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The fulfilled promise: a green way for seawater desalination through reverse osmosis

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ABSTRACT

Reverse osmosis (RO) is a widely used technology for producing drinking water from seawater. The energy needed for RO water treatment has decreased, but energy costs remain a challenge, especially in communities where drinking water consumption is far from seawater. This study explores the best RO configuration for energy efficiency in scenarios where solar and gravity energy are available. A case study is presented for the community of La Higuera (Coquimbo, Chile), that includes two small villages, La Higuera and Chungungo. The study evaluated two alternative hydraulic systems for operating the RO plant and delivering drinking water to the main tanks in Chungungo and La Higuera, completely independent of the power grid. The results showed that the most energy-efficient system uses solar energy and filtered seawater accumulated at high altitudes in a coastal mountain range. A 20-y evaluation showed that while the investment may not be fully recovered, the implementation of this RO scheme would have significant economic gains with the addition of public financial incentives and reduction of CO_2 emissions.

Keywords: Desalination; Solar energy; Renewable energy; Reverse osmosis; Water scarcity

1. Introduction

Chile is among the countries with the highest risk of being affected by water stress and droughts [1], due a macro drought that dates from 2008 affecting the north and center of the country [2]. In response to the increasing water scarcity, desalination has become a viable alternative for water supply over the past 30 y, globally [3]. Among the desalination processes, reverse osmosis (RO) is the most feasible in terms of production, energy efficiency and cost [4]. However, RO requires a significant amount of energy, which can be supplied by renewable energies when the connection to the

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public power grid is not profitable or not feasible [5]. On the other hand, RO can significantly help to reduce greenhouse gas emissions [5]. In addition, renewable energy and desalination plants comprise a variety of technologies that can be customized for specific situations, offering a range of tailored solutions [6].

Technologies used for desalination have gone through several stages, starting with multi-stage flash (MSF) desalination until the 1990s [7]. MSF presents an energy consumption ranging from 191 to 290 MJ/m^3, equivalent to 15–25 kWh/m^3. MSF technologies has a pumping electricity requirement of 2.5–5.0 kWh/m^3. Thus, the total electricity consumption using this technology varies between 20 to 30 kWh/m^3 [7–9]. Later, multiple effect distillation (MED) and RO technologies replaced MFS, where the first peaked in 2008 and 2009, and RO from 2009 onwards [7]. Energy consumption for MED varies between 145 to 230 MJ/m^3. This is equivalent to 12–19 kWh/m^3, where pumping requires 2.0–2.5 kWh/m^3 and the remaining consumption regards thermal energy [7,8]. RO requires 3–8 kWh/m^3 for seawater and 1.5–2.5 kWh/m^3 for brackish water on large to medium size plants, while for smaller plants the energy consumption is about 15 kWh/m^3 [7,8]. These technologies generate important environmental impact concerns, given the discharge of brines and the emission of CO_2 that, for example, can range from 20 to 25 kg/m^3 for MSF [7,10,11]. As so, the technology mix defined as optimal should consider several local parameters, such as geographic conditions, site topography, amount, and type of energy available at a low cost, availability of local infrastructure, plant size, and the salinity of water at the intake location [12].

In the Canary Archipelago, water desalination is a well-established technique, which has undergone considerable changes since, initially, steam-based technologies were adopted. Nowadays, this technology has been almost completely replaced by membrane technologies [13]. One of the challenges that constitute the use of membranes is the constant need for energy supply, given the current trends towards increasing energy costs and the pollution caused by burning fossil fuels to generate energy [14]. The electric power of the installed plant in Gran Canaria, in 2015, was of 1,150.40 MW, where 89% came from oil derivates as a primary energy source, while only 11% came from renewable sources, mainly wind and, to a lesser extent, solar [13]. The objective of promoting the use of renewable energy in desalination plants is to reduce the use of fossil fuels, which, in addition to safeguarding environmental integrity, increases sustainability and favors the reduction of end-user costs [15].

Several researchers have focused their work on searching the optimal configuration of RO-based desalination plants operating with renewable energy [16]. Alberto Vázquez Figueroa, a well-known writer, in his novel "El Agua Prometida" [The Promised Water] [17] describes a system that includes the operation of a seawater desalination plant using potential (gravity) energy. This gravity energy is originated from an elevation difference equivalent to the working pressure of the osmosis membranes (osmotic pressure). Elhadidyand Shaahid [18] and Kalogirou [19] proposed the design of RO-based desalination systems with renewable energy sources, the authors reached the conclusion that, when selecting a renewable energy desalination system, factors such as the local availability of renewable energy resources, water quality to be desalinated, plant size, remoteness, and infrastructure must be considered carefully to determine the most appropriate and economically feasible technology. The feasibility of providing wind power to a desalination plant was evaluated by Markus Forstmeier [20], The authors found that wind-powered desalination systems can compete with other desalination methods while efficiently providing safe and clean drinking water in an environmentally responsible way, thus representing a sustainable solution to meet the growing demand for drinking water. Fadigas and Dias [21] proposed an alternative configuration to conventional RO desalination systems, incorporating the use of wind energy and potential gravity energy. A thorough theoretical analysis demonstrated the technical feasibility of this proposal. Cherif and Belhadj [22] estimated the energy and drinking water production, considering a large temporal scale, of a hybrid solar-wind system coupled to a RO desalination unit. Qian Li et al. [23] proposed to integrate different configurations of renewable energy sources in the RO desalination process and, considering electric storage (from batteries), to reduce the energy losses of the system components and increase the overall energy efficiency.

The geographical, topographic, and climatic characteristics of northern Chile, specifically in the community of La Higuera, located in the north of the Coquimbo region, are ideal to study potential gravity energy accumulation systems. This community is located between parallels 29°20′ S and 32°15′ S, between the Cordillera de la Costa mountain range and the Pacific Ocean, where the mountain range acts as a climatic screen, creating an area with low cloudiness and high potential for solar radiation [24]. The use of solar energy and accumulated potential gravity energy systems can assure major benefits for the local communities, especially in rural coastal areas. In these areas, where in many occasions the communities suffer from water scarcity, it becomes vital to take advantage of the environmental and geographical conditions for a better and more sustainable management of the water sources. Integrating renewable energy in water production systems is also a green way to reduce CO_2 emissions. According to the Chilean Energy Transition report, Una Verdad Inconveniente [An Inconvenient Truth] [25], for each MWh of electrical energy generated, on average, 0.4 tons of CO_2 are released to the atmosphere.

The case study here presented comprises two communities located in the Coquimbo region, Chungungo and La Higuera, both included in the La Higuera administrative region. This region shows an average rainfall of 89 mm/y, with extreme values ranging from zero in the north to 220 mm/y in the south. The main source of drinking water in the region is the accumulation of snow in the Andes mountains, which feeds the course of the three main rivers in the region: the Elqui, the Limarí, and the Choapa. The communities located along the north coast of Chile have the greatest difficulty in obtaining drinking water. These are rural localities, many times suffering from water and sanitation issues. Therefore, the development of innovative and sustainable solutions with low operating costs is essential.

