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Hybrid Engineering System for Freshwater Production

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Abstract

This work focuses on a new engineering design for water resources application. The system includes a hybrid reverse osmosis desalination plant, a solar pond set, and a thermal power plant, which receives energy from the pond set and powers the desalination plant. The solar pond set is modular and adaptive, facing variable working conditions and energy demands. The engineering design is feasible and energetically viable since it uses renewable energy as a power source with a positive or null energy balance. The system is especially suitable for arid, semi-arid, and desert areas with high solar radiation levels. A set of seven solar ponds of 100 m diameter and a smaller one with half the area for a global area of 30 Ha collects 5.4 kWh of solar radiation to supply hot water to a thermal power plant that generates enough energy to maintain operative the desalination plant throughout the whole day. The system operates 24 hours a day due to the solar pond heat capacity retention, whose design avoids thermal losses by convection. The solar pond set generates more than 250 MWh per day, with an energy factor coverage slightly higher than 100%. The desalination plant produces fresh water for one million people, with an average daily consumption of 100 liters per person. The system avoids brine disposal to seawater at higher concentrations than water intake, preserving marine life and the ecosystem and reducing the risk of high environmental impact.

Keywords: Water resource, engineering system, freshwater production, heat generation, solar pond set

INTRODUCTION

Fresh water for human needs is one of the most relevant challenges today. Despite water representing 75% of the Earth's surface, drinking water is not accessible to 30% of the world's population [1], and another third has no access to fresh water [2]. Even in developed countries, access to fresh water becomes a problem due to the lack of water resources [3].

Countries and supranational organizations apply different methods and policies to mitigate the world's water inequality gap, promoting water conservation practices, developing efficient techniques for irrigation, enhancing water infrastructures, and using technological solutions to produce fresh water from sea, saline, or wastewater [4–7]. To this goal, many works focus on this subject, proposing solutions or developing measures to help solve the water inequality gap [8–12].

Among these technological solutions, the most widely used is reverse osmosis (RO), which converts seawater into fresh water, removing sediments and chlorine from water using a filter (*pre-filter)* before forcing the water to pass through a semipermeable membrane to eliminate dissolved solids and passing the water through a second filter (*post-filter)* to purify drinkable water before driving to the carrying duct or storage tank [13].

Reverse osmosis is a relatively efficient technique and desalinates water for many purposes like drinkable water for human needs, cattle raising,

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agriculture, and specific industrial applications. Reverse osmosis, however, does not produce drinkable water since it does not deionize water, which is a requirement for drinkable water [14–16].

Reverse osmosis operates by applying pressure on one side of the membrane, forcing water molecules to pass and retaining salt particles (Figure 1) [17].

Pressure application requires power, which consumes a large amount of energy currently supplied by fossil fuels, contributing to increased atmospheric pollution and global warming [18–20]. Another problem derived from reverse osmosis use is the highly concentrated saline solution (brine) residue [21]. This solution should be rejected, versing it to the seawater or the ground, increasing salt concentration in the local area and hurting marine life, or causing soil salinization and terrain eutrophication, degrading life and the environment [22]. Alternative management of brine solution includes specific treatment through forward osmosis or a second reverse osmosis process [23–26].

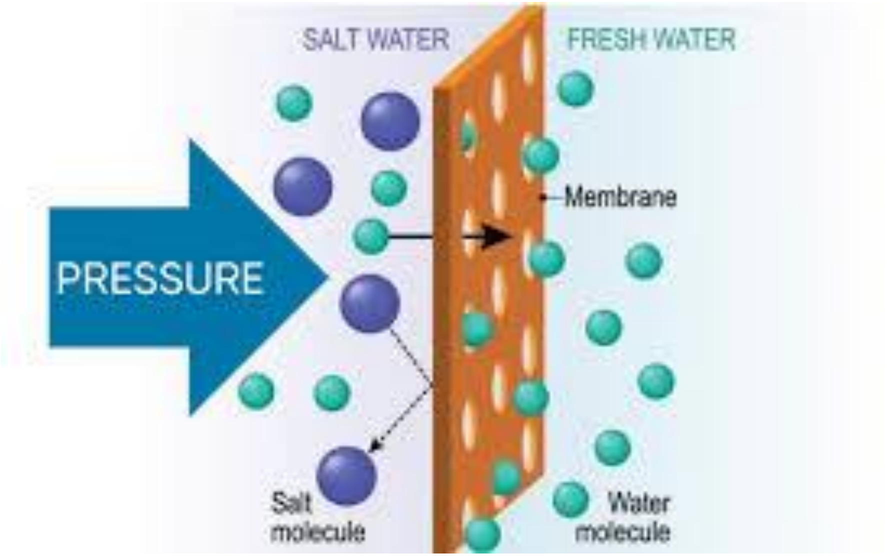

Figure 1. Schematic view of the reverse osmosis (RO) process [17].

Salinization of seawater and soil is a common problem for reverse osmosis and other desalination techniques like evaporation, distillation, or electrodialysis; all of them must reject the brine solution, becoming one of the principal problems in desalination techniques [27, 28].

A solution arises in managing water resources, using the brine solution for solar ponds, where a highly concentrated salt solution is required to generate the necessary concentration gradient. Furthermore, solar ponds generate thermal [29–31] and electric energy [32–34] that may power desalination processes, which require heat or electricity to power desalination plants [35].

The hybridization of a solar pond with reverse osmosis or any alternative desalination system may solve the brine solution problem and reduce energy dependence on fossil fuel, helping to reduce atmospheric pollution and global warming.

ENVIRONMENT

Desalination plants and solar ponds are adequate for hot, arid, and semi-arid climates where fresh or drinking water is scarce or non-existent and solar radiation is high. Many world zones with access to seawater fulfill these conditions, with a water scarcity population of between 5 and 50 million people. Other countries do not have freshwater resources but have access to seawater and solar radiation (Figure 2).

In countries marked with a dot in Figure 2, millions of people suffer from freshwater scarcity despite the country getting access to seawater and receiving abundant solar radiation. Another common characteristic is the available land for desalination and power plants. A hybrid reverse osmosis desalination plant and a large set of solar ponds represent a defiant challenge to solve the water scarcity problem using natural and local water resources and renewable energies.

