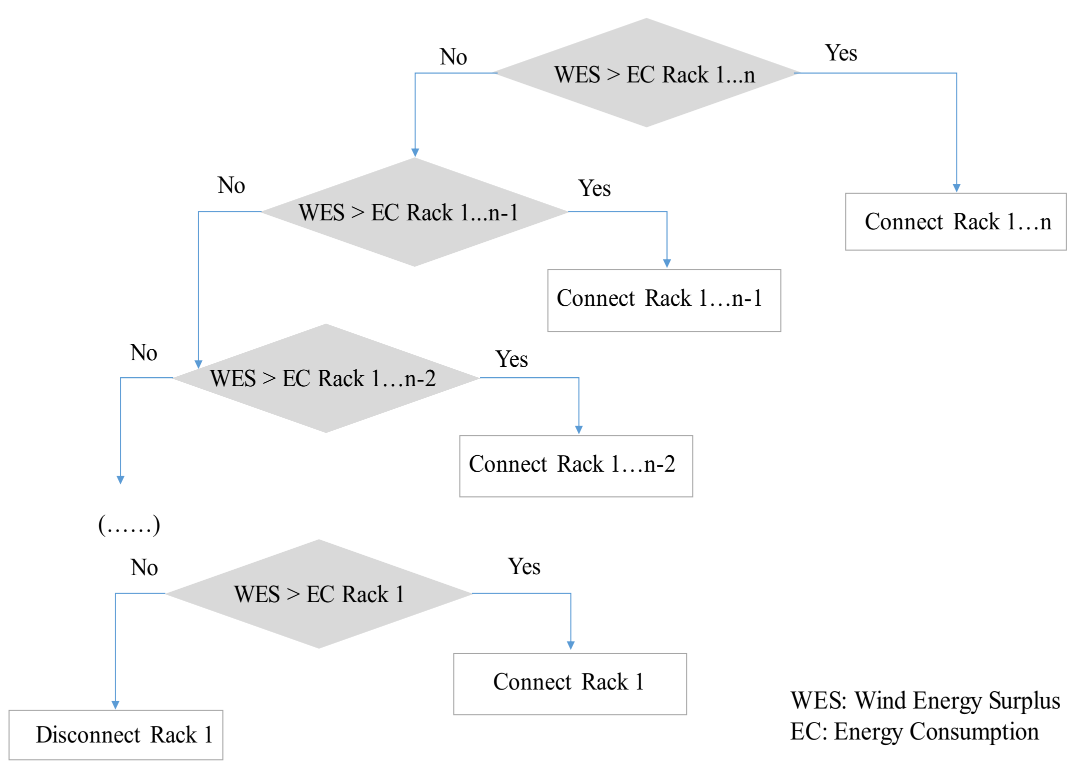


Fig. 4. Centralised water system: logic diagram of the proposed modular desalination plant operation.

scientific community with the aim of reaching this goal in El Hierro [40–42]. In order to provide electrical system stability, the grid operator allows wind penetration up to a certain limit [40]. As a result, there is a surplus of wind power that cannot be injected into the grid and, thus, the wind power is curtailed [27]. In this paper, this surplus wind energy potential, called here the WES, will be used to drive the water cycle.

The domestic loads and the water cycle (including desalination) represent the highest percentage of the island's electricity demand [43]. In the particular case of El Hierro, the water cycle represents around 35% of the annual electricity demand of the island. The distribution of the electricity consumption within the water cycle is the following: 51% for SWRO desalination and 49% for groundwater extraction, pumping and distribution. The SWRO plants supply a large amount of freshwater (1.1 hm^3, 2018), but also demand a high amount of electricity, a clear indicator of the close interdependency of the energy-water nexus in El Hierro Island.

3.1.2. *Description of the power system*

In 2018, the installed electrical power in the island was 37.8 MW: 14.9 MW (diesel), 22.8 MW (wind-hydro power plant) and 0.03 MW (PV) [37]. The generation structure was as follows: 60.5% of the electrical power was supplied by RES and 39.5% by diesel [37].