The Chungungo community is served by a drinking water administration system named Rural Drinking Water

(RDW). RWD developed a seawater desalination station (SWDS) on the near the seashore, at an elevation of 10 m above the mean sea level (10 masl). This station produces 5 l/s of drinking water, that are pumped into a storage tank located at an elevation of 89 masl by a 1,312 m pipeline. From the storage tank, the water will be supplied to Chungungo by gravity. Currently, the demand of drinking water from the Chungungo community does not exceed 1 L/s, thus, the plant has an oversized capacity. The La Higuera community is also located at the same elevation as Chungungo, but 12 km further inland. Nowadays, drinking water is supplied to La Higuera through a RDW system from a well located in the "Los Choros" ravine, 22 km north of La Higuera. This ravine is sometimes affected by droughts, and so the water must then be supplied by tank trucks. An adequate solution for mitigating the scarcity of water in these communities could be to use the additional capacity of the Chungungo plant to supply drinking water to La Higuera. However, it must be taken into consideration that, even though La Higuera is only 12 km from the coast, it is located at an average elevation of 585 masl. Furthermore, there is a coastal mountain range with an elevation of 700 masl between these two localities, and so, any drinking water supply system to be developed (e.g., a pipeline from the desalination plant) would have to overcome it.

The Chilean Ministry of Public Works has developed innovation projects to face the water scarcity in the north of Chile, through the incorporation of renewable energy sources. None of these projects considered the use of accumulated gravity energy by pumping, where solar energy is the energy source for pressurization. This solution is already in operation in other regions of the world, such as in the Canary Islands [26]. A pumped-storage hydropower plant (PSHP) is a closed-circuit hydraulic system that generates electricity using energy surpluses [5]. In this case, solar energy is used to accumulate water at higher elevations (as in the mountain range), thus storing potential (gravity) energy. Later, the potential energy can be transformed into electrical energy by using a hydro turbine, for example, in the absence of solar radiation (cloudiness, storms, etc.). An alternative to PSHP is to use the mountain range to store microfiltered seawater under an equivalent hydraulic head to the pressure level required by the osmosis membranes to operate (osmotic pressure), thus producing desalinated water only from a gravity energy source.

The objective of this work is to analyze, at a conceptual engineering level, two different hydraulic operation schemes (configurations I and II; Section 2) including a desalination station of seawater by RO and a drinking water supply system. Both these operation schemes use solar radiation as the main source of energy, combined with the potential gravity energy of water accumulated at the Cordillera de la Costa. The first hydraulic scheme operates using gravity energy to produce electrical energy. The second one uses microfiltered seawater stored at a high elevation to operate a RO process. To find an optimal configuration of the water supply towards the summit of the Cordillera de la Costa, simulations were carried out using EPANET software. Finally, the environmental benefit of the proposed solution was evaluated by quantifying the reduction in CO_2 emissions achieved with these water resources operation and management systems. This reduction in CO_2 emissions was assessed by benchmarking against the $kgCO_2/kWh$ ratio attained considering this system was to operate powered by the Chilean power grid.

2. Methodology

This study was carried out at a conceptual engineering level, based on a SWDS operation scheme, and the drinking water supply to the local communities. The system uses solar power, available in the La Higuera community, as the main source of energy, in combination with the potential gravity made possible by the nearby coastal mountain range.

Two different configurations of energy supply for the desalination and supply of drinking water were studied. Configuration I is detailed in Section 2.1 and configuration II in section 2.2. Both configurations can operate during daytime or nighttime (with or without direct sunlight). Configuration I operate using gravity energy to produce electrical energy. Configuration II uses microfiltered seawater stored at a high elevation to operate a RO process. In both configurations I and II solar energy is used to power to electric equipment.

2.1. Detail of configuration I

Configuration I, as shown in Fig. 1a and b, is an operation scheme based on generating electrical energy from a solar park during the day and from a hydraulic turbine during the night. This is attained through a pipeline closed circuit between two tanks at different elevations, and a hydraulic turbine connected to an electric generator. This system is similar to the one currently operating in the Canary Islands [26]. The operation of the SWDS is continuous (24 h/d), but the supply of drinking water to La Higuera is only assured when the solar park is producing, that is, approximately 7 h/d.

Fig. 1a shows how this system operates during sunlight hours. The energy is produced by a solar plant [A] and then transformed by an electrical transformer [B] while the PSHP is storing process water in the upper tank [J] from the lower tank [H]. This system energizes the intake of seawater [C], the SWDS pump [D], the Chungungo pump [G], and the PSHP pump [I]. Fig. 1b shows how this system operates with the absence of solar energy. The energy is originated from the PSHP, through the PSHP turbine [K], that uses gravity energy produced by the solar park (in the form of electrical energy) and stored in the upper tank [J] (in the form of gravity energy. Under this operating scheme, the PSHP pump [I] is inactive.

2.2. Detail of configuration II

Configuration II comes from the idealization of the famous Spanish writer, Alberto Vázquez Figueroa, in the novel "El Agua Prometida" [17], where he described a system conceptually like the one presented in Fig. 2. This scheme combines solar and potential gravity energy for the operation of the SWDS, with a hydraulic head equivalent to the working pressure of the osmosis membranes (osmotic pressure). This system works accordingly to the availability of solar energy (Fig. 2a), which is produce by a solar plant [A] and then transformer by an electrical transformer

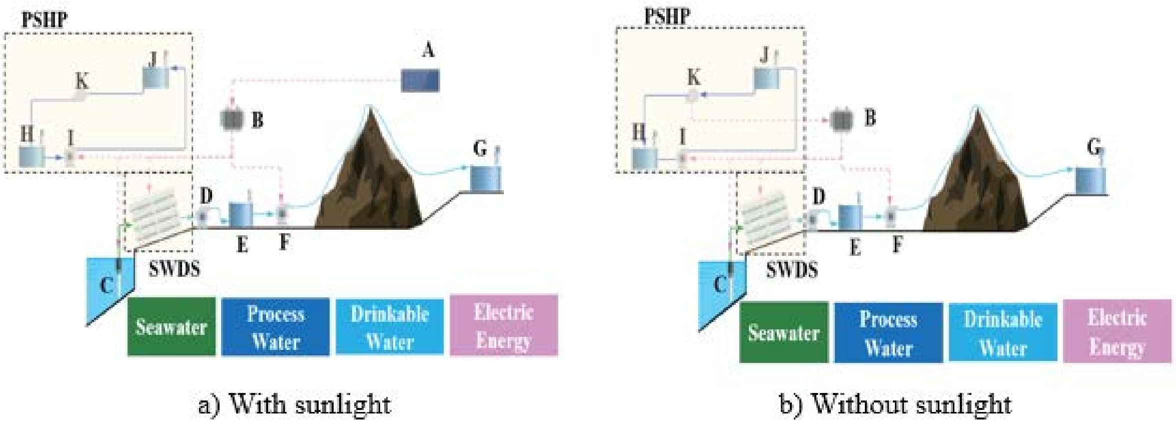


Fig. 1. Process flow diagram of configuration I for conditions: (a) with sunlight and (b) without sunlight. A: Solar plant, B: Electrical transformer, C: Intake of seawater, D: SWDS pump, E: Chungungo tank, F: Chungungo pump, G: La Higuera tank, H: PSHP lower tank, I: PSHP pump, J: PSHP upper tank, and K: PSHP turbine.