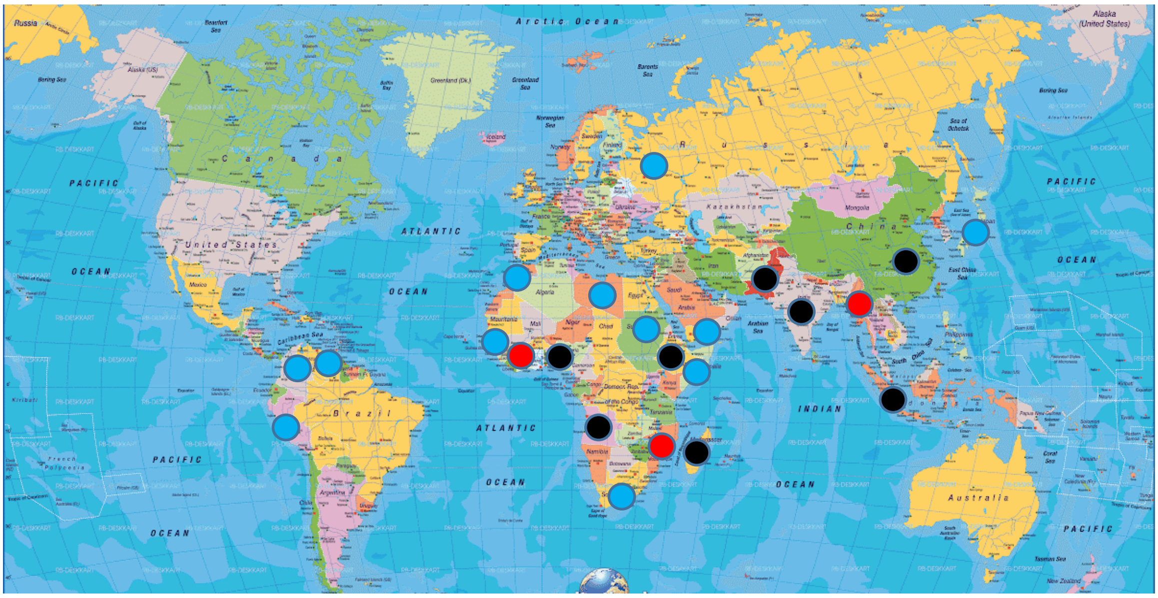

Figure 2. World distribution of water scarcity countries by involved population (Black dot: 10–50 million people; Red dot: 5–10 million people; Blue dot: 1–5 million people).

WATER ENGINEERING SYSTEM AND OPERATION

Reverse osmosis is a mature technology widely used in developed countries. The engineering design includes a reverse osmosis desalination plant and a set of solar ponds (Figure 3). The rejected brine from the reverse osmosis plant is carried to the solar ponds, injecting the brine solution at the bottom of the pond (Figure 4).

The system includes a three-way valve at the brine disposal duct, automatically controlled by a density sensor at the bottom of every solar pond. If the density of the salt solution exceeds the limit corresponding to the maximum salt concentration, the valve opens the connection to the seawater and lets the brine solution flow; otherwise, the valve opens the connection to the solar ponds set.

Water intake is double, one for the reverse osmosis unit and the other for the solar pond set. Water for reverse osmosis pumps continuously to maintain a constant flow for freshwater production; however, a control unit regulates the water flow for the solar ponds to avoid spilling in any of the solar ponds of the set.

A water circuit connects the solar pond set and a power plant, which operates under a Rankine thermodynamic cycle to generate electricity. The water circuit includes a heat exchanger at the bottom of every pond, which collects the transferred heat from the hot brine solution to the water flow. Hot water is carried to the power plant, exchanging energy with the working fluid.

The power plant supplies energy to the pumping system, water intake for the reverse osmosis plant and solar ponds set, brine solution, and the reverse osmosis compressors, low and high-pressure units.

Solar radiation provides thermal energy to the pond, heating the brine solution at the bottom. The solar pond avoids upward thermal transfer losses because of the brine solution heat retaining capacity due to its high salt concentration.

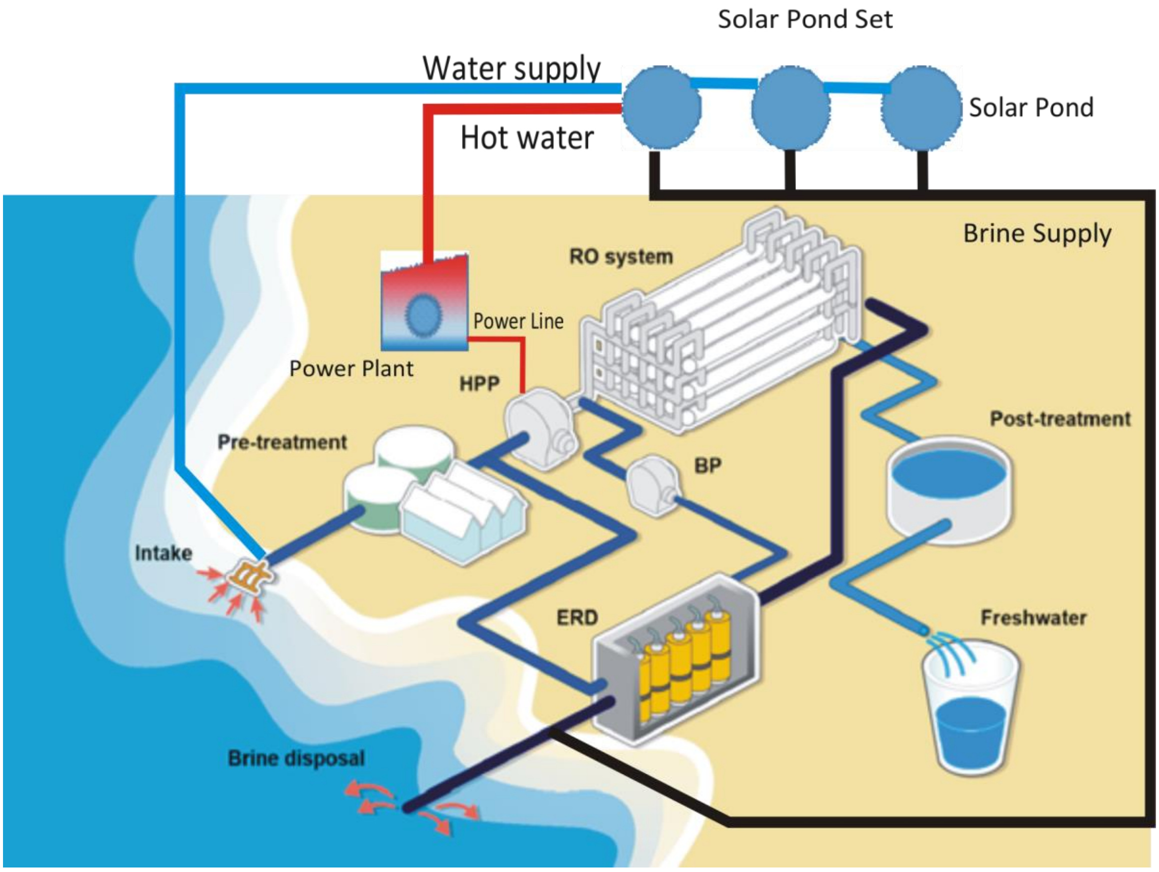

Figure 3. Schematic view of the hybrid desalination plant and solar pond set.