The Gorona del Viento wind-hydro power plant (Fig. 5) consists of a wind farm (capable of simultaneously supplying electricity directly to the grid and to the pumping station), a pumping station (which pumps desalted water from the lower to the upper reservoir exclusively using wind energy) and several hydroelectric Pelton turbines (to produce electricity when there is insufficient wind energy and to guarantee the stability of the network). The upper reservoir constitutes a massive energy storage system. Table 1 summarizes the characteristics of the Gorona del Viento wind-hydro power plant [44].

A thermal power plant "Llanos Blancos" was previously in place and continues in operation with 10 diesel generators and a total capacity of 14.9 MW (see Table 2).

Currently, stability restrictions limit the instant wind energy contribution to a maximum of 75–80% of the electricity demand [45]. Therefore, the hydraulic turbines and/or the diesel generators have to cover at least 25% of the instant electricity demand [45]. Other restrictions of the system are related to the technical minimums of the diesel groups and the technical limitations of the electromechanical equipment (pumping groups and Pelton turbines). The eight pumps which make up the pumping group reach a maximum power of 6 MW. The technical minimum of the installed Pelton turbines is estimated at 280 kW each [45].

Table 1
Technical characteristics of the wind-hydro power plant [44].

Wind farm	
5 wind generators (Enercon E-70)	5 × 2.3 MW Total power: 11.5 MW
Reservoir	
Lower reservoir	150,000 m^3
Upper reservoir	373,000 m^3 (altitude: 655 m)
Pumping station	
8 pump units	2 × 1500 kW 6 × 500 kW Total power: 6 MW
Turbine plant	
4 Pelton turbines	4 × 2830 kW Total power: 11.32 MW

Table 2
Conventional electricity units [37].

Generators	Number	Total net power (kW)	Total gross power (kW)
Diesel 7	1	670	780
Diesel 9	1	880	1100
Diesel 10 & 11	2	2140	2190
Diesel 12	1	1260	1460
Diesel 13	1	1360	1460
Diesel 14 & 15	2	3800	4000
Diesel 16	1	1860	1910
Diesel mobile 1	1	1070	1280
Total	10	13,040	14,910

3.1.3. *Water system in El Hierro*

The available water resources in El Hierro amount to 3.3 hm^3 (2018), divided mainly between groundwater (66%) and desalinated seawater (34%). As summarized in Table 3, four wells practically concentrate all of the natural water resources consumed on the island. As for unconventional water resources, these are supplied by three SWRO desalination plants, one in each municipality.

Energy is consumed across every stage of the water cycle. Approximately 18% of the total electricity demand of the island is consumed in the SWRO desalination plants and 17% in the groundwater extraction, distribution and storage processes. The energy consumption varies substantially from municipality to municipality, depending on local factors such as number of inhabitants, topography, pipe dimensions, number of pumps, etc. In general, the hydraulic infrastructure is extremely complex and presents losses in water piping networks of 20% in El Pinar, 27% in La Frontera and 45% in Valverde [46].

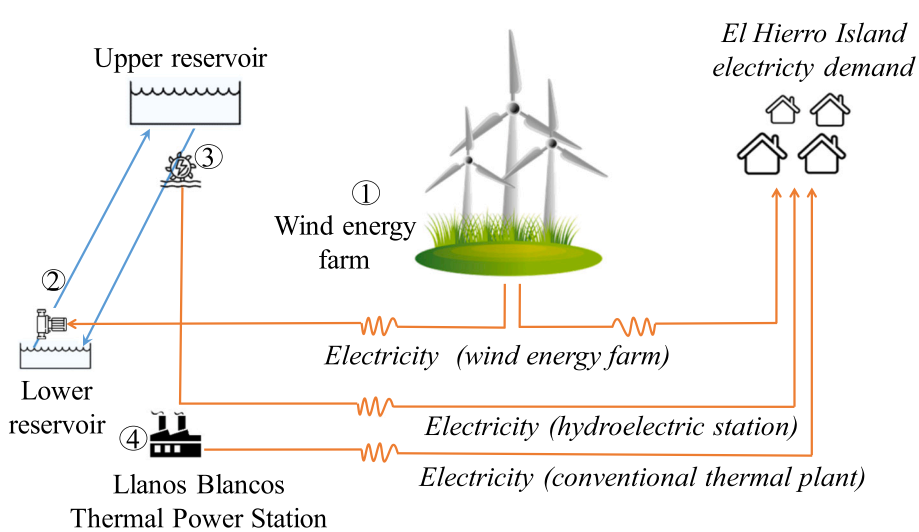


Fig. 5. Schematic representation of the Gorona del Viento wind-hydro power plant.

