world

MDPI

Article

Addressing Water Scarcity in Isla Huichas, Chile: A Tecno-Economic Sustainable Solution

Benjamín Borquez [1], José Ahumada [2], Michael Mendoza [2], Renny Guillén [3] and Victor Contreras [2,*]

[1] CMC Engineering, Plaza Justicia 59, Valparaíso 2340000, Chile; benjaminborquezo@gmail.com
[2] Institute of Naval Architecture and Ocean Engineering, Universidad Austral de Chile, Campus Miraflores, General Lagos 2086, Valdivia 5110566, Chile; jose.ahumada@uach.cl (J.A.); michael.mendoza@uach.cl (M.M.)
[3] Institute of Mechanical Engineering, Universidad Austral de Chile, Campus Miraflores, General Lagos 2086, Valdivia 5110566, Chile; renny.guillen@uach.cl
* Correspondence: victor.palma@uach.cl

Abstract: Islas Huichas, located in Chile's remote Aysén region, has long faced water scarcity due to a lack of natural sources. The community relies on rainwater collection pools managed by the Rural Drinking Water Committee (RDWC), which face increased pressure during the summer tourist season, leading to frequent shortages. In 2014, a Reverse Osmosis (RO) plant with a 240 m^3 daily capacity was installed to address the issue. While the RO plant helps alleviate summer shortages, it has high energy costs and maintenance challenges, exceeding the financial capacity of the RDWC. This study evaluates various scenarios to reduce the plant's operational costs and emissions reduction.

Keywords: water scarcity; reverse osmosis; water resource management; sustainability

check for updates

Citation: Borquez, B.; Ahumada, J.; Mendoza, M.; Guillén, R.; Contreras, V. Addressing Water Scarcity in Isla Huichas, Chile: A Tecno-Economic Sustainable Solution. *World* **2024**, *5*, 1367–1385. https://doi.org/10.3390/world5040069

Academic Editors: Manfred Max Bergman and Mohammad Aslam Khan Khalil

Received: 1 September 2024
Revised: 14 November 2024
Accepted: 27 November 2024
Published: 10 December 2024

1. Introduction

The planet's freshwater accounts for only 3% of the total available, with just 0.7% in a liquid state; the remaining is found in the sea and, due to its salinity, is unsuitable for human consumption. Seawater desalination has become a viable method that has allowed humans to generate water suitable for different uses amidst the scarcity of fresh water in certain territories worldwide. Global warming and the excessive water use by large industries have exacerbated this scarcity.

Other methods are available for desalination, including evaporation through various distillation systems, crystallization through freezing systems, hydrate formation, selective membrane processes such as electrodialysis, and resin processes through ion exchange. Finally, semi-permeable membrane systems can be used through the Reverse Osmosis (RO) process, which uses pressure as energy for desalination. Different energy scenarios could be implemented to energize RO systems [1]. RO has been implemented as a desalination method since the 1970s, and it is one of the most beneficial techniques for generating water suitable for different uses. In addition, it eliminates microorganisms and organic and inorganic compounds contained in seawater. As a result, it is the most widely used desalination technique globally for domestic and industrial uses, including agriculture, tourism, and the military. Chile has used this technique since 1998, taking its first steps in the north of the country for use by the community and the mining industry [2].

In 2014, a second RO plant was implemented in Islas Huichas, Aysén Region, Chile. This was managed to replace the first that failed due to maintenance problems. This was done at the request of the Municipality of Puerto Aysén and funded by the Undersecretary of Regional and Administrative Development (SUBDERE) with technical support from both a potable water company and the Directorate of Hydraulic Works (DOH). However, the high fuel costs in the area make its prolonged use almost unsustainable, adding to the low revenue generated by the RDC, which is the organization in charge of domestic water, and the absence of regular training and certification of personnel operating the plant increased the problem. These factors resulted in decreased efficiency and maintenance, which put the operation and the availability of drinking water on the island at severe risk. Therefore, through a literature review and interviews with the managers of the RO plant of Islas Huichas. The authors of the study detected the factors that reduce plant efficiency. From this, they generated a project to optimize the system by an energy optimization of the plant by evaluating the most appropriate energy resource, considering its geographic location and climatic conditions, and by recommending good management and maintenance practices for the plant.

Several studies related to the integration of the optimization of RO plants have been developed from different perspectives. Jung [3] studied the optimization of RO systems by chemical treatment to reuse RO membranes, Okampo [4] investigated the desalination plant's prospective application of renewable energy sources, with focus in RO, Shalaby [5] addressed the challenges of brine disposal and preheating solar-powered reverse osmosis systems, Alawad [6], focuses on the efforts of companies to use renewable energy in RO systems, with focus on economics and technical advancements, Alireza [7] conducted a review analysis of the studies done on the effects and solutions of integrating renewables resources on water systems. Finally, Nurjanah [8] provided an overview of renewable energy in reverse osmosis, including, among others, the use of wave power.

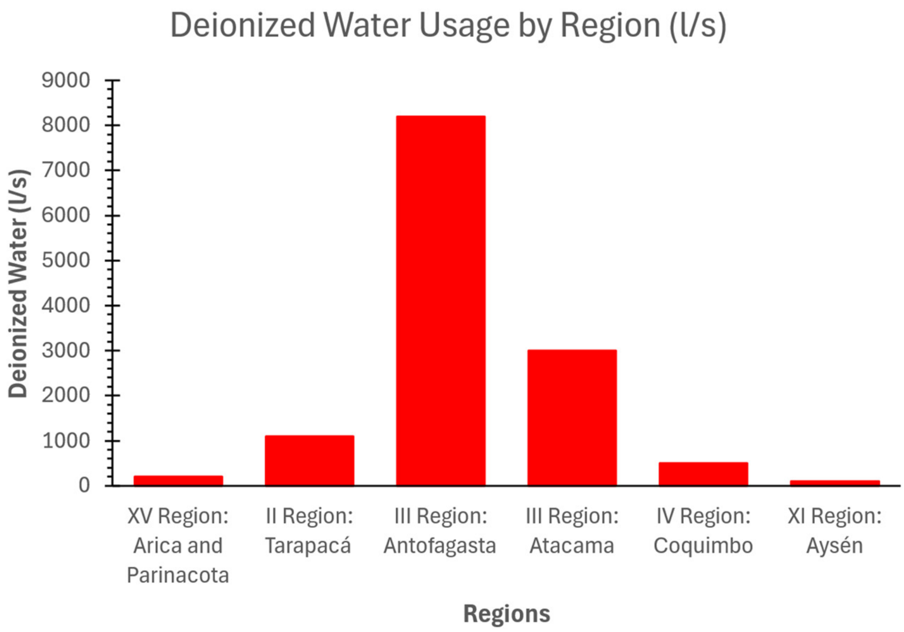
This work aims to study the feasibility of energy optimization of an RO in an isolated zone of the south of Chile, which presents problems related to its efficiency in the water production plant. To do so, the study will evaluate, using a cost-effective analysis and a cost-effectiveness Ratio (CER), which power generator to RO plant is more accurate in the specific case of Islas Huichas.