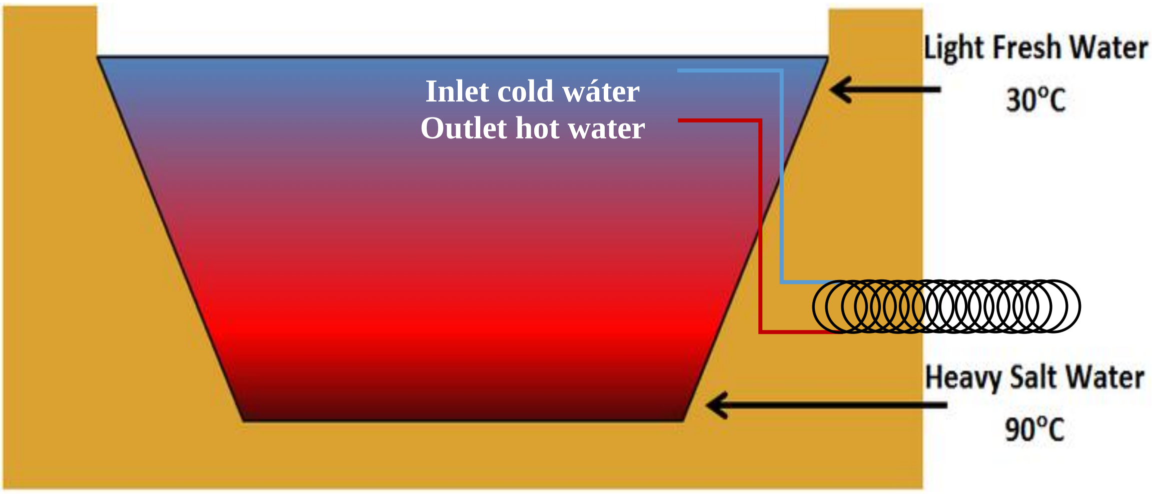

Figure 4. Schematic cross view of a solar pond.

The brine solution at the bottom of the solar pond currently operates at temperatures of 90º C, which provides a high enthalpy level for the working fluid at the power plant heat exchanger. For an adequate size, the solar pond set supplies enough energy to generate as much electric energy as required for electricity consumption in the hybrid system.

FUNDAMENTALS

Water desalination operating under reverse osmosis process works against the osmotic pressure, which is defined by [36]:

$$P_{osm} = 1.19T\sum_i \sigma_i \tag{1}$$

where T is the Kelvin temperature and σ is the molar concentration of any of the solution constituents.

In practical terms, a 1000 ppm total dissolved solids (TDS) equal about 0.76 bar (11 psi) of osmotic pressure.

Despite the water and salt separation at the reverse osmosis process not fully understood, a salt concentration across the membrane occurs; by selecting the appropriate membrane, we obtain a water flow or water retention.

We determine the water flow by using the following expression:

$$\dot{V}_w = \kappa_w \left(S/d\right)\left(\Delta P - \Delta P_{osm}\right) = C_w \left(NDP\right) \tag{2}$$

ΔP and ΔP_{osm} are the hydraulic and osmotic pressure differential across the membrane, κ_w is the membrane permeability coefficient for water, S and d are the membrane surface and thickness, and NDP is the net driving pressure.

Equation 2 shows that freshwater production is proportional to the NDP.

Because the membrane cannot retain all salt particles, there is a salt flow across the membrane that contaminates fresh water; the salt passage is given by:

$$SP = 100\left(C_p / C_{fm}\right) \tag{3}$$

C_P is the salt concentration in the permeate, and C_{fm} is the mean salt concentration in the feed stream.

The salt concentration in the permeate depends on the salt-to-water flow ratio across the membrane:

$$C_p = \frac{\dot{V}_s}{\dot{V}_w} = \frac{\left(\Delta c\right)\kappa_s\left(S/d\right)}{\kappa_w\left(S/d\right)\left(\Delta P - \Delta P_{osm}\right)} = \frac{C_s\left(\Delta c\right)}{C_w\left(NDP\right)} \tag{4}$$

Δc is the salt concentration differential across the membrane, and κ_s is the membrane permeability coefficient for salt.

We observe that NDP increase reduces the salt concentration in the permeate, resulting in a purer fresh water. Since the osmotic pressure depends on the salt concentration, for a given location, we set up seawater salt concentration; therefore, NDP only depends on the hydraulic pressure.

Fresh water is not pure since it contains a moderate concentration of dissolved salt particles, later eliminated in a filtering process. If we consider a specific salt concentration for the produced fresh water, c_h, within healthy limits, and a seawater concentration, c_o, we have:

$$C_p = \frac{\kappa_s}{\kappa_w}\frac{\left(c_o - c_h\right)}{\left(\Delta P - \Delta P_{osm}\right)} \tag{5}$$

Operating in Equation (5):

$$\Delta P = \Delta P_{osm} + \frac{\kappa_s}{\kappa_w}\frac{\left(c_o - c_h\right)}{C_p} \tag{6}$$

Equation (6) expresses the required hydraulic differential pressure for specific working conditions, type of membrane and seawater, and permeating salinity.

Applying the Bernoulli principle to the hydraulics of the reverse osmosis process:

$$\frac{\Delta P}{\gamma} + \Delta z + \frac{\Delta v^2}{2g} - h_L = \frac{P_w}{\gamma \dot{V}_{ws}} = \frac{P_w}{\gamma}\frac{1}{\dot{V}_w\left(1 + C_p\right)} \tag{7}$$

γ is the water-specific weight, z is the gravimetric height, v is the seawater speed across the membrane, h_L is the mechanic losses, and P_w is the pumping power.