Table 3
El Hierro water balance in 2018 [46].

Production	Volume (m^3)
Los Padrones well	1,123,952
La Frontera well	633,550
Pozo Tigaday well	223,135
Pozo Tamaduste well	196,038
Frontera SWRO plant	212,193
Los Cangrejos SWRO plant	568,170
La Restinga SWRO plant	345,567
Total production	3,302,605

Consumption	Volume (m^3)
Water for human consumption	
Municipality: La Frontera	427,617
Municipality: Valverde	858,916
Municipality: El Pinar	287,718
Irrigation	
Echedo-Costa Norte	108,623
Sur - El Pinar	18,049
Frontera	1,547,995
Los Padrones	8960
Other	53,627
Total consumption	3,311,505

Table 3 summarizes the water balance of the island in 2018. 51% of the water consumption is used for irrigation and 48% for human consumption. The remaining 2% includes evaporation water losses in the reservoirs and a water reserve for firefighting. Around 47% of the water for irrigation is taken from groundwater and amounted to 1.2 hm^3 in 2018, highlighting the intensive use of groundwater resources for irrigation purposes.

Table 4 specifies the main technical data of the three SWRO plants that make up the desalinated water production system on El Hierro island. The current desalination capacity installed in El Hierro is 5900 m^3/day with a specific energy consumption of 2.67–5.72 kWh/m^3 (see Table 4). Table 5 summarizes the monthly production of each SWRO desalination plant. El Golfo desalination plant stopped its production during the last 3 months of the year due to operation problems.

3.1.4. Wind energy surplus

Table 6 summarizes the electricity production (by energy source) in 2018 and the WES available to drive the water cycle. The total electricity demand of the island corresponds to the total electricity generation (by the different energy sources) minus the electricity used for pumping and auxiliary services (internal consumption of the Gorona del Viento plant).

The contribution of RES represented around 56.7% of the total electricity demand compared to the 43.3% produced by fossil fuels. This renewable energy is distributed as follows: 66.1% corresponds to wind energy and 33.9% to hydroelectricity. Note that the electricity demand figures do not contemplate the wind energy used to pump the water to the upper reservoir. Around 37.5% of the electricity is directly injected into the grid, while the pumping consumes 47%.

Fig. 6 shows the energy data analysis of the island in 2018, including the wind energy used to produce electricity, the potential wind energy to produce electricity and the total energy demand of the island. The wind energy in the island shows a strong seasonal behaviour, with a much higher energy production in summer than in winter. This is consistent with the predominance of the trade winds, a typical feature in the Canarian archipelago. The electricity demand of the island also presents a moderate peak in the same period which is associated to a higher influx of tourism. Fig. 6 shows that the difference between wind potential and actual wind energy production follows a similar pattern throughout the year. The difference is estimated at ca. 22% of the total wind potential in 2018.

Table 4
El Hierro SWRO desalination plants technical data [46].

Name	El Golfo	La Restinga		El Cangrejo	
Municipality	La Frontera	El Pinar de El Hierro		Valverde	
Use	Irrigation	Population and irrigation			
No. Racks	1	2		2	
Production capacity (m^3/day)	1300	1000	1200	1800	1300
Real production (m^3/day)	1248	935	1008	1800	1075
Specific energy consumption (kWh/m^3)	3.90	4.92		2.67–5.72	

Table 5
Monthly SWRO desalination plant production (El Hierro, 2018) [46].