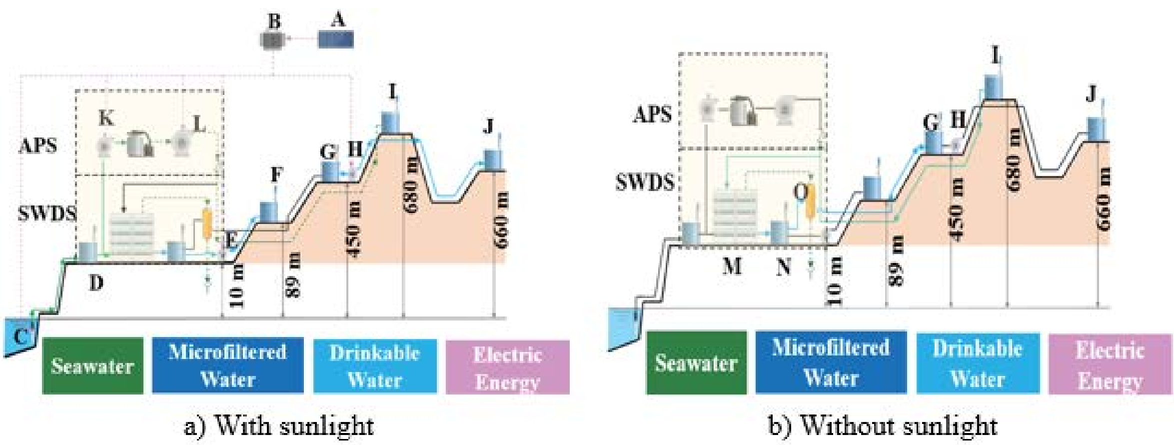


Fig. 2. Process flow diagram of configuration II for conditions: (a) with sunlight and (b) without sunlight. A: Solar plant, B: Electrical transformer, C: Intake of seawater, D: Raw seawater tank, E: SWDS pump, F: Chungungo tank, G: Intermediate tank, H: Intermediate tank pump, I: Upper tank, J: La Higuera pump, K: APS pump, L: high-pressure APS.

[B]. This energy is then used to supply the following subsystems: intake of seawater [C], SWDS pump [E], that drive the drinking water towards Chungungo tank [F], an Additional Pretreatment Station (APS) pump [K] that convey the water from the intake seawater tank [D] toward the microfiltration, the APS high-pressure pump [L] to accumulate the microfiltered water at an elevation equivalent to the osmotic pressure of the membranes, in this case, on the top of the coastal mountain, in the upper tank [I]. An intermediate tank pump [H] is also energized to convey the drinking water to La Higuera from an intermediate tank [G], located at an intermediate elevation, where the water is stored using the energy originated from the osmosis rejection, during the night cycle.

Fig. 2b shows the operation of configuration II during the absence of direct solar energy. The system operates using only the potential gravity energy of the microfiltered seawater accumulated in the upper tank [I], to directly feed the SWDS membranes [M], where the drinking water is stored in a tank [N]. From this storage tank, drinking water is pumped to the Chungungo tank [G], using both the residual energy from the upper tank [I] and the energy recuperator [O]. During nighttime the following subsystems will not operate: seawater supply [C], drinking water supply pump to Chungungo tank [F], APS pumps ([K], [L]), and the intermediate tank pump [H].

As can be inferred from the above-mentioned, configuration II produces and conveys drinking water without the need of a connection to the power grid during the absence of sunlight for its main units (approximately 17 h/d).

3. Assessment of energy requirements

The University of Chile's solar energy database [24] was the main source of information to estimate the size requirements for the solar park, where only the month with the lower availability of sunlight hours in the year was considered. This database provides detailed information on solar radiation, (sunlight azimuths) and availability of clear days, among other information.

Chilean Law 20,571 [27] allows the surplus of energy to be injected into the power grid thus, partially, or totally, compensating the investment or operating expenses. Different scenarios were analyzed using EPANET, to find the best operating scheme in terms of energy production and compatibility with the operation of the solar park. To establish the total costs, investment (CAPEX) and operating (OPEX) costs per item were estimated at a prefeasibility level, that is, to determine, analyze, and select the best business scenarios. Consequently, the following economic performance indicators were set:

Present value of costs (PVC): corresponds to the current value (6% interest rate, 20 y evaluation) of annual operation costs and maintenance of the system added to the investment value (CAPEX).

Equivalent annual costs (EAC): corresponds to the PVC transformed into an annuity, which in this case is calculated at 6% for 20 y.

3.1. Seawater desalination station energy demand

The SWDS energy demand depends on the operation of the pumps conveying the seawater through the pre-treatment system and the osmosis membranes, and finally to the accumulation tank located at an elevation of 89 masl. Fig. 3 presents the pipeline from the seawater intake to the head tank. The seawater is collected from a "dock" through a submersible pump that drives the seawater along a 1,363 m pipe (HDPE PN10 5'') to a 30 m^3 storage tank, prior to the SWDS. Then, seawater undergoes a chlorination process for disinfection, using a 0.25 kW (1/3 hp) metering pump. Stored seawater is then re-pumped through the pretreatment system, consisting initially of four sand filters (1.2 m of diameter with a filtering capacity of 20 μm), then two activated carbon filters, (1.2 m of diameter), to eliminate the excess of chlorine. Finally, the water is microfiltered (to 5 μm using 10 cartridge filters 50" long) before entering the high-pressure pump. The flow of seawater that feeds the membranes is 42 m^3/h, meaning, the sand filtration system was designed for a filtration load of 8.8 m/h. Permeated water is diverted to a 30 m^3 storage tank, after the injection of chlorine and sodium bicarbonate to condition the water as drinking water. As a last step in the SWDS, the stored drinking water is re-pumped to the head tank located at an elevation of 89 masl, later to be distributed to Chungungo.

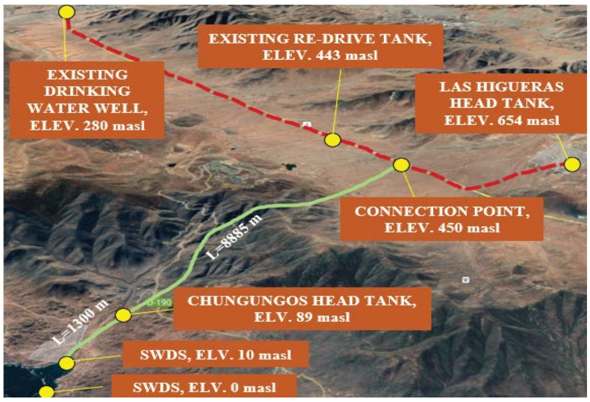


Fig. 3. Layout of the drinking water pipeline from Chungungo to La Higuera.