Applying the continuity equation:

$$P_w = \gamma \dot{V}_w\left(1 + C_p\right)\left[\frac{\Delta P}{\gamma} + \Delta\left(\frac{\dot{V}_w}{S}\right)^2 + \frac{\Delta v^2}{2g} - h_L\right] \tag{8}$$

Since the pressure differential term is predominant in the bracket term:

$$P_w = \dot{V}_w\left[\Delta P_{osm} + \frac{\kappa_s}{\kappa_w}\frac{\left(c_o - c_h\right)}{C_p}\right] \tag{9}$$

Equation (9) defines the required power to produce fresh water in the reverse osmosis plant.

Additional power for brine pumping is:

$$P_b = \frac{16 f \gamma_b L \dot{V}_b^3}{\pi^2 D^5} \tag{10}$$

f, L and D are the reverse osmosis system to solar pond duct friction factor, length and diameter, and γ_b and $\dot{V}_b$ are the brine specific weight and flow.

At the power plant, the working fluid operates under the Rankine cycle; the power to compress the fluid flow is expressed as:

$$P_{comp} = \frac{\Delta P_{wf}}{\rho_{wf}} F_R \frac{\dot{m}_w c_w \Delta T_w}{L_{v,wf}} \tag{11}$$

ΔP_{wf} is the working fluid pressure differential at the compression process, ρ_{wf} is the density, and $\dot{m}_w$, c_w, and ΔT_w are the mass flow, specific heat, and temperature drop of the water coming from the solar pond. F_R represents the heat exchange factor between water and working fluid at the power plant heat exchanger and $L_{v,wf}$ is the latent heat of the working fluid.

SYSTEM LAYOUT

Solar Pond

Solar pond consists of a water basin containing a downward increasing salt concentration gradient (Figure 5).

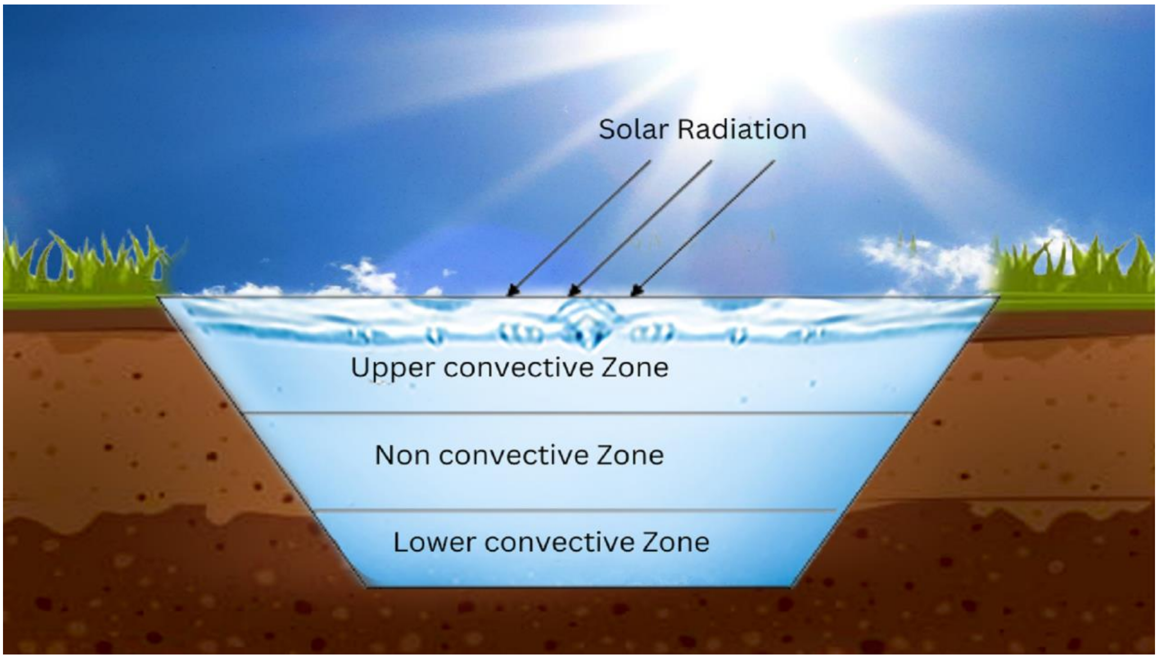

Figure 5. Structure of a solar pond.

The solar pond structure has three zones: lower, upper, and non-convective. The pumping system injects the brine solution into the lower convective zone where salt concentration and heat capacity are higher. Because of the higher heat capacity, the convection mechanism occurs in the lower convective zone, with the intermediate non-convective zone acting as a heat transfer barrier. Convection at the upper convective zone is due to the action of wind on the solar pond surface, not influencing heat transfer from the lower convective zone.

The injection of brine solution has a limit imposed by the lower convective zone capacity of salt concentration; beyond this limit, the salt precipitates and is no longer dissolved. When we reach this point, a four-way valve derives the brine solution flow to a second solar pond, and the process continues until reaching the lower convective zone saturation point when the process repeats. Once the last solar saturates, the water management system starts injecting the brine solution at an intermediate point of the non-convective zone of the first pond, dissolving the brine solution and displacing the border layer between zones upwards (Figure 6).

The control system activates the four-way valve deriving the brine solution flow to the corresponding duct, 2 for the current operation, 3 when the solar pond lower convective zone saturates, and 4 if the solar ponds set achieves the maximum salt capacity at the lower convective zone.

Reverse Osmosis Unit

The reverse osmosis unit uses thin-film composite (TFC) polyamide membranes in spiral wounds (Figure 7).

The reverse osmosis plant consists of a set of membranes grouped in parallel, configuring a reverse osmosis module (Figure 8). The reverse osmosis plant may contain as many modules as necessary to produce the required freshwater flow (Figure 9).

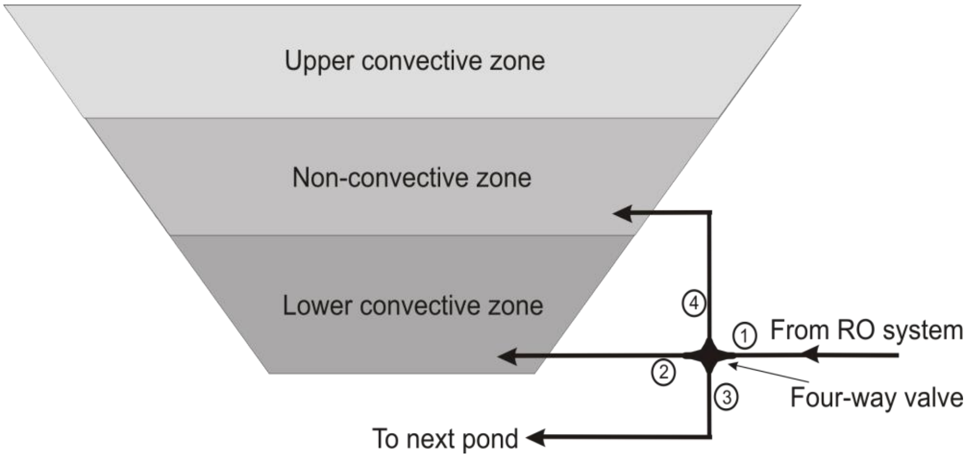

Figure 6. Brine solution flow distribution.