2. Materials and Methods

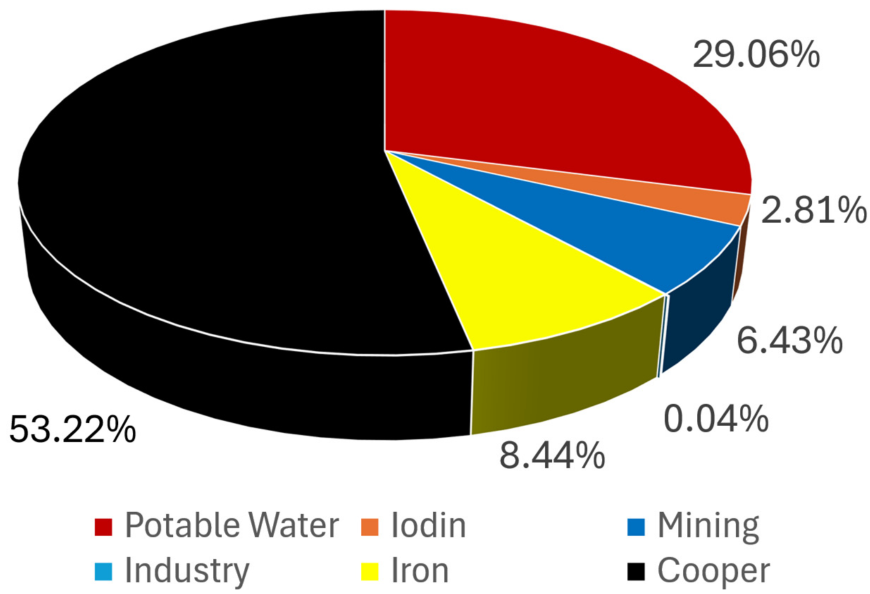
Chile has 20 RO plants in operation: 8 for drinking water treatment for human consumption, 1 for industrial use, and 11 for mining. Except for the Islas Huichas plant, all are in the Northern Macrozone. The Antofagasta region uses desalination the most to cover its needs since it has 12 RO plants [3]; a summary of desalinated water capacity by region in Chile is shown in Figure 1a.

In recent years, the Antofagasta region has been projected to have 61.07% water production, with 21 plants at production rates of 7.60 L/s; the plants installed in regions XV and IV will produce 38.91% with 4842.5 L/s. The only one installed in the southern region with 2.8 L/s will make the remaining 0.02% of the national desalinated water production [9]. Paposo plant will have the lowest with the lowest production capacity at 1.4 L/s, and its counterpart with 2500 L/s corresponds to the expansion of the Coloso plant owned by "Minera Escondida" for the copper industry [10]. Figure 1b compares the different uses of desalinated water in the country.

From Figure 1, it can be observed that the Antofagasta region produces the most desalinated water because it has the highest level of extractive mining in the country. Additionally, this method is used to generate domestic water for the regional capital. On the other hand, the Aysén region is the one that produces the least desalinated water; this is mainly because the water resource is abundant in most localities; the only RO plant is located in the town of Islas Huichas, providing water to approximately 1671 people to address shortages during the summer months.



(**a**)



(**b**)

Figure 1. (**a**) Desalinated water by region in the Chilean territory, (**b**) Comparison of desalinated water uses at the national level, data obtained from [10].

2.1. Case-Study: Huichas Islands Territory

The Huichas Islands are located 4 h by boat from Puerto Chacabuco and 7 h from Coyhaique, which is the regional capital of the XI Region of Aysén. It is located a few miles from the Moraleda channel, the main route for vessels that make cabotage to the southern south. It has a cold oceanic climate and rugged relief typical of the islands of the Chonos archipelago, named after the locals who sailed in canoes through the Patagonian channels. Figure 2 shows the island's location in red and black squares. The main cities of the Aysén region are highlighted.

Figure 2. Location of Huichas Islands (45°09′00″ S 73°31′10″ W).

There are 1671 people, mostly salmon workers, shellfish divers, artisanal fishermen, and operators of the seafood processing plants in the area. The islands lack a natural water source, so the inhabitants depend on rainfall to have water available for consumption and industrial use. However, due to increasing connectivity and tourism, the population increases during the summer, and with this, water consumption, so reserves are depleted in a few weeks without rain [11].

2.2. Huichas Islands RO Plant Description

The plant was modularly designed in a 40-foot container and mounted on a metal structure; its desalination capacity of 10 m^3/h allows 240 m^3/day under ideal conditions.

The layout of the facilities is designed to allow seawater to circulate from the washing pond to the sand filter, pass through the pumps, and then enter the RO membrane holding tubes with the product water exits on the left side (black pipe on the left side of the Figure 3a). Figure 3c shows the feed pump that transports the seawater to the pretreatment line, where 10% sodium hypochlorite is added with an injection rate of 0.302 L/h, antifouling for membrane durability at a rate of 0.078 kg/h and 32% hydrochloric acid at a rate of 0.685 L/h. After collection, the water circulates towards the 130 µm ring filter, trapping the colloids. Manual and electronic pressure signals are captured through a pressure gauge and valve, as shown in Figure 3c.