Month	El Golfo	La Restinga	El Cangrejo
	Production (m^3)		
January	1283	23,285	60,983
February	2915	18,837	47,046
March	16,640	25,363	45,629
April	40,357	24,060	23,811
May	31,911	34,512	42,748
June	34,893	31,789	53,463
July	37,062	38,872	57,530
August	30,171	36,288	61,932
September	16,944	35,773	52,499
October	–	39,794	66,176
November	–	20,370	39,562
December	–	16,624	16,791
Total (m^3/year)	212,193	345,567	568,170
Total (m^3/year) = 1,125,930			

3.2. Decentralised water system

The electricity consumption of the water cycle in 2018 was around 15,000 MWh (51% for SWRO desalination and 49% for groundwater extraction and pumping) [45,46]. The decentralised scenario considers the water production units currently in place. Under this scenario, two assumptions were considered: (i) a reduction of losses in the water piping networks to a value of 20% and (ii) a reduction of the specific energy consumption of desalination plants to 4 kWh/m^3. Taking into account these two assumptions, the energy needs for the water cycle are reduced to 10,900 MWh/year.

The estimated WES in 2018 amounted to approximately 20,300 MWh (see Table 6). This value is higher than the amount of electricity demanded by the water cycle in the same year. Thus, it is theoretically feasible to cover the freshwater demand using the WES. If there were no water storage restrictions, the total water volume produced using only the WES would be higher than the water demand (see Fig. 7). However, the WES does not cover all the hourly electricity demand of the water cycle. In 2018, there were 300 h with no WES and 47% of the time there was insufficient wind energy to meet the instant water demand. In order to further evaluate this data, an hourly analysis was carried out based on a simulation of the water supply system following the logic diagram of Fig. 2.

A total of nine pumping lines were defined, five for water human consumption and four for irrigation. By way of example, Fig. 8 shows the water supply distribution system of the municipality of Valverde (lines 2, 5 and 9). The current water supply system comprises 28 pump groups and 61 reservoirs [46].

The total volume of water produced by each line using the available WES (see Fig. 2) is shown in Table 7 along with a comparison with the water demand. The amount of freshwater produced by the desalination plants (lines 1–3) is sufficient to cover 93% of the annual water demand (2018). That is, there is an annual average water deficit in lines 4 to 9 (wells) of 490 m^3/day, which represents 7% of the annual water demand. El Hierro Water Council is planning to increase the capacity of El Golfo SWRO desalination plant to 1700 m^3/day [46], which could be used as back-up cover in lines 4 to 9 [46].

Under this scenario (including the increased capacity of the El Golfo

Table 6
Monthly and annual electricity production (El Hierro, 2018) [45].

2018	Wind potential (MWh)	Wind farm production (MWh)	Turbines production (MWh)	Pumping demand (MWh)	Diesel production (MWh)	Gorona auxiliary services (MWh)	Total electricity demand (MWh)	Wind energy surplus (MWh)	Energy consumed by the water cycle (MWh)
January	4517	3523	1002	-2136	1141	−124	3406	2051	1206
February	3289	2498	677	−1315	1304	−99	3065	1541	1086
March	3340	2556	641	−1479	1657	−113	3262	1550	1297
April	4463	3386	913	−1913	918	−114	3191	2093	1296
May	3889	3045	699	−1588	1409	−104	3461	1758	1327
June	4088	3256	774	−1576	1293	−120	3627	1809	1249
July	7040	5503	1318	−2932	784	−146	4527	3188	1313
August	5071	4185	910	−2076	1170	−139	4050	2142	1428
September	3892	3083	727	−1510	1666	−117	3849	1734	1283
October	1676	1301	276	−597	2847	−100	3728	765	1264
November	1835	1394	280	−715	2244	−58	3146	859	1052
December	1757	1409	310	−708	2374	−114	3271	771	973
Total	44,858	35,139	8527	−18,545	18,149	−1346	41,924	20,260	14,774