During the field activities carried out during this study, the instantaneous operating power of the equipment was measured (consumption of electricity). The SWDS records indicate that the unit energy consumption of drinking water produced and stored in Chungungo head tank is 4.31 kWh/m^3, for a water production capacity of 5 l/s (18 m^3/h). The RDW committee reported a 30% loss in the operation. Taking this loss into account, the unit cost for electrical energy at the consumption points rises to 6.16 kWh/m^3. Considering a unit cost of electrical energy of €0.15 kWh (unit cost in Chile regulated by the Government), the operating unit cost obtained for the Chungungo population was of €0.92/m^3, considering only the electrical energy.

3.2. Pipeline layout between Chungungo and La Higuera

The surplus of water available in Chungungo (4 L/s) can be transported to La Higuera through a pipeline (Fig. 3). This pipeline starts in the SWDS, climbs through the coastal mountain range to 771 masl, and then descends and intersects the existing pipeline at 450 masl, continuing with gravity pressure up to the tank in La Higuera, located at 654 masl. This pipeline has a total length of 14,335 m (Fig. 4).

4. Results

4.1. Design of the system configurations

Two different configurations of the hydraulic system were considered in this study, aiming to obtain the maximum

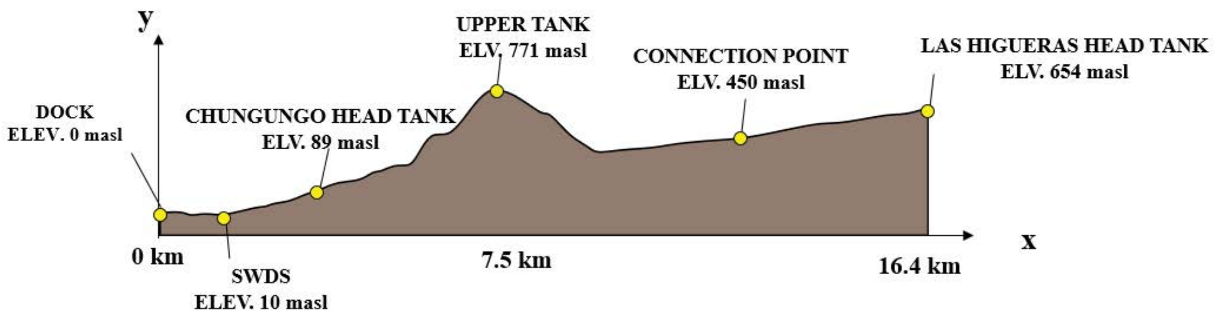


Fig. 4. Elevation profile of the drinking water pipeline from Chungungo to La Higuera.

productivity of the SWDS, that is, 18 m^3/h for 24 h/d, and to provide the ability to manage and supply this drinking water to the head tanks in Chungungo and La Higuera.

In configuration I the SWDS operates continuously, conveying water when solar energy is available, that is, approximately 7 h/d. The flow rate is 46.48 m^3/h, thus providing 325 m^3/d to La Higuera, according to Chungungo RDW surplus. Configuration II is similar, but drinking water will be pumped to La Higuera from a tank at 450 masl (tank G; Fig. 2). Table 1 shows a summary of the production and supply of drinking water to La Higuera accordingly to configuration II.

Fig. 5a and b show, respectively, the system layout of configurations I and II over the topography of the terrain. In configuration II, the storage tank is located at an elevation of 450 masl, to where the drinking water was pumped using the energy recuperated from the rejection water of the RO process. The microfiltered seawater upper storage tank is located at an elevation of 680 masl.

4.2. Design of the drinking water supply system from Chungungo to La Higuera (configuration I)

To supply the drinking water from Chungungo to La Higuera, it is necessary to pump the water in the head tank, located at elevation of 89 masl, using a 4,230 long pipeline, to the maximum elevation (771 masl) (Table S1). From there to the head tank in La Higuera water will flow by gravity. The hydraulic analysis was carried out using EPANET, considering the ASME B 31.4 regulation (ASME, 2019) to select the best piping solution. The energy demanded along the day both for the operation of the SWDS and the supply of drinking water is presented in Table S2. Regarding the above-mentioned, it can be estimated that configuration I require an energy demand of 3,599 kWh/d.

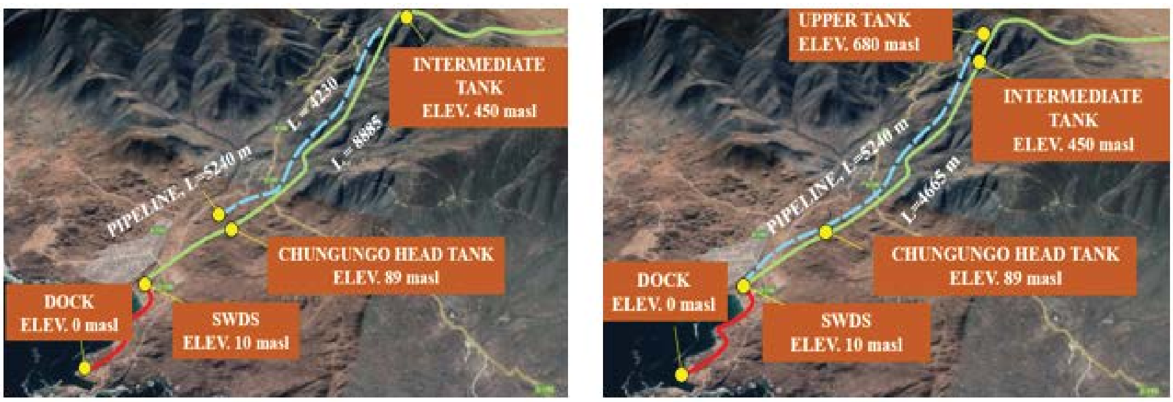
4.3. Design of the electricity generation system by PSHP (configuration I)

The electricity generation system by PSHP requires defining the potential (gravity) hydraulic head, the turbine type, the required flow for the system to operate, and the volume of the upper and lower storage tanks (Fig. 1[H] and [J]), as well as the power of the pumping system required to return the water to the upper tank when solar energy is available. Fig. 5a shows the system layout over the local terrain conditions.

Configuration I includes a closed circuit between an upper tank located at 771 masl and another tank, at the same elevation than the head tank of Chungungo RDW (89 masl), generating an available hydraulic head of 682 m. The hydraulic turbine located in the lower tank produces electrical energy through the transformation of the potential energy (682 m) of the water stored in the upper tank. The type of turbine to be used will depend on the available head and flow, following [28]. Considering the energy required for configuration I to operate (Table 3) and the available hydraulic head, the water flow required to produce the

Table 1
Production and supply of drinking water to La Higuera (configuration II)

Flow	Night cycle				Day cycle (7 h)				Night cycle			
	Midnight to 10:00 am				10:00 am to 04:00 pm				4:00 pm to Midnight			
Chungungo gravitational to elevation 450 (m^3/h)	18.0	18.0	18.0	18.0	0	0	0	0	18.0	18.0	18.0	18.0
Chungungo (SWDS) to elevation 88 (m^3/h)	0	0	0	0	18.0	18.0	18.0	18.0	0	0	0	0
Supply to La Higuera (m^3/h)	0	0	0	0	46.5	46.5	46.5	46.5	0	0	0	0



(a) Layout configuration I (b) Layout configuration II

Fig. 5. System layout over the terrain topography for (a) configuration I, with drinking water circuit (continuous green line), and PSHP (dashed blue line) and (b) configuration II, with drinking water circuit (continuous green line), and the circuit of microfiltered seawater using the gravity energy (dashed blue line).