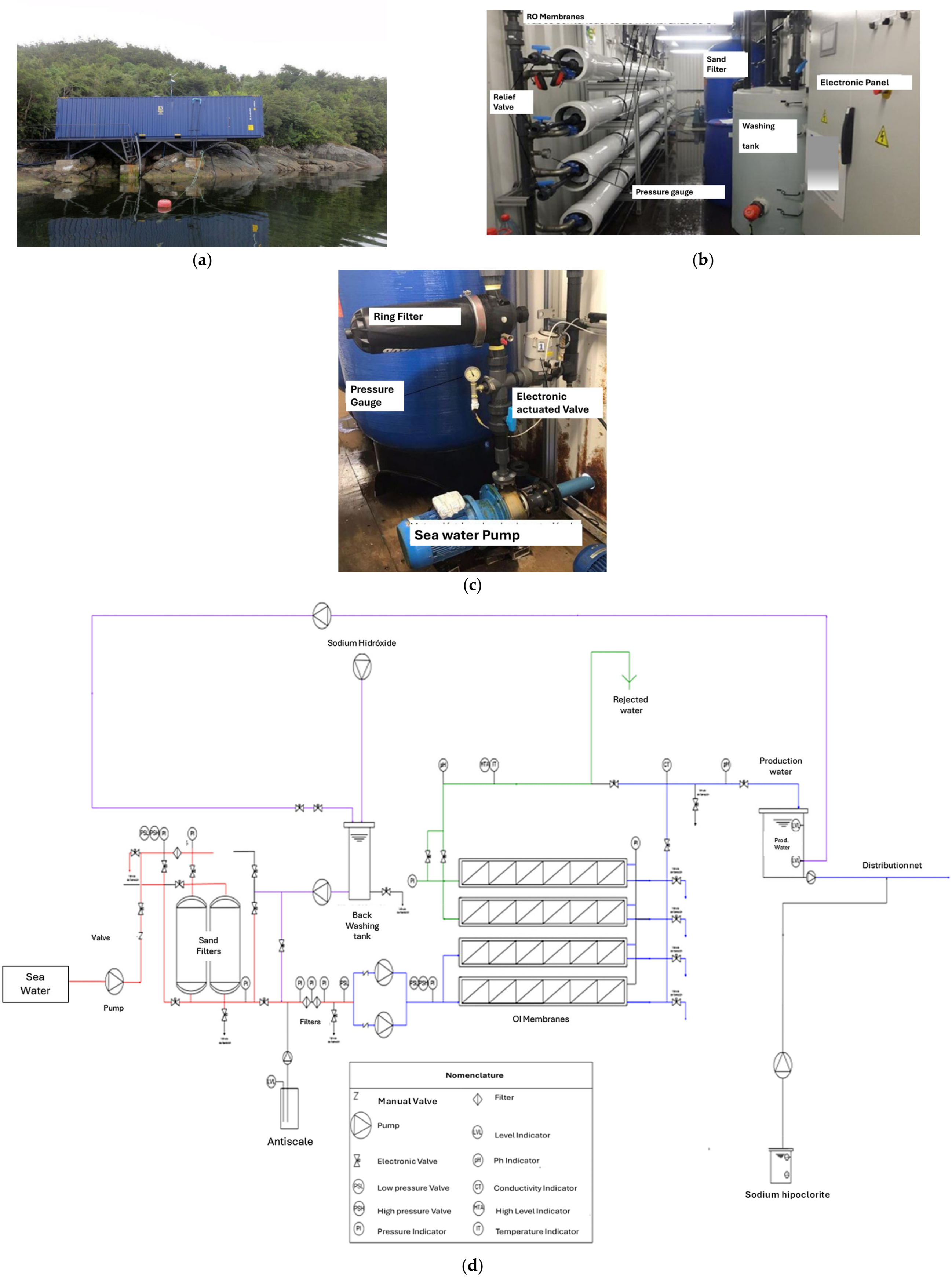


Figure 3. (**a**) Location of the OI plant container, (**b**) Interior of the container with components, (**c**) Components and seawater collection pump, (**d**) Schematic diagram of the Plant.

2.3. Problem Statement

Up to 80 days without rain have occurred during the all the summer seasons [5], so the accumulation pools are insufficient, and consequently, the shortage affects the population. Figure 4 shows the accumulator pools at different months of the year, the first during rainfall season and the right one during summer. To reverse this situation, from 2012 to 2016, €1,854,578.22 has been invested in projects to increase storage and prevent water loss [11].

(**a**) (**b**)

Figure 4. Accumulator pools during the rainy season (**a**) compared to the summer season (**b**).

Because of the area's water deficit, local authorities implemented RO plants to supply fresh water to the population.

The plant is intended to produce 10 m^3/h of water suitable for human consumption. Water demand is projected to be 150 m^3/day, and in summer, this could increase to 300 m^3/day due to the arrival of tourists [11]. According to the report, the plant would produce 240 m^3/day. In March 2021, a visit was made to the plant in operation, where a structured interview with the operator in charge showed that it operates 10 h/day and produces 12 m^3/h of potable water, i.e., 120 m^3/day, which means that water is rationed and available to the population from 9 : 00 to 18 : 00 h. during the summer season while waiting for the rain to start. One of the most important reasons for rationing is that no resources are available to finance its operation 24 h/day. Concerning plant maintenance, the operator stated that there is no scheduled maintenance of the instruments. An example of this deficit is the durability of the RO membranes, which have an average life of 12 months despite the manufacturer's projects of 5 years of durability. Finally, it is essential to note that there is no periodic training for the personnel operating the RO plant, with the operator having only 5 training days. In summary, 4 main problems were detected at the RO plant:

- The economic resources do not cover the operating costs necessary to operate the plant continuously.
- Low durability of RO membranes, estimated at around 20% according to the manufacturer, due to the lack of maintenance.
- Lack of data collection to increase process efficiency.
- Lack of continuous training of plant operators to ensure proper use of the facilities, including maintenance.