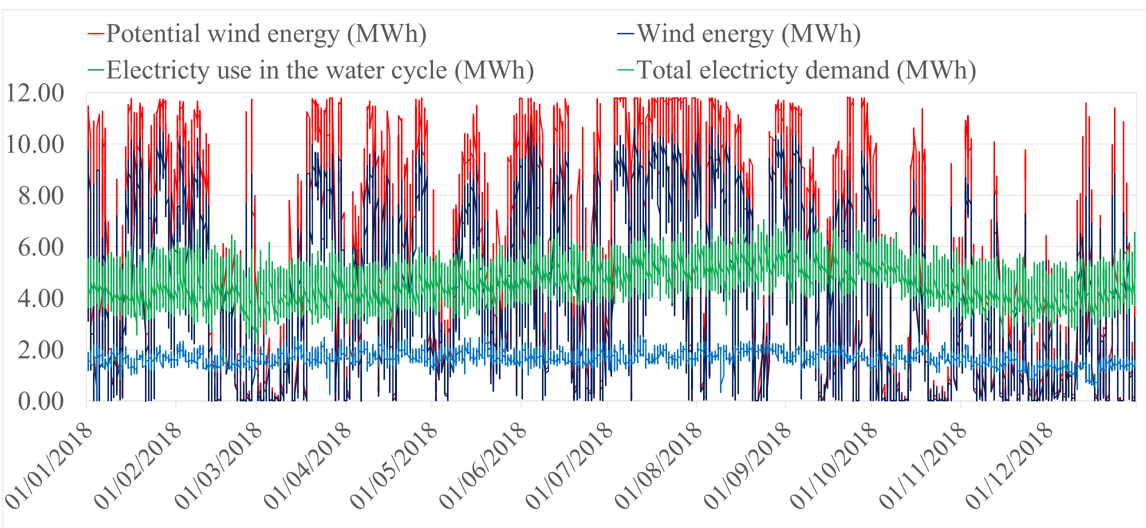


Fig. 6. Annual energy data analysis (El Hierro, 2018) [36,37].

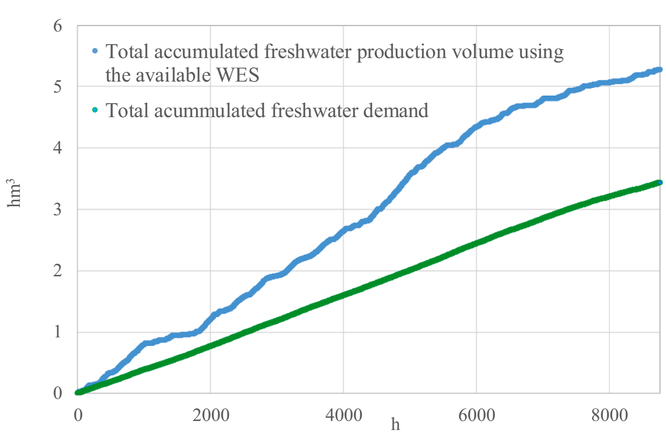


Fig. 7. Total accumulated volume of freshwater produced without storage restrictions (El Hierro, 2018).

SWRO desalination plant plant), 39% of the WES is used. This would mean an increase in wind energy penetration from 37.6% (current data) to 46%, representing a 22% increase.

3.3. Centralised water system

Under this scenario, the whole water demand of the island is provided by a single desalination plant that is driven only by the WES, Thus, an important factor is the analysis of the current storage capacity in each municipality of the island. Currently the water storage capacity is distributed as follows: 48,814 m^3 in Valverde, 144,105 m^3 in La Frontera, 21,924 m^3 in El Pinar (in 47 water tanks, 3 reservoirs and 11 ponds). Additionally, if the lower and upper reservoirs of the Gorona del Viento wind-hydro power plant (located in Valverde) are also included, a total storage volume of 523,000 m^3 is obtained.