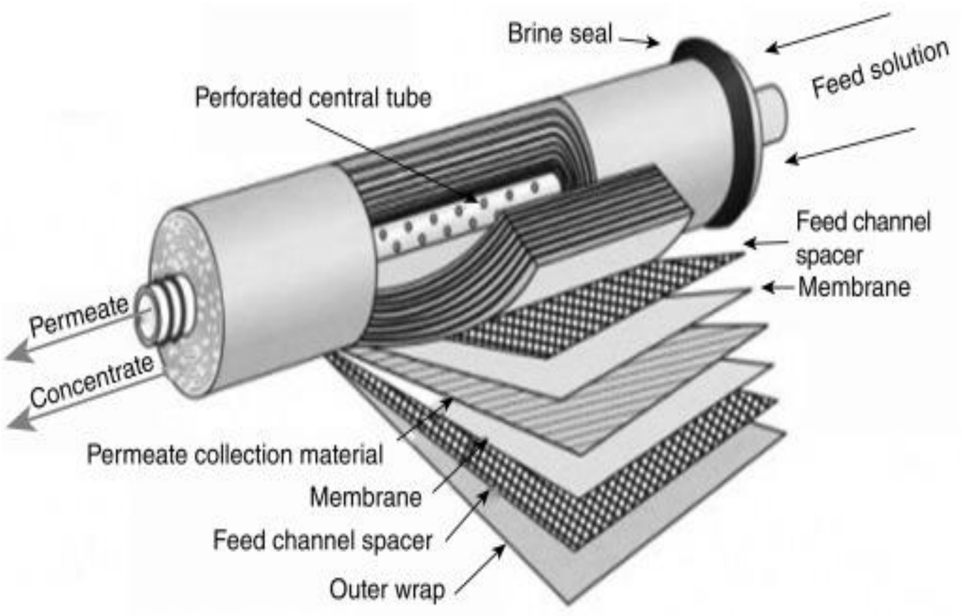

Figure 7. Membrane structure for the reverse osmosis system [37].

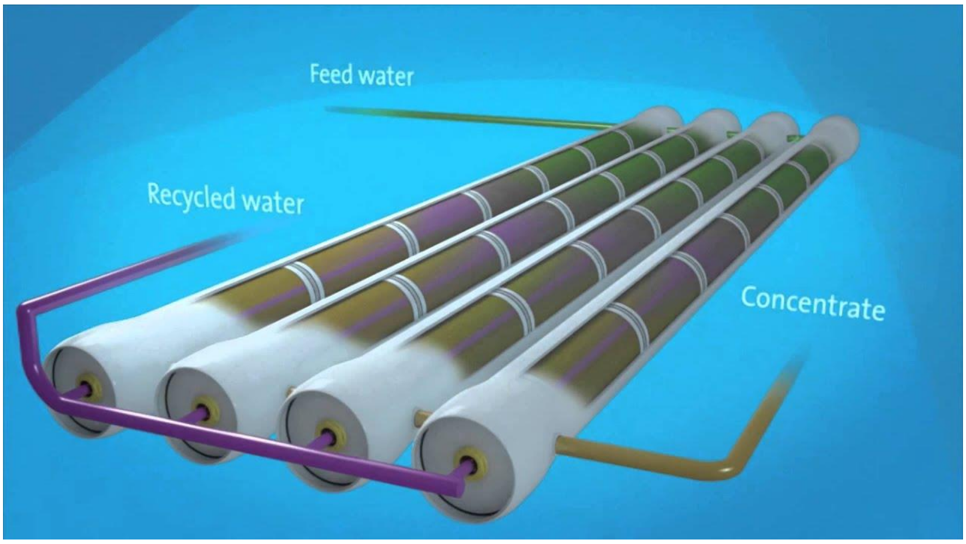

Figure 8. Reverse osmosis module.

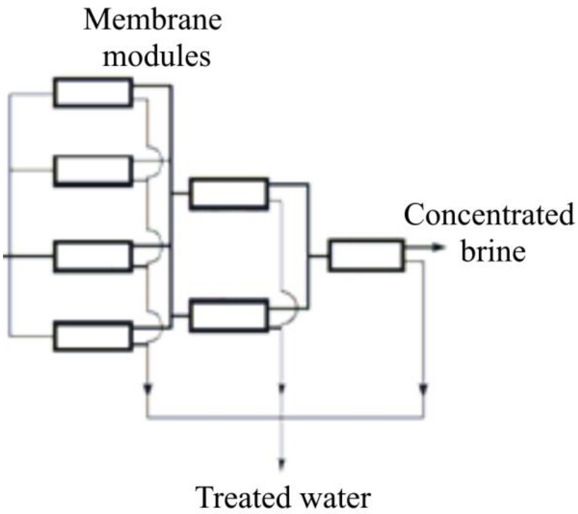

Figure 9. Schematic representation of the membrane module grouping in a reverse osmosis plant.

A reverse osmosis plant requires a boost pump to elevate pressure until reaching the NDP value, a pre-filter to eliminate solid particles that may obstruct the membrane pores, and a post-treatment unit consisting of a recirculation pump, a UV lamp to kill bacteria and microorganisms harmful to health, and a sub-micron filter to purify fresh water (Figure 10).