Taking into consideration the above statements, the Water Stress Index (WSI) could be calculated for summer and the rest of the year scenario, the *WSI* indicates the levels of water stress in a particular region, country, or basin, by using Equation (1)

$$WSI(\%) = \frac{water\ use}{water\ resources - enviromental\ flow\ requirements} \cdot 100 \quad (1)$$

To compute the *WSI* for the Islas Huichas, the water use was separated in summer at 300 tons/day of water use in summer, maintaining the water resources produced by the RO plant at 120 tons/day. For the rest of the year, the water use was 150 tons/day. According to [12], the water environmental flow requirements vary between 25% and 46% of the mean annual reported water resources; with this in consideration, the two scenarios of summer and the rest of the year can be evaluated by varying the environmental flow requirements as shown Figure 5:

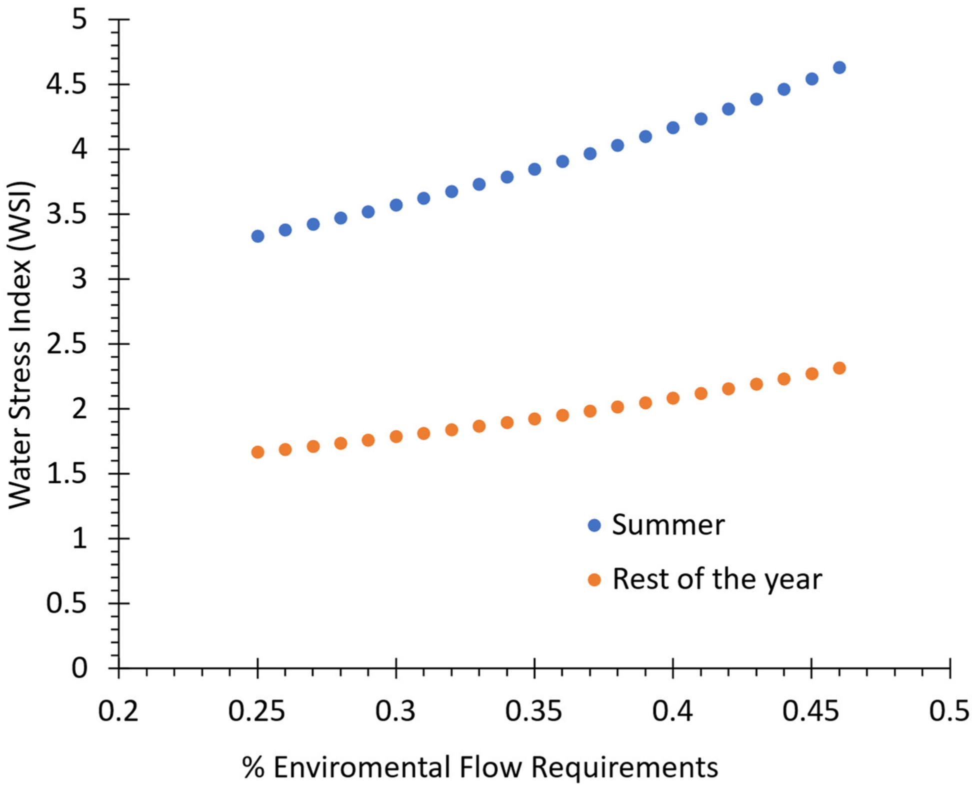


Figure 5. Water stress Index for the yearly scenarios, summer season, and rest of the year.

Figure 5 illustrates that in the case of Islas Huichas, the *WSI* surpasses 100%. Critical scenarios indicate high to critical levels of stress under the hypothetical scenario of 100% dependence on the OI system. Additionally, in the summer scenarios, where there is a higher probability of 100% OI dependence, the Water Stress Index (*WSI*) is almost twice that of the rest of the year scenarios. The *WSI* values are presented in Table 1.

Table 1. Values indicators of *WSI*.

Values	Level of Water Stress
$WSI \geq 100\%$	Critical
$75\% \leq WSI \leq 100\%$	High
$50\% \leq WSI \leq 75\%$	Medium
$25\% \leq WSI \leq 50\%$	Low
$WSI \leq 25\%$	No Stress

2.4. Scenarios for the RO Plant Optimisation

As mentioned above, the objective was to optimize the current project to reduce the maintenance costs of the plant by comparing the following energy alternatives and their respective CO_2 equivalent emissions. For this purpose, the following scenarios are contemplated:

- Grid power
- Use of diesel generator
- Hybrid use of diesel and 10% photovoltaic energy
- Hybrid use of diesel and 10% wind energy
- Use of 100% photovoltaic energy
- Use of 100% wind energy

All scenarios are calculated considering the same daily production of 240 tons/day, which is referred to as the original production of the RO plant.

Energy recovery devices (ERD) allow for recuperating the energy contained in the rejected water before its disposal, reducing the plant's energy consumption and associated costs (In this study, the ERD system is not considered because it implies a substantial modification of the RO system). Although the permeate produced after the reverse osmosis process may have low dissolved solids and be considered potable, it requires disinfection, degassing, pH adjustment to mitigate corrosion in the distribution system, hardness addition for taste, and the incorporation of essential ions for health reasons.

2.5. Grid Power Scenario

Table 2 presents the required power and associated costs for the calculation of the investment needed to operate the island's grid-dependent RO plant:

Table 2. Calculated power for the production of 150 m^3/day during 2021 [11–13].

Power Requirements	130 kVA
Fixed charge (€/kWh)	€5.36
Power charge (€/kWh)	N/A
Consumption partly present at peak	€23.11
Consumption present at peak	€32.74
Energy charge (€/kWh)	€0.13

2.6. Grid Power Green House Gas Emissions

In the case of power from the grid, is necessary to quantify greenhouse gas emissions, which are emitted indirectly into the environment. To this, Equation (2) was used [12], in which β corresponds to the unitary greenhouse gas emission generated in the study area, which corresponds to 0.2 kg of CO_2/kWh, according to [14], α represents the unitary electrical consumption of the desalination plant which is 5395 kWh/m^3, and Q represents the capacity of desalination plant, which is calculated in base of the maximum production capacity in two scenarios (120 and 240 m^3) during year.

$$GHG_{desal} = \beta\left[\frac{\mathrm{kgCO_{2eq}}}{\mathrm{kwh}}\right]\cdot\alpha\left[\frac{\mathrm{kWh}}{\mathrm{m^3}}\right]\cdot Q\left[\frac{\mathrm{m^3}}{\mathrm{h}}\right] \tag{2}$$

2.7. Diesel Generator Scenario

The generator plant is an AKSA model APD200C, with 200 kVA equivalent to 160 kW. The consumption data was obtained using the DG data sheet and operator interview, which stated that at 40% load, the consumption was 17 L/h. According to the plant operator, the combustible (Diesel) price during this research is 1.37 €/L. Therefore, calculations will be made using this data. Due to a lack of budget, the RO plant only operates for 10 h/day.