In this study, it is proposed to use the upper reservoir of the wind-hydro power plant to store the desalinated water. This reservoir, with a capacity of 373,000 m^3 and located at an altitude of 655 m, allows water storage for long periods, including when the wind resource is insufficient or in the event of a breakdown of the desalination system. This proposed solution, and the oversizing of the SWRO plant, guarantees that the water needs are met. The specific energy consumption of the RO units and the pumping of the water to the upper reservoir is 5 kWh/m^3. Storing water in the upper reservoir allows its distribution by gravity to the majority of the water tanks of the three municipalities of the island. However, a total of 9 water tanks (that correspond to 8% of the island's water demand) are located at a higher altitude than the upper reservoir. In this case, an electric pump will be required. The

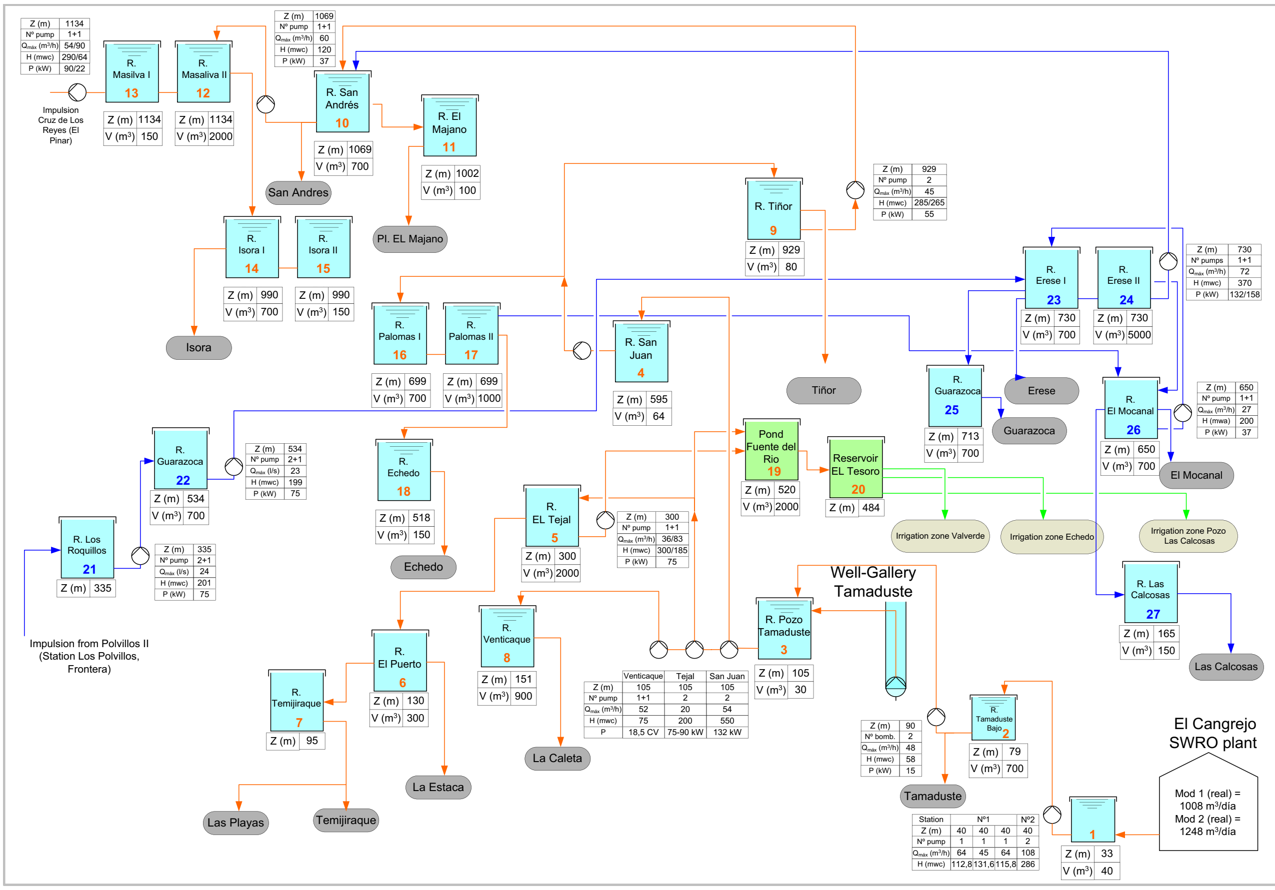


Fig. 8. Water supply system in Valverde municipality [46].

Table 7
Total volume of water produced per line.