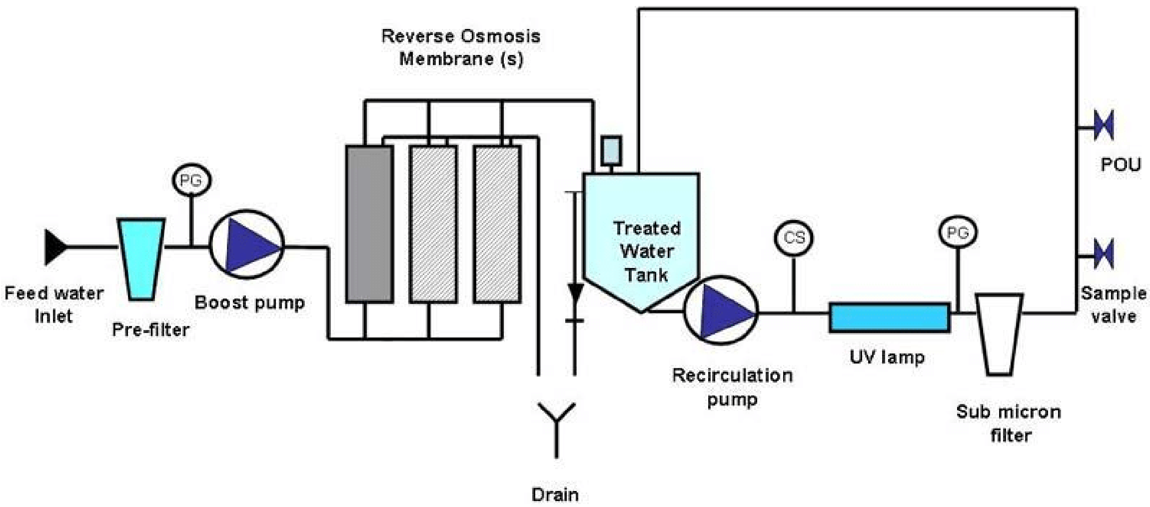

Figure 10. Layout of reverse osmosis power plant with post-treatment unit [38].

Operational Mode

The hybrid system works under a control system, which regulates the operational mode. The control unit has a built-in protocol to command all sections of the hybrid system, selecting the working mode depending on conditions. The flowchart of Figure 11 shows the hybrid system operational protocol.

The hybrid system operating protocol works as follows:

1. The control unit checks for freshwater demand rate and quality and applies developed algorithms for NDP determination using RO plant characteristics and seawater salt concentration.
2. The pumping system is activated, collecting seawater and regulating hydraulic pressure.
3. The system pumps the brine solution to the solar pond's set.

4. The solar pond set control unit activates the thermal power plant and water flow regulation, generating electric energy through the improved Rankine cycle to supply power to the water intake pumping system and reverse osmosis plant.
5. The control software checks the salt concentration at the first pond's lower convective zone (LCZ). If it is below the threshold, the process continues with inlets 1 and 2 open and 3 and 4 closed at the 4-way valve; otherwise, the control unit derives brine solution to the next pond by closing inlet 2 and opening inlet 3.
6. After the last pond, the control unit closes inlets 2 and 3 and opens inlet 4, deriving the brine solution to the first pond non-convective zone (NCZ).
7. The control unit checks the salt concentration at the NCZ; if it is lower or equal to the seawater concentration, the system pumps brine solution to the ocean; otherwise, the brine increases salt concentration, enlarging the LCZ thickness.
8. The system pumps the brine to a salt deposit after the last pond.

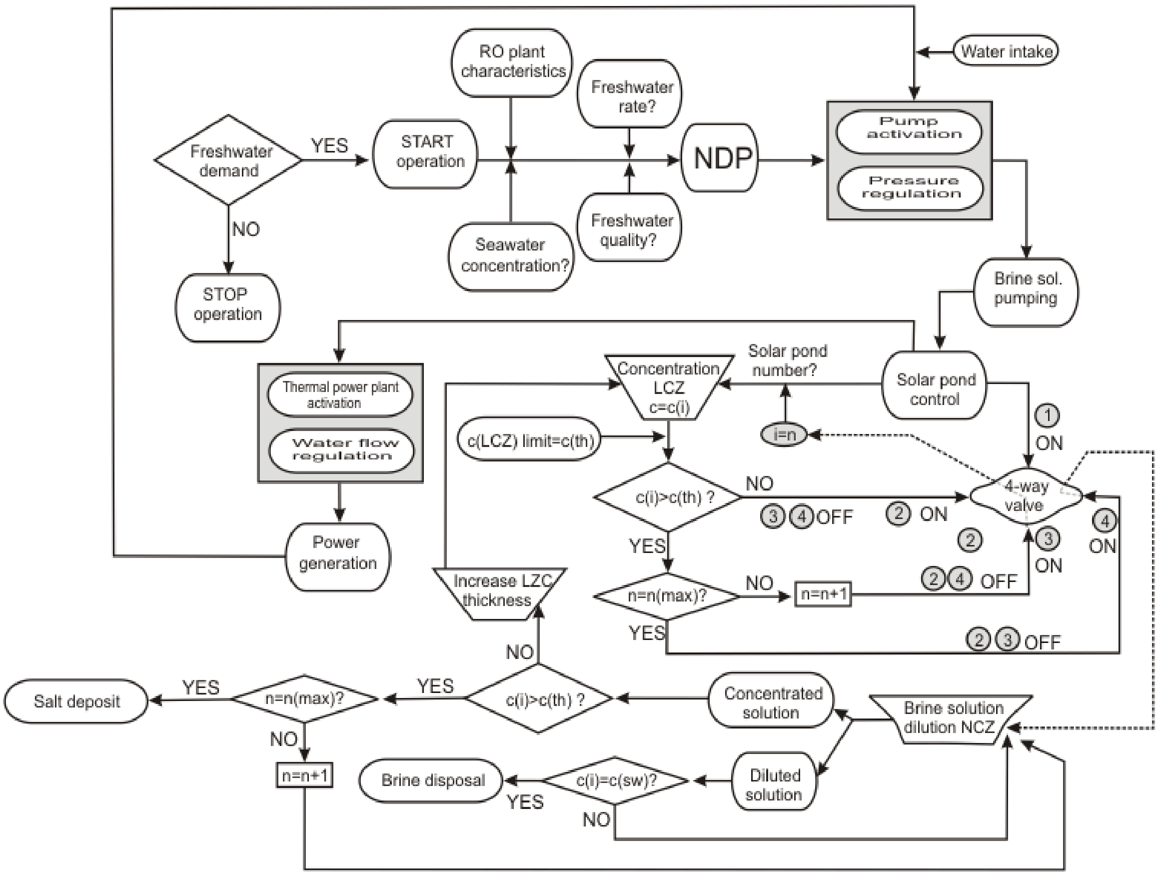

Figure 11. Flowchart of the hybrid system operating protocol.