The cost of operation for an uninterrupted month was evaluated. As an observation, the APD200C generator, for the calculations, 40% will be allocated for load losses and generator conditions that could impact an increase in fuel demand. Therefore, according to the manufacturer, 17 L/h is consumed if the generator works at this capacity. Table 2 shows the monetary detail according to the use of the projected RO plant operating during the year without interruption at 40%, 50%, and 75%.

According to Table 3, GHG emissions during the year could vary depending on the load of the diesel engine, taking into consideration the summer scenario as November to March, with DG working 24 h continuously and the rest of the year working 10 h, at 75% load, an estimation cost can be obtained. This cost is shown in Figure 6. To consider the emissions, the scenario changes to emissions of 75% in an ideal case and the actual case, which is the engine working at 40% load. Figure 7 shows that emissions are lower at 40% load, but water production is also not optimal.

Table 3. APD200C generator associated cost and emissions.

Load %	Consumption (L/h)	g/kWh	Emission ($kgCO_2/kWh$)	Tons CO_2 Month/24 h	Tons CO_2 Month/10 h	€/10 h Yearly	€/24 h Yearly
40	17	90	26	19	8	€6987.00	16,768.80
50	21	112	32	23	10	€8631.00	20,714.40
75	31	165	48	35	14	€12,741.00	30,578.40

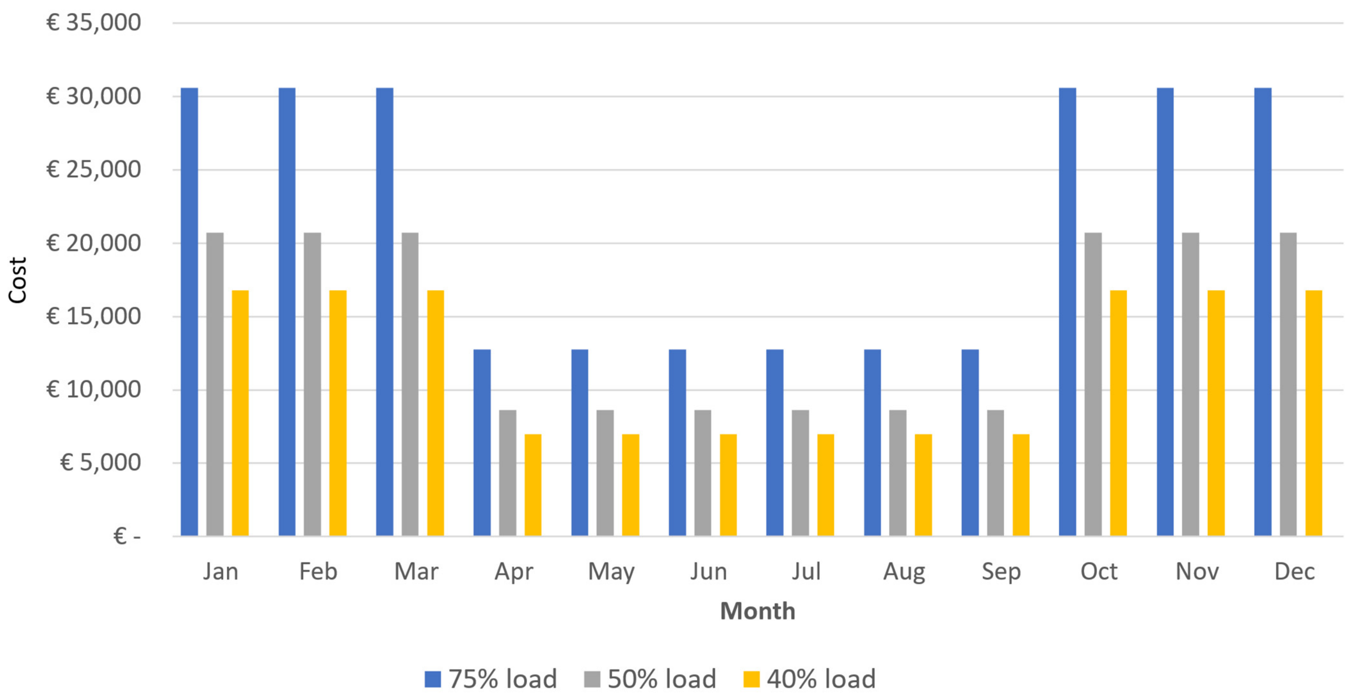


Figure 6. Cost against Diesel generator load during one year.