Table 2
Summary of power required by configuration I (values per hour)

Power	Night cycle				Day cycle (7 h)				Night cycle			
	Midnight to 10:00 am				10:00 am to 04:00 pm				4:00 pm to Midnight			
SWDS production (kW)	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5
Supply to La Higuera water supply (kW)	0	0	0	0	149.0	149.0	149.0	149.0	0	0	0	0
Pumping system, accumulation cycle (kW)	0	0	0	0	660.0	660.0	660.0	660.0	0	0	0	0
Total power demanded (kW)	106.5	106.5	106.5	106.5	915.5	915.5	915.5	915.5	106.5	106.5	106.5	106.5

Table 3
Summary of power required by configuration II (values per hour)

Power	Night cycle				Day cycle				Night cycle			
	Midnight to 10:00 am				10:00 am to 04:00 pm				4:00 pm to Midnight			
SWDS daytime production (kW)	0	0	0	0	106.5	106.5	106.5	106.5	0	0	0	0
SWDS nighttime production (kW)	5.0	5.0	5.0	5.0	0	0	0	0	5.0	5.0	5.0	5.0
Seawater supply, SWDS (kW)	0	0	0	0	15.0	15.0	15.0	15.0	0	0	0	0
Pretreatment pumping system (kW)	0.0	0.0	0.0	0.0	18.5	18.5	18.5	18.5	0.0	0.0	0.0	0.0
Battery charging system (kW)	0.0	0.0	0.0	0.0	15.0	15.0	15.0	15.0	0.0	0.0	0.0	0.0
Microfiltered seawater convey to 680 masl (kW)	0.0	0.0	0.0	0.0	264.0	264.0	264.0	264.0	0.0	0.0	0.0	0.0
Supply of drinking water to La Higuera (kW)	0.0	0.0	0.0	0.0	68.2	68.2	68.2	68.2	0.0	0.0	0.0	0.0
Total power demand (kW)	5.0	5.0	5.0	5.0	487.2	487.2	487.2	487.2	5.0	5.0	5.0	5.0

electrical energy was estimated using the RETScreen Clean Energy Management Software [29]. This software package includes a design module to calculate hydropower generation, considering the most typical technologies and efficiency levels. The results show that with a hydraulic head of 680 m and a flow of 0.027 m^3/s (97.2 m^3/h) it is possible to generate 120 kW. Based on this, the storage volumes of the PSHP upper and lower tanks were set (Fig. 1[H] and [J], 1,818 m^3 each), considering the duration of the generation cycle by the PSHP (17 h) plus an additional of 10% to prevent the tanks from emptying. Therefore, the water that must be conveyed to the upper tank through the pumping system, during the accumulation cycle or the availability of solar energy, was determined. This was carried out by splitting the water volume by the accumulation hours (7 h) and adding 10% volume as a safety margin in the upper and lower tanks.

For the SWDS to operate during the 17 h/d, when solar energy is not available, the generation system must supply 106.5 kW from the PSHP. In turn, the solar park must assure 915.5 kW to face the demand of the SWDS, or the drinking water supply system from Chungungo to La Higuera, and for the pumping system of the PSHP, power to be supplied by the solar park. Table 2 presents a summary of this configuration.

4.4. Design of the gravity-based desalination system (configuration II)

Configuration II includes the use of potential (gravity) energy of microfiltered seawater stored in a tank at the top of the coastal mountain range. This water is stored with a hydraulic head equivalent to the working pressure of the RO system (osmotic pressure; 65 bar or 650 m), to then feed the RO during the absence of sunlight (approximately 17 h/d).

The pipeline system energized by the solar park during about 7 h/d is presented in Fig. 5b. The red line represents the pressurized seawater pipeline, the green line the supply of drinking water to the La Higuera head tank, and the blue dashed line the conveyance of microfiltered seawater to an elevation of 680 masl.

A mass balance calculation was performed to determine the energy demand for the processes listed in Table S3. The desalination system was assumed to operate continuously at its nominal capacity of 18 m^3/h, with a production yield of 43%, requiring a seawater input flow to the MWDS of 41.9 m^3/h. Additionally, microfiltered seawater must be pumped and stored at an elevation of 680 masl (Table 5, item 6.0) at a flow rate of 111.8 m^3/h. This water will be used during the 17 h of absence of solar energy. As a result, the total seawater input flow required for this configuration is 153.7 m^3/h (41.9+111.8), only during daylight hours.

The total energy consumption of configuration II regards the energy required for pretreating and elevating 111.8 m^3/h of seawater (microfiltered seawater) to 680 masl, during sunlight hours (7 h/d). Fig. 5b shows the layout of configuration II over the terrain topography, where the blue dashed line starts in one end of the desalination plant, and goes up to the upper microfiltered seawater storage tank. The pipeline is of 5,530 m long, starting at an elevation of 10 masl and ending at the upper tank (680 masl), with a difference in hydraulic head of 670 m.

The ASME B31.4 [30] standard was used to design the pipeline. Because of the fluid's (seawater) corrosive nature it is necessary to protect these pipes with an internal HDPE pipe liner (Tite Liner® system), and the pumps are constructed of Super-Duplex steel. The pipeline system was designed using EPANET, considering two pumping units (Kamat Pump model K25090). The key features of the pumping system are outlined in Table S4.

By following a similar procedure, the power required to supply drinking water from the intermediate tank located at 490 masl (as shown in Fig. 5b) to La Higuera was calculated. The result was a pumping system with a power demand of 68.2 kW.

While configuration II does not consume energy during nighttime, energy is still required to power the electrical control circuits. This energy is supplied by a set of batteries with an estimated consumption of 5 kW. Additionally, during the day cycle, the batteries need to be recharged with a power of 15 kW. The power demand estimates for these systems are summarized in Table 3.

4.5. Design of the solar park

The solar park was designed based on the results of configurations I and II, which require an effective power of 916 and 487 kW, respectively, for 7 h/d. The solar park is located on the eastern slope of the coastal mountain range, at coordinates 29.4638 S, 71.2308 W. To determine the availability of energy, a database containing information on sunlight hours was obtained from an open-access website of the University of Chile [24]. Table 4 presents the energy availability for all months of the year. Based on this data, the solar park was designed using the solar radiation for the month of June, as it is the month with the least amount of solar radiation.

The correlation between power generation and consumption for both configurations I and II, during the month of June, which has the least amount of radiation, is illustrated in Fig. 6.

In both configurations, the solar park generates more energy than the demand during peak sunlight hours, which varies based on the month of the year. Table 5 provides a summary of the monthly generation–consumption and energy surplus. This data is utilized in the economic evaluation.

The economic evaluation for configurations 1 and 2 was carried out using the open-access database "Generation of Investment Prices" [31], for all the technical components of the project. Operating costs were estimated based on experience of the authors with projects of similar characteristics.