Line	Priority	Source	Water use	Municipality	Electricity consumption (kWh)	Production (m^3/year)	% Production vs. 2018 demand
1	1	SWRO	HC	El Pinar	454.6	321,130	101.0
2	2	SWRO	HC	Valverde	568.7	384,450	101.0
3	6	SWRO	I	Frontera	188.6	210,688	116.8
4	3	Well	HC	Frontera	85.3	150,151	79.2
5	4	Well	HC	Frontera	204.0	278,811	95.4
6	5	Well	HC	Valverde	8.1	13,630	61.5
7	7	Well	I	Frontera	63.3	329,094	91.7
8	8	Well	I	Frontera	104.1	632,841	95.4
9	9	Well	I	Valverde	37.9	67,126	61.5

HC: human consumption.
I: irrigation.

specific energy consumption associated to such pumping needs varies between 1.4 and 2.6 kWh/m^3.

Spanish Royal Decree 902/2018 of 20 July, amending Royal Decree 140/2003 of 7 February, establishes that water stored outdoors (as it is the case of the upper reservoir) is not apt for direct human consumption since it does not comply with the corresponding water quality criteria. Water destined for human consumption must be stored in a closed tank [47]. A potable water treatment plant is therefore required to eliminate suspended solids and chlorinate the water. The specific energy consumption of this treatment is 0.5 kWh/m^3. For agriculture purposes, the water stored in the upper reservoir can be used directly.

Consequently, this centralised solution also includes a closed water storage tank for human consumption, whose total capacity has been estimated at 19,000 m^3, a compromise of eight days' water demand in order to satisfy the maximum period of the year without wind. This volume was calculated taking into account the water demand for 2021 (205 L per person and day) [48].

The first analysis carried out considers the optimized desalination capacity per rack. Several modular configurations were studied. The results show that the SWRO operability is maximized (maximum number of hours in operation) by using 8 racks with a rated capacity of 2500 m^3/day each.

The nominal desalination production capacity considered under this scenario is 12,000 m^3/day, approximately double the current installed capacity in the island. The required investment cost to build a new centralised SWRO desalination plant of 12,000 m^3/day production is estimated at 380–390 € per/m^3/day of desalinated water production with a payback period of 15 years [49].

Under this scenario, 84.3% of the WES is used, which means an increase in wind penetration from 37.6% (current data) to 69%, which representing an 83.5% increase.

Taking into account the modular configuration of the SWRO desalination plant with 8 racks, Table 8 summarizes the total operating hours per year of each rack, operating independently or jointly depending on the hourly amount of available WES. As can be seen, rack 1 (the first to be connected and the last to be disconnected) is in operation 6446 h/year (73.6%), while rack 2 (the second to be connected) is in operation 5967 h/year (65%). In accordance with the logic diagram of Fig. 4, the proposed centralised SWRO plant is able to operate the 8 racks jointly during 2064 h/year (23.6%). None of the racks are connected and the plant is therefore shut down 26.4% of the time due to an insufficient wind resource.

Fig. 9 represents the annual evo1ution of the WES and the water production under this scenario.

Fig. 10 represents the cumulative annual volume of desalinated water under this centralised scenario (difference between desalinated water produced and water demand). The maximum cumulative volume represents 12% of annual water demand and will be distributed between the storage tanks of the three municipalities and the upper reservoir.

Table 8
Operation rates and production capacity.

	Operation rates	
	Operation hours	(%)
Non-connected racks	2313	26.4
Rack 1	6446	73.6
Rack 1–2	5697	65.0
Rack 1–3	4824	55.1
Rack 1–4	4248	48.5
Rack 1–5	3731	42.6
Rack 1–6	3220	36.8
Rack 1–7	2675	30.5
Rack 1–8	2064	23.6
Fresh water production (m^3/year)		3,414,959
Production vs. 2018 demand (%)		103.4