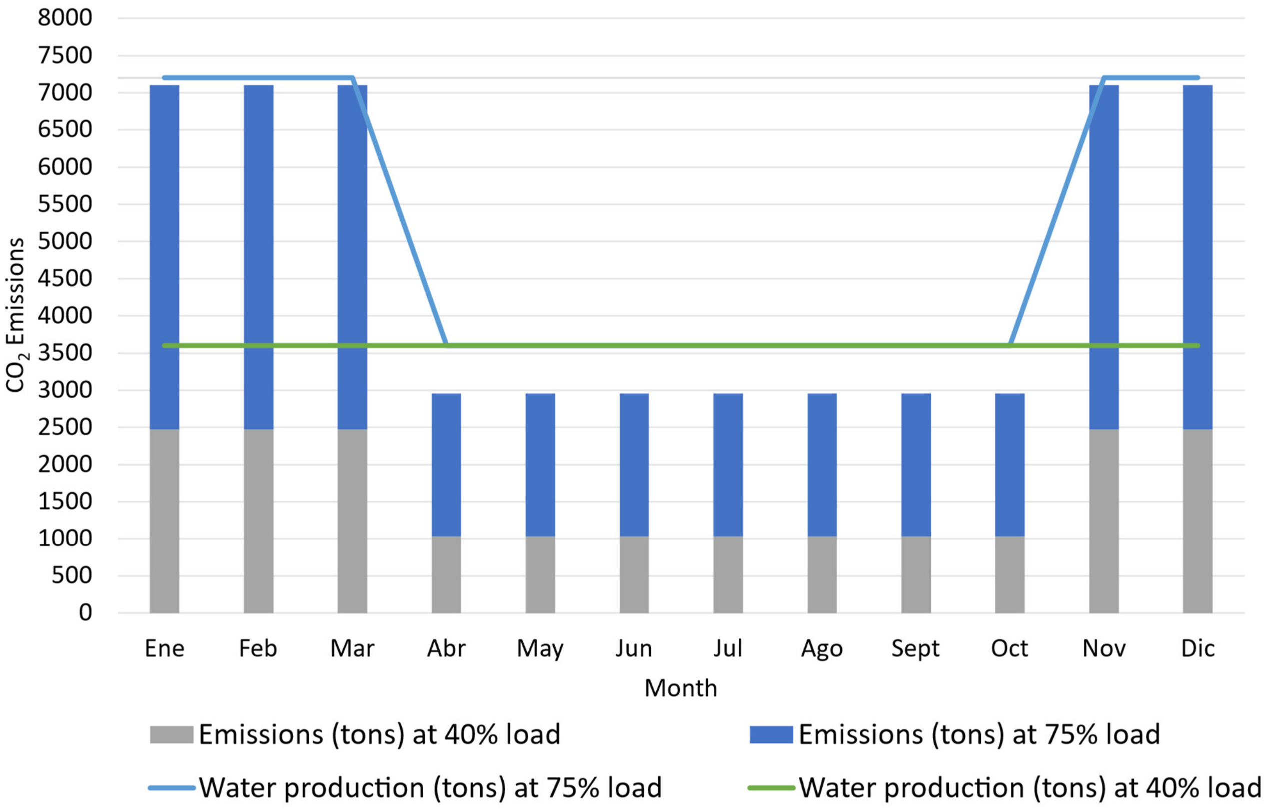


Figure 7. Emissions and water production per year at 40% and 75% load.

2.8. Diesel Generator, Greenhouse Gas Emissions Generated by the Desalination Plant of Islas Huichas

The GHG emissions using DG can be calculated using the average value emitted by diesel-burning of 0.402 kg CO_2/kWh, so the annual number of tons generated for the RO process can be calculated through Equation (3). Furthermore, the power consumption of the RO plant is 5.395 kWh/m^3; based on the hours of operation per year, the amount of GHG that will be emitted to the environment by the OI desalination can be projected using Equation (3).

$$\frac{t_{CO_2}}{\text{year}} = \frac{\text{m}^3}{\text{day}} \cdot \frac{5.395\ \text{kWh}}{1\ \text{m}^3} \cdot \frac{365\ \text{day}}{1\ \text{year}} \cdot \frac{1\ \text{ton CO}_2}{1000\ \text{kgCO}_2} \cdot 0.402\ \text{kgCO}_2/\text{kWh} \quad (3)$$

Emissions can be calculated according to the use time and water production; the values can be extrapolated to 24 h, 10 h, and the three different load scenarios. The results are shown in Table 4.

Table 4. Annual CO_2 emissions generated by the plant running on diesel fuel.

m^3/day	Tons CO_2/year
1	0.79
100	79.16
240	189.99

2.9. Renewable Energy Scenarios

Renewable energy is unlimited, dependent on nature, and its use is not harmful to the environment [15,16]. According to Law No. 20,257 in Chile, the following are recognized: hydro, solar, wind, tidal, biomass, biogas, and geothermal, among others. In Chile, up to June 2017, the Central Interconnected System (SIC) has an installed capacity of 17.5 GW; 45%

of its power generation through fossil fuels, 38% corresponds to hydraulic generation, and the rest is generated by wind, solar, and biomass systems with 8%, 7%, and 3% respectively. The country's objective through law 20/25 is to generate 20% of the demand through RE by 2025, a goal that is approaching due to the growing investment in this type of energy and the climatic conditions in the north. It is important to note that the Aysén Region has the lowest solar radiation levels after the Magallanes Region [17]. However, its feasibility will be evaluated in Islas Huichas since it is urgent to find a way to reduce energy costs and reduce the environmental impact generated by burning diesel from the generator. Wind energy is currently one of the most used REs and has been increasing over the years, along with the development of the industrial sector. The Aysén region has an abundance of this resource [18]. Figure 8 compares the two sources during a year.

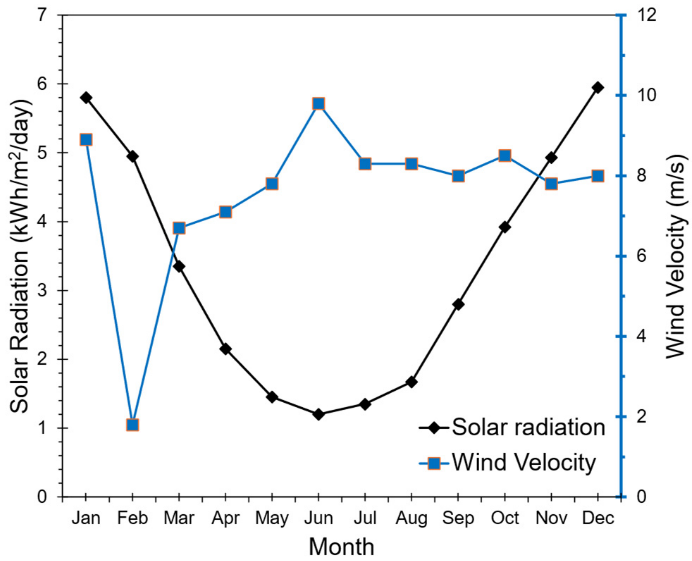


Figure 8. Graph showing the intensities of radiation and wind speed in Huichas Islands during the months of the year [13].