The evaluation of both configurations was based on the projected income from the sale of surplus energy generated by the solar parks. The income estimate considered Law 20,571 [27], which enables self-generation of energy from non-conventional renewable sources and grants users the right to sell surplus energy directly to the utility company at a regulated price.

In this study, a conservative sale price of 0.06 € kWh and of only 80% of the surplus energy was considered (Table S5).

The drinking water sale price was considered the same as the regulated sale price for urban systems, corresponding to 0.83 €/m^3. The sale of 70% of drinking water was considered in this study, thus corresponding to an estimate of 30% loss. An exchange ratio of 780 Chilean Pesos per Euro was considered, as reported by the Statistical Database of the Central Bank of Chile [32].

5. Discussion

5.1. Economic evaluation

The proposed management models envision generating revenue through the sale of surplus energy and drinking water (as outlined in Table 6). However, for a more comprehensive analysis, it is important to consider consumption patterns and align the projected values with actual supply and demand.

During the operation of configurations I or II there are no direct energy costs as these systems are not connected to the power grid, but only the cost of operation and maintenance of the solar, electrical, and hydraulic systems. As a

Table 4
Solar radiation available in the solar park area [24]

Months	Hours (am)						Hours (pm)							
	6	7	8	9	10	11	12	1	2	3	4	5	6	7
January	1.4	54.3	169.4	384.8	606.0	806.9	965.6	1,009.70	967.3	865.5	688	463.6	222.5	35.2
February	0	31.4	156.3	360.9	587.6	785.6	960	1,031.50	1,006.5	887.5	717.2	485.3	229.6	25.9
March	0	11.8	229.4	335.9	576.9	769.5	959.5	1,006.60	972.2	861.9	676.9	436.7	157	3.4
April	0	0	218.1	321.3	518.7	705.0	861.2	911.0	879.9	751.6	559.9	329.6	19.9	0
May	0	0	156.6	275.9	449.7	623.6	760.0	799.0	754.6	622.5	456.6	248.9	0	0
June	0	0	90.0	261.2	441.1	564.0	694.9	766.2	713.9	596	457.4	243.6	0	0
July	0	0	90.1	276.6	464.2	596.1	737.2	796.5	746.1	632.3	462.8	265.1	2.4	0
August	0	0	171.2	333.6	506.2	676.3	790.9	824.5	785.8	674	498.7	292.1	15.9	0
September	0	26.5	239.6	398.5	590.1	747.5	869.4	922.5	870.9	746	562.9	334.9	29.6	0
October	0.5	94.5	220.9	439.2	660.0	830.3	950.8	983.6	921.1	780.8	582.7	345.4	39.6	0.1
November	14.1	91.0	235.0	455.7	672.5	831.2	957.8	994	928.4	795	600.6	364.5	118	14.5
December	15.1	77.7	214.0	431.6	645.1	807.5	928.9	984.5	946.6	823.7	640.1	409.4	176.2	30.3

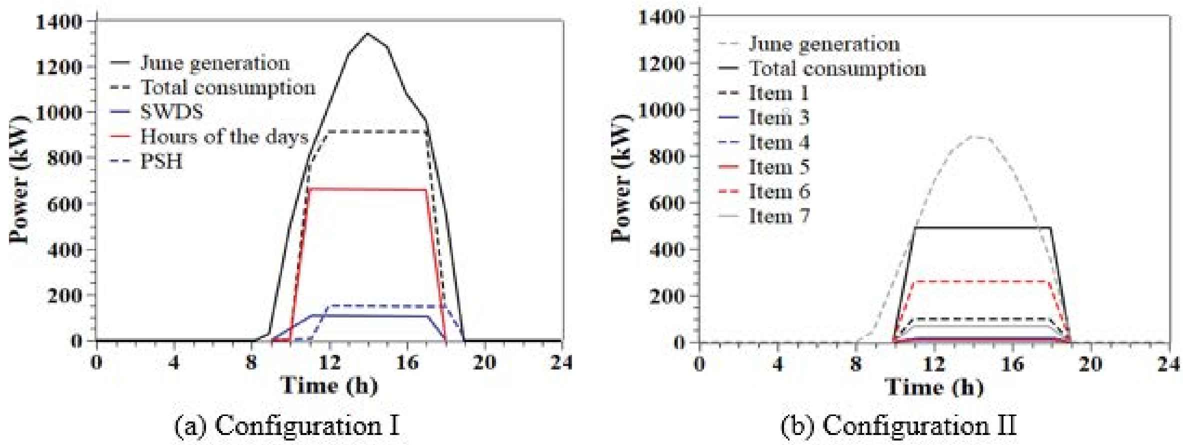


Fig. 6. Generation and consumption for configurations I and II. The system's items are detailed in Table 3.

Table 5
Result of generated-consumed energy and surpluses

Month	Day	Configuration I				Configuration II			
		Generation (d)	Consumption (d)	Surplus (d)	Total surplus (Month*)	Generation (d)	Consumption (d)	Surplus (d)	Total surplus (Month*)
		kWh	kWh	kWh	kWh/Month	kWh	kWh	kWh	kWh/Month
January	31	11,651	6,412	6,521	202,164	8,123	3,410	3,770	116,864
February	28	12,750	6,412	7,620	213,373	8,140	3,410	3,784	105,954
March	31	11,934	6,412	6,804	210,928	7,853	3,410	3,554	110,182
April	30	9,725	6,412	4,596	137,868	6,836	3,410	2,741	82,222
May	31	8,925	6,412	3,795	117,652	5,838	3,410	1,942	60,192
June	30	8,792	6,412	3,662	109,870	5,499	3,410	1,671	50,122
July	31	9,123	6,412	3,993	123,792	5,755	3,410	1,875	58,135
August	31	9,933	6,412	4,804	148,918	6,264	3,410	2,283	70,759
September	30	10,553	6,412	5,423	162,703	7,066	3,410	2,924	87,723
October	31	11,562	6,412	6,433	199,418	7,788	3,410	3,502	108,555
November	30	10,778	6,412	5,648	169,454	8,005	3,410	3,676	110,282
December	31	11,296	6,412	6,166	191,148	8,021	3,410	3,689	114,352
Total					1,987,289				1,075,341

*Only the 80% was considered.

Table 6
Summary of projected income for configurations I and II

Income	Configuration I	Configuration II
Energy surpluses (€/month)	119,237	64,520
Drinking water consumption (€/month)	91,414	91,414
Year total revenue (€/y)	210,651	155,934
Income per m^3 produced (€/m^3)	1.33	0.98

Note: Total factor for energy surplus 80%. Total factor for drinking water consumption 70%.

result, the operating costs (OPEX) of both options are limited to the operation and maintenance of systems. This allows for the calculation of the final operating value, which represents the cost of operating per cubic meter of desalinated, drinking, and stored water, the latter in the head tanks of Chungungo and La Higuera.

The operating cost per unit indicator for configuration I and II is 0.92 and 0.78 €/m^3, respectively, indicating that configuration II is more efficient. Both configurations generated positive outcome regarding energy and drinking water sales balances after 1 y of operation, excluding investment amortization (Table S6).