Simulation

A reverse osmosis system produces between 90 and 165 liters of fresh water per cubic meter of seawater [39]. Human water consumption depends on the application since water purity is not the same for drinking water as for domestic, commercial, or industrial uses. If we only deal with drinking water, the World Health Organization (WHO) considers a minimum of 3.7 and 2.7 liters per day for males and females; this amount, however, depends on activity, climate, age, and state of health [40]. Nevertheless, water human needs include sanitary services, cooking, and cleaning, representing a daily water consumption of 100 liters per person in Europe and 500 liters in the USA [41]. In non-developed countries, however, the water needs are much lower, around 40 daily liters per person [42].

We required specific power for freshwater production, according to Bernoulli's principle:

$$P_w = \gamma \dot{V}_w \left(\frac{\Delta P}{\gamma} + \Delta z + h_L \right) \quad (12)$$

Δz corresponds to the hydraulic height.

The daily freshwater requirement per person and day, using an average value of 100 liters represents 10^5 cubic meters per day for a simulated population of one million people; for a highly efficient reverse osmosis plant, the minimum water intake is about 6 x 10^5 cubic meters, corresponding to a water flow of 25000 m^3/h. Considering a water intake duct of 20 cm, the hydraulic losses are 0.64 m/km [43]. On the other hand, the required pressure differential to operate the reverse osmosis system is 4.2 kg/m^2 [44]; therefore, for a hydraulic difference of 5 m and an intake duct of 2 km, we have:

$$P_w = (9800)(6.94)\left[\frac{4.2 \text{ x } 10^5}{9800} + 5 + 2(0.64)\right] = 3322.7 \text{ kW} \quad (13)$$

Averaging for the whole population, we obtain a density power of σ = 3.32 W/person, or σ = 0.033 W/L.

Now, considering the pumping system efficiency:

$$P_{el} = \frac{P_w}{\eta_p} = \frac{3322.7}{0.8} = 4153.4\, kW \quad (14)$$

Equivalent to 4.15 W/person and σ = 0.0415 W/L.

If there is no hydraulic difference between the reverse osmosis plant and the solar pond set, the required power to pump the brine solution to the solar ponds is:

$$P_w = (9800)(0.835)(6.94)\left[2(0.3)\right] = 34.1\, kW \quad (15)$$

We estimate a 2 km distance between the reverse osmosis plant and the solar pond's set and a duct diameter of 20 cm for carrying the brine solution. The brine solution flow is the difference between the seawater intake and the freshwater production.

We observe that the pumping power represents 0.8% of the electric power for the reverse osmosis plant.

The generated thermal energy in every solar pond depends on the solar radiation level, the pond size, the water transmissivity, and the heat storage efficiency of the LCZ. Building a circular solar pond of 100 m diameter, the pond unit surface is 7854 m^2. Considering a highly sunny place, which is current for places where reverse osmosis plants are installed, the daily average solar radiation is 5.4 kWh/m^2 · day [45]; this value provides a daily potential solar energy of 42411.5 kWh per pond unit.

Since the solar radiation is partially reflected by water surface and partially absorbed by the upper convective and intermediate non-convective zone, the available energy at the lower convective zone is:

$$\xi_{LCZ} = \tau_w \xi_o \left(1 - \vartheta_w\right) \quad (16)$$

ξ_o is the potential solar energy, and τ_w and ϑ_w are the water transmissivity and reflectivity.

Since water transmissivity depends on the particle's concentration in water, and because we deal with moderate clean water, the water transmissivity responds to the following exponential law as a function of the depth, z [46]:

$$\vartheta_w = 91.46\exp(-0.051z) \tag{17}$$

The typical depth of a solar pond is around 2 m, with the LCZ layer starting at 1.2 m; therefore, the water transmissivity at the borderline between the LCZ and the NCZ is:

$$\vartheta_w = 91.46\exp(-0.102) = 82.6\% \tag{18}$$

According to this value and considering an average water surface reflection of 3.8% in the 0--50º solar radiation incidence angle [47], the net solar energy at the low convective zone is:

$$\xi_{LCZ} = (0.826)(42411.5)\left(1-0.038\right) = 33700.7\ kWh \tag{19}$$

The electric power plant should generate energy to maintain the reverse osmosis plant and the pumping system in operation 24 hours a day; considering an efficiency of 40% for the improved Rankine cycle [48], the required power is:

$$P_g = \frac{4153.4+34.1}{0.4} = 10468.75\ kW \tag{20}$$

Representing a daily energy demand of:

$$\xi_g = (24)\left(10468.75\right) = 251250\ kWh \tag{21}$$

Since the reverse osmosis plant operates the whole day.

According to data in Figure 4, water from the solar pond drops its temperature by 60º C; therefore, the water flow to generate the required power shown in Equation (20) is:

$$\dot{m}_{wt} = \frac{P_g}{c\Delta T} = \frac{10468.75 \text{ x } 10^3}{(4180)(60)} = 41.7 \text{ kg/s} \tag{22}$$

The pumping power to move water from solar pond to power plant and back to the pond is:

$$P_{wt} = g\,\dot{m}_{wt}\,h_p = g\,\dot{m}_{wt}\,h_{L,wt} \tag{23}$$

$h_{L,wt}$ is the hydraulic losses between solar pond and power plant.

Using the Hazen–Williams pipe flowchart [49] for the fluid flow shown in Equation (22), and maintaining the duct diameter in 20 cm, we obtain a hydraulic losses coefficient s_T = 22 m/km, which is a high value; therefore, we decide to use a 25 cm diameter duct that reduces the coefficient to s_T = 4.5 m/km. Applying this value to the distance between the solar pond's set and the power plant, which we estimate in about 2 km, we obtain the hydraulic losses as:

$$h_{L,wt} = s_T d = (4.5)(2) = 9\ m \tag{24}$$

Replacing in Equation (23):

$$P_{wt} = (9.8)(41.7)(9) = 3677.9\,W \approx 3.7\,kW \tag{25}$$

This power slightly modifies the global power requirement obtained in Equation (14), resulting in a global value of:

$$P_T = \frac{4153.4 + 34.1 + 3.7}{0.4} = 10478\,kW \tag{26}$$

If we apply this new value to the Equation (22), we obtain a mass flow of:

$$\dot{m}_{wt} = \frac{P_g}{c\Delta T} = \frac{10478 \text{ x } 10^3}{(4180)(60)} = 41.78 \text{ kg/s} \tag{27}$$

Now, repeating the calculation process to determine the power requirement to pump water between solar pond and power plant, it results:

$$P_{wt} = (9.8)(41.78)(9) = 3684.8\,W \approx 3.7\,kW \tag{28}$$

We observe that the new power differs 0.2% from previous value, which is negligible; therefore, we can accept the global power shown in Equation (20) as the reference for the system.