2.10. Solar Energy Scenario

Because of the lowest radiation levels in Huichas, its feasibility will be evaluated, since it is of utmost urgency to find a way to reduce energy costs, and the environmental impact generated by burning diesel from the APD200C generator. The energy consumption of the RO plant is 53.95 kWh of operation; if it operates 24 h/day, 1294.8 kWh are used [19], which is added to 20% for possible load losses and low efficiency of the elements. Therefore, the estimate will be made with 1553.8 kWh/day.

$$\text{Photovoltaic power} = \frac{\text{day consumption}}{\text{Minimal solar time}} = \frac{1553.8\ \text{kWh}}{1.17\ \text{h}} = 1328\ \text{kW} \tag{4}$$

There are currently installed panels adapted to the island's solar conditions, which work to energize a small lighting system so that the same type was used for the projection. These are model DHP 72–320 W with a maximum power of 320 W and open circuit voltage of 45.8 V, with dimensions 1956 × 991 × 40 mm.

Since 2004, data has been collected in Chile to facilitate the implementation of photovoltaic installations and thus reduce uncertainty for those who dare to invest in this renewable energy [20,21]. In the town of Islas Huichas, the minimum solar hours during which the panels can capture energy occur in June, with 1.17 h, and the maximum occurs in December, corresponding to 5.94 h. Therefore, for the number of modules or solar panels to be installed, it is recommended to employ Equation (6):

$$\text{Modules} = \frac{\text{photovoltaic power}}{\text{module power}} = \frac{1328\ \text{kW}}{320\ \text{W}} = 4150\ \text{modules} \tag{5}$$

Currently, the price of each module is €152.8 [16], so the total cost of the 4150 photovoltaic modules that should be obtained to meet the plant's energy demand during June [15] is €634, 152.00. Chilean money in panels exceeds the RO plant's total value [19]. In addition, the battery bank was calculated to allow the system to operate for one day of autonomy.

$$\text{Battery Autonomy} = \frac{E \cdot A}{DOD \cdot V_{Syst} \cdot E_c \cdot E_{inv}} \quad (6)$$

where Q is the capacity of the battery bank in Ah; E, the daily system power demand (1553.8 kWh/day); A, the system autonomy in days (1 day); DOD, the depth of discharge (0.7); V_{syst}, the voltage (12); Ec, the efficiency of the regulator (0.95); and E_{Inv}, the inverter efficiency (0.95). The result of the equation is 204, 960 Ah. The market was searched, and Ultracell brand deep cycle batteries 12 V and 100 Ah were selected. According to the named model, the quantity to be installed is calculated as follows:

$$N\ Batteries = \frac{Q_{syst}}{Q_{battery}} \quad (7)$$

where Q_{syst} is the capacity of the system in Ah. $Q_{battery}$ is the battery capacity in Ah. The number of 100 Ah Ultracell batteries that satisfy the demand for one day is 2050. The Chilean market has a value of €214.32, and this price multiplied by the quantity implies an investment of €439, 356.00. Therefore, to obtain the total cost, it should be considered first and based on data available from the Ministry of Energy, that the panels represent only 33% of the total cost of a photovoltaic installation; the rest corresponds to electrical materials, installation, and inverters with 28%, 24%, and 15% respectively [22], so the total cost of the photovoltaic installation amounts to a total of €1, 923, 360.53 this plus the battery bank amounts to €2,361,030.00 which would be equivalent to the purchase and installation of approximately 5.4 RO plants of the same current characteristics, which is why it is not a viable method from the economic point of view. To calculate the space to be used for the installation, the inclination of the panels must be determined first. Those must be up to ±10 than the latitude of the installation area. Due to the Huichas Islands location, 40° of latitude will be used for calculation purposes. The Ground-coverage ratio (GCR), the ratio between the panel's area and the ground's total area, must then be calculated. The literature recommends a minimum ratio of 0.47 to obtain a maximum of 2.5% energy loss due to shading [23]. Equation (8) shows the calculation of the minimum distance between rows of panels to have the lowest possible energy loss.

$$GCR = \frac{length_{panel} \cdot width_{panel}}{\left(width_{panel} \cdot \cos 40^\circ + distance\ between\ rows\right) \cdot length_{panel}} = 0.47 \quad (8)$$

Using the dimensions of the DHP 72–320 W model, it is obtained that to comply with the minimum GCR of 0.47, a distance of 1.35 m between rows of solar panels is required in Huichas Islands. If 4150 panels are installed in 50 rows of 83 panels each, 160.89 m^2 per row will be used; this multiplied by 50 results in 8044 m^2 in panels, to this is added the minimum separation of 1.35 m by the length of the row of 83 panels multiplied by 50 which results in 5552.1 m^2. In summary, to install 4150 photovoltaic panels of 1.956 m × 0.991 m, 13, 597 m^2 must be used, which would energize 100% of the RO plant.

2.11. Wind Power Scenario

According to the data collected, the Aysén region has an abundance of this resource [24]. In Islas Huichas, the wind resource is presented with a monthly distribution, as shown in Figure 9, and the average wind on the island is 8.1 m/s. Due to the average wind in the area, a wind turbine is sought in the market, resulting in the proven model of 15 kW as the most suitable for the island. This wind turbine weighs 1.1 tons and has a blade diameter of

9 m, characteristics that allow its hypothetical transfer on the barge in charge of supplying the island, which has a load capacity of 480 tons.