The region where the towns of Chungungo and La Higuera are located is characterized by severe water scarcity, with low or no rainfall. These two communities are separated by a coastal mountain range, making it difficult to supply them with drinking water produced from the desalination of sea water, due to the high energy demands of approximately 9.2 kWh/m^3 (operation and distribution). However, this complex process also presents an opportunity to utilize renewable energy sources, as the mountain range traps clouds and provides a high number of sunlight hours, without cloud cover. Additionally, the high elevation of the mountain range provides potential for the storage of solar energy, which can be used during periods of limited sunlight. The two proposed configurations for the operation and distribution of drinking water do not require connection to the electrical grid, resulting in positive social and environmental impacts, thus contributing to address a point of conflict in the region [33].

Configuration II requires less capital investment than configuration I, with €3,487,517 compared to €5,082,422 (Table S7). The economic indicators were determined using a 20-y horizon and a 6% year interest rate, with a residual value of 15% of the initial investment being considered at the end of the evaluation period.

The social evaluation of the project was analyzed by considering the financial gain for consumers, specifically the difference in the sale value of drinking water, with and without the implementation of the proposed project. A scenario without the project was considered, where the price of drinking water for consumers is 1.92 €/m^3, corresponding to the price in Chungungo. However, in La Higuera the price for consumers is currently 0.77 €/m^3, but this price is subsidized by the municipality. During droughts, the real cost of water in La Higuera can be over 7 €/m^3, and the supply is guaranteed by tanker trucks. This difference in the financial gain for consumers of drinking water is considered beneficial and represents the social benefits that the project can promote.

The difference of income per m^3 produced constitutes a social price (shadow price) that is transferred as a global social benefit for the project. In this evaluation, this social price reaches a value of 120,848 €/y, from which the social evaluation was established (social PVC and social EAC). Table S8 summarizes the main components for economic analysis and assessment.

Accordingly, to the above-mentioned, configuration II shows a better performance with EAC representing a commitment 28% below configuration I.

In both configurations, even with the revenue generated from selling surplus energy from the solar park and producing drinking water at market rates for Chungungo and La Higuera and a yearly interest rate of 6%, it is impossible that the initial investment will be fully recouped. Even incorporating the social benefit, which is a result of the lower cost for the availability of drinking water, it is still not possible to obtain a positive EAC, thus, configuration II can be considered more appealing than configuration II (Table 7).

5.2. Comparison to operational results from other plants

A comparison of the results of configuration II with those presented by Alberto Vázquez Figueroa [17] shows that: (a) his proposal for a gravity-based desalination system using an underground gallery would have a higher energy consumption of 2.83 kW/m^3, and (b) additional costs for water distribution, operation, and administration. In contrast, our results for configuration II indicate that this system does not require any energy supply from the power network and has a lower cost of 0.78 €/m^3.

Previous systems have proposed systems to produce drinking water that operate based on renewable energies. Fadigas et al. [21] considered a system that uses wind and gravity energy which demanding 2.81 kWh/m^3, considering the wind energy availability factor. Cherif and Belhadj [22] analyzed a system that uses a hybrid solar-eolic system to operate a RO unit (SWDS). Although this study considers an autonomous operation, not connected to the electric grid, the results show major fluctuations in the production of drinking water throughout the year due to the natural varying availability of renewable energy sources.

5.3. Reduction in CO_2 emissions

The reduction of CO_2 emissions from the reverse osmosis plant and the conveyance of drinking water to the head tanks of Chungungo and La Higuera is estimated based on the assumption that the system's operation obtains energy directly from the power grid, with a flat rate during both the day and night. It is assumed that the plant operates continuously throughout the year, with an energy demand of 4,332 kWh/d (1,581 MWh/y) from the Central Interconnected System (CIS). According to the Chilean Energy Transition

Table 7
Economic performance indexes of configurations I and II

Indexes	Configuration I	Configuration II
Rate (%)	6%	6%
PVC (6%)	–4,084,684	–2,952,850
EAC (6%, 20 y)	–356,121	–257,443
Social PVC (6%)	–3,458,601	–1,489,096
Social EAC (6%, 20 y)	–301,537	–129,826
Investment per m^3 at 20 y (€/m^3)	1.61	1.11

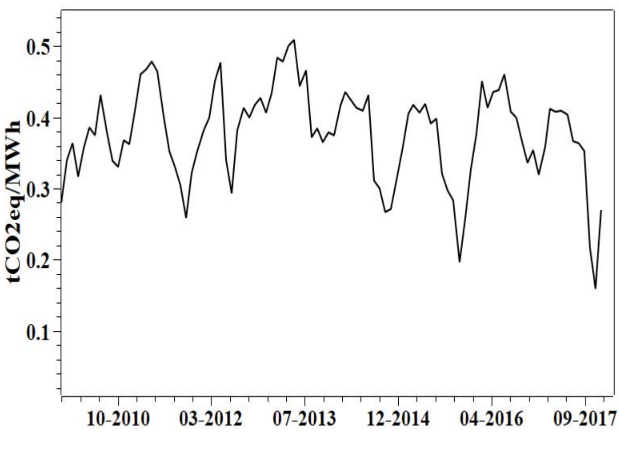


Fig. 7. CO_2 emissions emitted by the Central Interconnected System [34].

report, "An Inconvenient Truth", on average, the CIS emits 0.4 tCO_{2eq} (equivalent tons of CO_2) per MWh of electrical energy generated (Fig. 7). If configuration I or II was implemented, emissions of 632 tCO_{2eq}/y would be avoided.

The most efficient way to minimize investment and operating costs in a solar-energy pumping-water-accumulation hybrid system is to operate all subsystems during sunlight hours. This way, only essential operations such as the operation of the SWDS and the accumulation of drinking water are carried out during the remaining 17 h/d. This operating scheme is referred to as configuration I in this study.

The primary energy demand is for pumping water to be stored as gravitational energy, effectively capturing and storing solar energy for later use during periods of low sunlight, typically 7 h/d. To fully harness these hours of daily sunlight at the chosen location for the solar park, it is necessary to install solar panels with a capacity of 3.1 times the power demand. From a financial perspective, configuration II demands 31% less energy compared to configuration I, making it the most cost-effective option for the area under study.

6. Conclusions

This study aimed to determine the optimal configuration for a reverse osmosis (RO) system in terms of energy consumption by utilizing both solar energy and the energy generated by gravity. The study was conducted through a case study of the Chungungo and La Higuera communities located in Coquimbo, Chile. These communities are characterized by having near-zero total annual rainfall.

The primary objective of the study was to achieve complete independence from the power grid and to evaluate the two alternative energy supply configurations for the RO plant and drinking water supply system. The two configurations were thoroughly analyzed to determine which configuration would result in the least energy consumption. The results of the study indicated that the system that requires the least energy is the one that utilizes solar energy and microfiltered seawater accumulated at high elevations in a coastal mountain range.

In terms of the direct operating costs, configuration I was found to have a cost of 0.92 €/m^3 while configuration II had a cost of 0.78 €/m^3. These costs did not include the amortization of the investment. The sale of 80% of the surplus of solar energy and 70% of the drinking water, which was assumed to have a 30% loss, was found to be enough to fully cover the operational costs. Furthermore, the results indicated that configuration II was the more favorable option as it had a 28% lower EAC compared to configuration I.