Regarding the energy balance, the power demand is 251250 kWh per day (Equation (21)), and the daily generated energy by every single pond is 33700.7 kWh (Equation (19)), meaning a set of 7.5 ponds, which corresponds to seven ponds of 100 m diameter, and a smaller pond of 70 m diameter. This configuration has a total surface of 58826.3 m^2, equivalent to 7.5 single ponds of a regular size of 100 m diameter.

SOLAR POND ENGINEERING DESIGN

The most efficient engineering design for this configuration is an octagonal polygon with a solar pond on every corner (Figure 12).

The set of solar ponds includes a double central collector. The inner connects to the inlet pipe carrying the brine solution from the desalination plant. The outer collector transports hot water to the thermal power plant. The set includes a solar pond in each corner of an octagonal polygon, with all ponds interconnected by a double ring of pipe, inner and outer. Both rings divide into sections between ponds. Each section of the two rings has electronic valves on both sides of each solar pond and is connected to the corresponding collector through a distribution duct to operate each pond independently. The engineering design allows individual or collective pond operation, which provides versatility and increases output power depending on energy demand.

CONCLUSIONS

This paper studies and analyzes a new system for the application of water resources, consisting of a reverse osmosis plant and a solar pond set. The engineering design, based on a hybrid configuration, proves the viability of the proposed system, especially in high solar radiation locations near the coastline. The project is suitable for many environments, but more specifically for arid and semi-arid zones with large available areas for system installation.

The analysis of power generation and demand shows the feasibility of the system considering the energy balance. The coupling of a thermal power plant, powered by a solar pond's set, to a desalination plant is energetically sustainable since it uses renewable energy as a power source, eliminating the dependence on the grid, which is very convenient in places where the electrical network is not accessible, or the cost of access is very high.

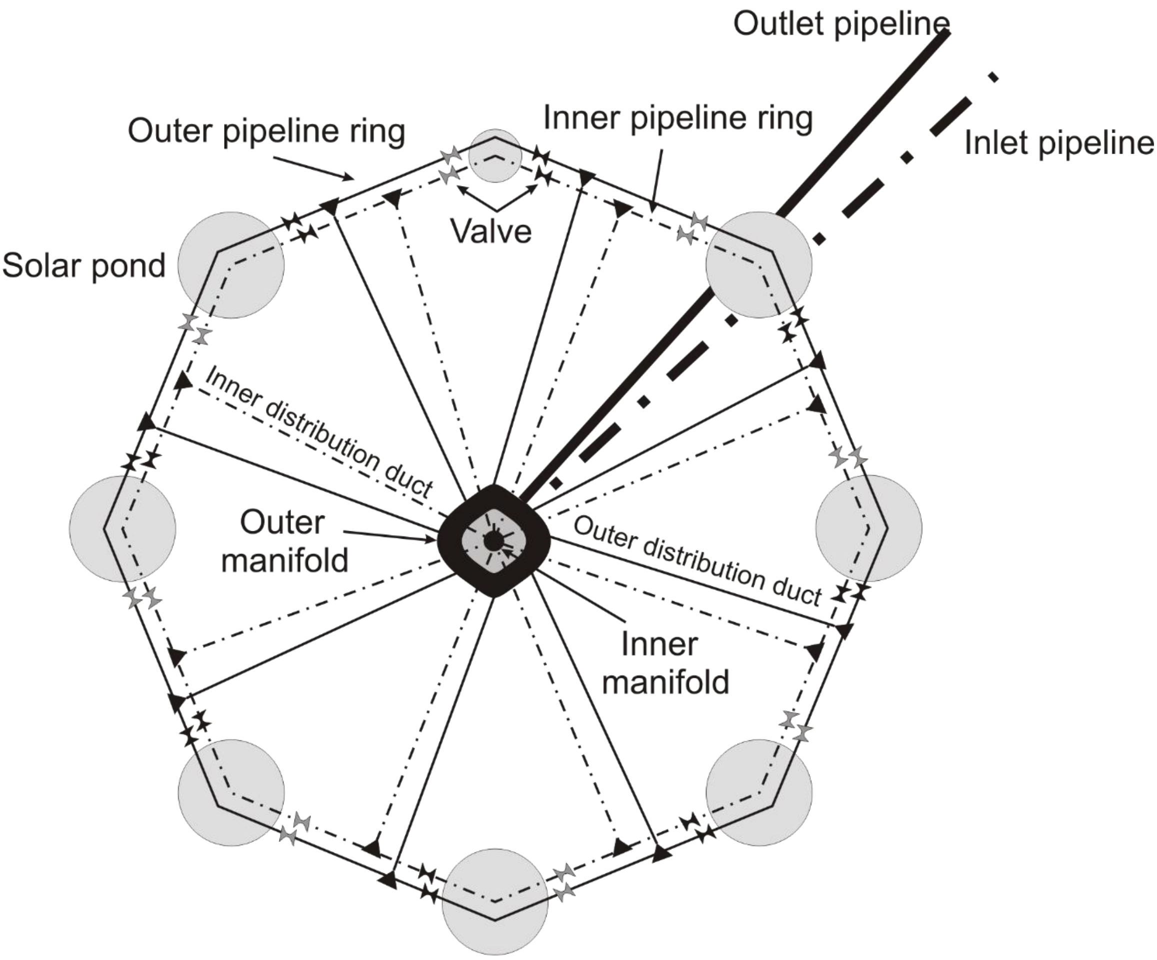

Figure 12. Layout of solar pond set.

The engineering design is modular and adaptive to variable operating conditions because we can change the thermal power supplied by the solar pond set according to power demand due to the specific interconnection network between the solar ponds, the desalination system, and the thermal power plant. The engineering design is simple and easy to manage, which reduces maintenance and investment costs.

The specific configuration of the solar pond system avoids versing brine solution to seawater at a higher concentration than water intake, preserving marine life and ecosystem and reducing environmental impact. The engineering design allows the injection of highly concentrated brine solution into the low convective zone (LCZ) of the solar pond or in the lower level of the non-convective zone, increasing the LCZ thickness and the thermal capacity of the solar pond. The hydraulic layout permits the derivation of highly concentrated brine solution to a salt deposit when the solar pond is saturated.

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