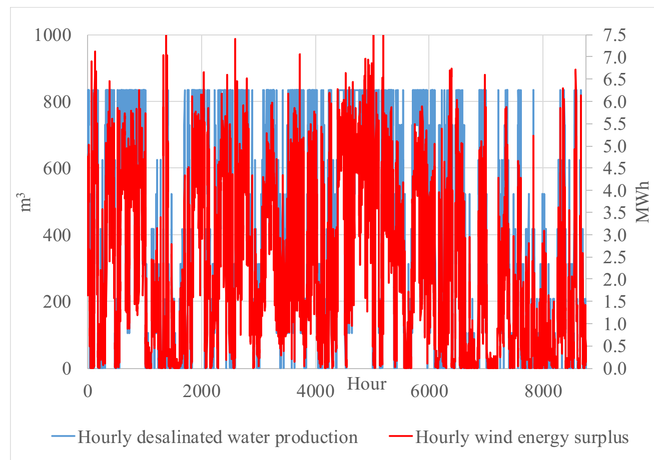


Fig. 9. Annual WES and desalinated water production for the centralised water scenario.

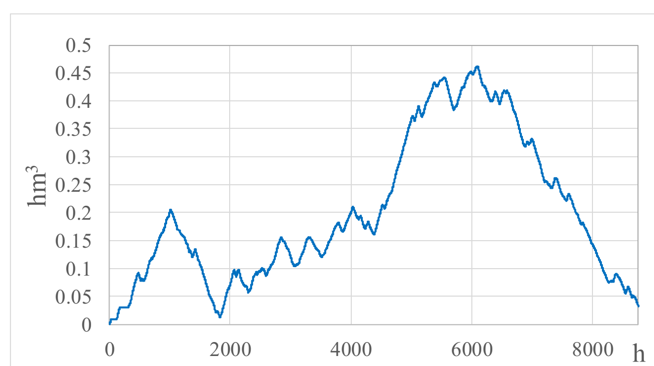


Fig. 10. Cumulative annual volume of desalinated water.

4. Conclusions

This research work proposes solutions to overcome the challenge of increasing the share of RES penetration by covering the electricity demand of the whole water cycle only with the wind energy surplus. From the technical point of view, the results show that this surplus could directly be used to cover the energy demand of the water cycle on El Hierro island (Canary Islands, Spain). Two different scenarios (centralised and decentralised) according to the configuration of the water cycle are defined and simulated. Under both scenarios, the supply of the whole water cycle using the wind energy surplus is feasible and increases the share of wind energy penetration.

The scenario modelled on the basis of a decentralised water supply system (which is the existing one) leads to an increase in wind penetration of around 22%. However, this scenario does not solve the intensive use of the aquifers, mainly for irrigation purposes, which currently represents 47% of total water production. This could lead to future overexploitation of the aquifers, leading to a lowering of the phreatic level, the introduction of seawater into the aquifers and depletion of the water resource, among other consequences.

On the other hand, the scenario based on a centralised water supply system, with only one SWRO desalination plant that also uses a centralised storage reservoir, is capable of satisfying the whole water demand of the island. Under this scenario, it is possible to increase the yearly wind penetration by approximately 83%. The study demonstrates that the installation of one modular SWRO plant, capable of operating the trains independently or jointly, adapts better to the WES profile. The deployment of a single SWRO desalination plant coupled to a centralised storage reservoir and powered by renewable energy sources can play an important role in sustainable groundwater management.

According to these results, the nexus between wind production and the water cycle not only contributes to better integration of intermittent renewable energy generation but also to decarbonization of the water cycle.

CRediT authorship contribution statement

Noemi Melián Martel: Resources, Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing- Original draft preparation, valiation, Writing- Reviewing and Editing, Visualization.

Beatriz Del Río Gamero: Conceptualization, Methodology, Investigation, Software, Data curation, valiation, Writing- Reviewing and Editing, Visualization.

Julieta Schallenberg Rodriguez: Conceptualization, Methodology, Validation, Writing- Reviewing and Editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research has been co-funded by the ERDF, INTERREG MAC 2014-2020 programme, within the E5DES (MAC2/1.1a/309) and DESAL+ (MAC/1.1a/094) projects. No funding sources had any influence on study design, collection, analysis, or interpretation of data,

manuscript preparation, or the decision to submit for publication.

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