The implementation of this project will result in significant social and environmental benefits for the communities of Chungungo and La Higuera. In addition, the efficient configuration presented in this study can be adapted for other purposes, such as providing electricity for the community, with the necessary adjustments to the system. Additionally, this project will result in a significant reduction in carbon emissions, with a yearly reduction of 632 tCO_2eq/y.

In conclusion, even though the economic indicators may not seem favorable at first glance, this project is a social initiative without a full return on investment and its implementation would have a positive impact on both the social and environmental fronts.

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Conflicts of interest

The authors declare no conflict of interest.

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Supporting information

Table S1
Summary of design parameters, and daily demand and supply of drinking water in Chungungo and La Higuera

Design parameters	Values		Units	
SWDS production	5		1/s	
SWDS production	18		m^3/h	
Daily hours of operation	24		H	
Volume of daily production	432		m^3	
Initial elevation	89		M	
Final elevation	771		M	
Static head	682		M	
Pipeline length	4,230		M	
Daily demand	Current		Projected in 20 y	
	Winter	Summer	Winter	Summer
Chungungo demand (m^3/d)	59	84	143	179
La Higuera demand (m^3/d)	180	180	366	366
Daily total (m^3/d)	239	264	509	545
Surplus/deficit (m^3/d)	193	168	–77	–113
Daily distribution	%		m^3	
Chungungo	28.3		122	
La Higuera	71.7		310	
Total	100		432	

Table S2
Energy required by the PSHP

Energy	Night cycle				Day cycle (7 h)				Night cycle			
	Midnight to 10:00 am				10:00 am to 04:00 pm				4:00 pm to Midnight			
SWDS production (kWh)	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5	106.5
Supply to La Higuera (kWh)	0	0	0	0	149.0	149.0	149.0	149.0	0	0	0	0
Total (kWh)	106.5	106.5	106.5	106.5	255.5	255.5	255.5	255.5	106.5	106.5	106.5	106.5

Table S3
Mass balance of seawater and drinking water flows (configuration II)

	Night cycle				Day cycle				Night cycle			
	Midnight to 10:00 am				10:00 am to 04:00 pm				4:00 pm to Midnight			
SWDS daytime production (m^3/h)	0	0	0	0	18.0	18.0	18.0	18.0	0	0	0	0
SWDS nighttime production (m^3/h)	18.0	18.0	18.0	18.0	0	0	0	0	18.0	18.0	18.0	18.0
SWDS efficiency (%)	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0	43.0
Microfiltered seawater supply, SWDS night cycle (m^3/h)	41.9	41.9	41.9	41.9	0	0	0	0	41.9	41.9	41.9	41.9
Microfiltered seawater supply, SWDS day cycle (m^3/h)	0	0	0	0	41.9	41.9	41.9	41.9	0	0	0	0
Microfiltered seawater elevation to 680 masl (m^3/h)	0	0	0	0	111.8	111.8	111.8	111.8	0	0	0	0
Total supply of microfiltered seawater from the dock (m^3/h)	0	0	0	0	153.7	153.7	153.7	153.7	0	0	0	0

Table S4
Key features of the pumping system

Item	Concept	Unit	Value
1	Flow	m^3/h	112
2	Initial elevation	masl	10
3	Final elevation	masl	690
4	Upper tank effective capacity	m^3	784
5	Length	m	5,434
6	Type of pipe	–	API 5L 8″
7	Inner liner		Tite Liner®, 6 mm
8	Pressure drop	m	26.8
9	Number of pumps	–	2
10	Pump model	–	Kamat, K25090
11	Outlet pressure	m	706
12	Flow	m^3/h	59
13	Efficiency	%	85.6
14	Unit power	kW	132
15	Total power	kW	264

Table S5
Summary of surplus energy for both solar parks

Month	Configuration I			Configuration II		
	Surplus	Sale price	Sale/month	Surplus	Sale price	Sale/month
	kWh/month	€/kWh	€/month	kWh/month	€/kWh	€/month
January	202,164	0.06	12,130	116,864	0.06	7,012
February	213,373	0.06	12,802	105,954	0.06	6,357
March	210,928	0.06	12,656	110,182	0.06	6,611
April	137,868	0.06	8,272	82,222	0.06	4,933
May	117,652	0.06	7,059	60,192	0.06	3,612
June	109,870	0.06	6,592	50,122	0.06	3,007
July	123,792	0.06	7,428	58,135	0.06	3,488
August	148,918	0.06	8,935	70,759	0.06	4,246
September	162,703	0.06	9,762	87,723	0.06	5,263
October	199,418	0.06	11,965	108,555	0.06	6,513
November	169,454	0.06	10,167	110,282	0.06	6,617
December	191,148	0.06	11,469	114,352	0.06	6,861
Total €/y			119,237			64,520

Table S6
Operation and maintenance costs for configurations I and II

Cost	Configuration I	Configuration II
	€/y	€/y
PV and drive operation and maintenance staff	101,923	83,577
Chemicals and supplies for the SWDS	112,60	11,260
Vehicle and fuel	17,308	17,308
Spare parts and others	13,897	11,396
OPEX	144,388	123,541

Note: The annual production desalinated water it is 157,680 m^3/y.

Table S7
Investments required for configurations I and II

Investments	Unit	Unit value	Configuration I		Configuration II	
		(€)	Quantity	Total (€)	Quantity	Total (€)
Solar panels 320 W	gv	225	8,750	1,968,571	4,689	1,054,929
Inverters 30 kW	gv	6,859	95	651,600	51	349,582
Cables and accessories	m	1.15	157,585	181,829	94,551	109,097
Panel, inverter, and wiring installation	gv	191,663	1	191,663	0.6	114,998
MT network, sub-stations, equipment, and others	km	14,523	12	174,272	11	159,749
Hydraulic equipment and pipelines for drinking water supply to La Higuera	gv	682,051	1	682,051	1	682,051
Seawater supply and hydraulic installations	gv	120,795	1	120,795	1	120,795
Equipment, upper and lower tanks and ducts, hydraulic pumping station	gv	1,111,642	1	1,111,642	N/A	0
Expansion of the seawater intake system	gv	109,841	N/A	0	1	109,841
Expansion of the seawater pre-treatment system	gv	102,176	N/A	0	1	102,176
Equipment, upper tank, and pipelines for microfiltered seawater supply	gv	535,725	N/A	0	1	535,725
Intermediate drinking water tank (elevation 450)	gv	148,572	N/A	0	1	148,572
CAPEX				5,082,423		3,487,515

Note: gv stands for "global value".

Table S8
Components for economic analysis and assessment

Components	Configuration I		Configuration II
Total investments (€)	5,082,422		3,487,517
Residual investment value (%)		15	
Level of distribution losses (%)		30	
Annual drinking water production (m^3)		157,680	
Sale price without project (€/m^3)		1.92	
Sale price with project (€/m^3)		0.83	
Revenue from drinking water sale (€/m^3)		120,048	
Social benefit – difference in cost (€/m^3)		1.09	
Social benefit – with project (€/y)		120,848	