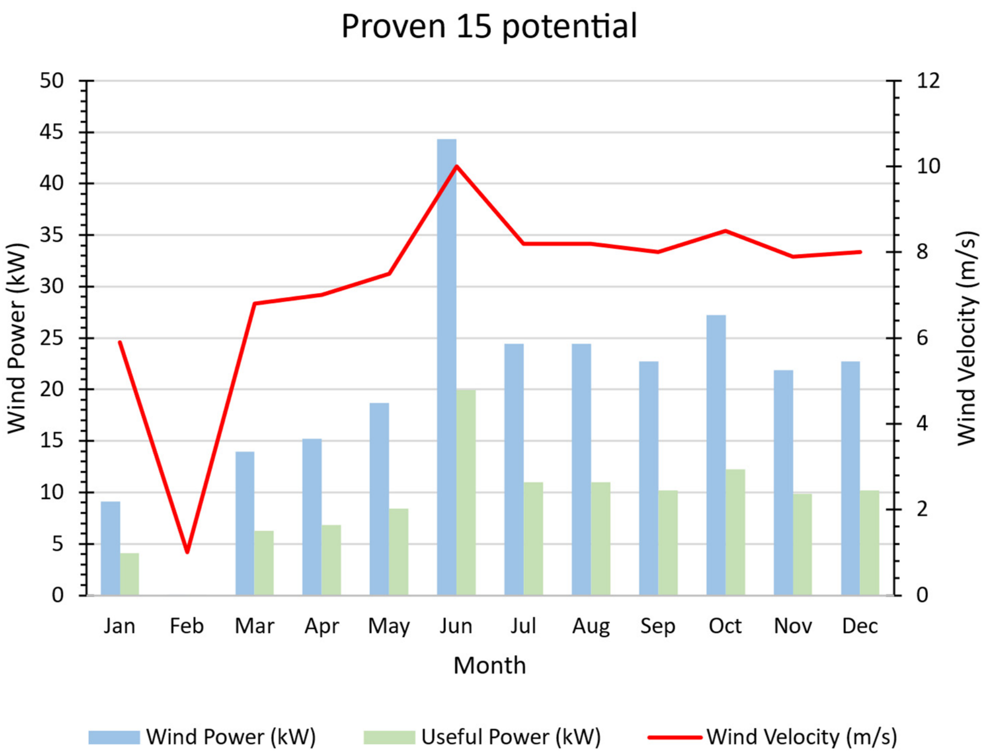


Figure 9. Efficiency of the wind power in the selected zone.

A wind installation supplying 100% of conventional energy was evaluated, equivalent to the daily consumption of the RO plant, corresponding to 1294.8 kWh/day with a safety factor of 20%, resulting in 1553.8 kWh/day. The wind explorer of the Ministry of Energy [24] projects that this wind turbine, could generate an average of 195.45 kWh/day of energy in Huichas Islands with a load factor of 54.3% (the load factor is the percentage of the day during which the rotor is generating energy [25]). With this in consideration an estimation of the annual power production is presented using Equation (9) according to Letcher [25]:

$$P_w = \frac{1}{2}\rho A V^3 \tag{9}$$

where P_w is the wind power, ρ is the air density (1225 kg/m^3) and V is the annual wind velocity. In terms of electric energy, only a certain proportion of kinetic energy of the wind can be converted (this value is known as the Betz limit C_p, indicating a factor of 59%). Equation (10) shown the corresponding expression for the energy generation, P_e:

$$P_e = \eta_m \eta_e C_p P_w \tag{10}$$

where η_m is the mechanical efficiency, η_e is the electric conversion efficiency. C_p in the best cases is 0.59, but 0.45 for consideration in this study case.

Therefore, the daily demand can be supplied with 8 Proven 15 kW wind turbines that will deliver 1563.6 kWh/day, i.e., when installed, they can provide the daily demand required by the RO plant. However, the price of the 15 kW wind turbines averages €25, 102.00, additionally, 30% for transportation must be added, since they must be purchased in Europe, China, or the United States, and finally 19% for VAT, resulting in a total investment of approximately € 37, 369.00 per unit; therefore, if eight wind turbines are purchased, approximately € 298, 954.00 will be invested.

Wind energy is intermittent, and there could be days when it is too low; that is why a battery bank is projected to support the daily consumption of the RO plant, being the same projected bank of solar energy, since the energy to be covered during a day is the same, resulting in a value of 204, 960 Ah using the same Ultracell brand deep cycle batteries of 12 V and 100 Ah. Assuming an investment of € 439, 741.40. In summary, the calculated with 8 wind turbines plus the battery bank should be invested €738, 309.60 which represents 39.81% of the invested during the 2012–2016 period, 169.3% of the total cost of the RO plant, 31.27% of the solar array, 367% regarding the diesel that would be spent if the plant would operate for an uninterrupted year with the APD200C generator and 1000% over the operation of the grid-dependent RO plant for one continuous year under the 2021 tariff. Assuming that this wind array is installed, there is a minimum distance between each wind turbine depending on the rotor diameter; if the maximum distance is taken and the same configuration for safety reasons, the space used by these 8 wind turbines is 12, 150 m^2.

3. Results

The costs of all scenarios were compared: the current cost of the RO plant running on diesel for 10 h/day the value that would result from running the RO plant uninterruptedly on diesel and electricity, and the cost of the investment with solar and wind energy. These data will be compared with the investment costs that the RPA incurred from 2012 to 2016, as well as the cost of the current RO plant.

As described above and according to the study reported by the Controller General of the Republic, the total investment cost from 2012 to 2016 in the RO plant of Islas Huichas amounts to a total of €1, 854, 578.22 (Table 5). The investment for the installation of a photovoltaic array to cover the total energy demand of the RO plant would be 27.31% higher than what was invested between 2012 and 2016; in addition 5.4 RO plants could be afforded, so it is possible to conclude that the investment cost, that the use of photovoltaic energy is not the most efficient option at present. On the other hand, the investment in wind energy is, from the economic point of view, a more viable option since its installation represents 39.8% of what was invested from 2012 to 2016; however, it equally exceeds the installation cost of the RO plant, corresponding the investment cost with wind energy to 1.7 plants approximately, however, given the scarcity of resources and compared to the cost through diesel and electricity, it still represents a high sum of money for the local reality. Therefore, it can be observed that the operation of the RO plant by the electric grid is the most viable option since it represents an annual cost of €70, 595.00 as opposed to the cost of a diesel generator for one year, which amounts to approximately €200, 931, 00 in fuel (Table 5). It is also important to note that it is 15.68% cheaper than the current operating cost of the RO plant, which operates only 10 h/day with diesel, so changing the operation of the plant to the local power grid could operate continuously generating a positive impact on the quality of life of the community of Islas Huichas, from generating 100 m^3/day to 240 m^3/day of water.

Table 5. Economic comparison between the different scenarios.

CAPEX OI	436,062.54
OPEX 2012–2016	1,854,578.22
Power Grid for one year	200,931.84
DG 24 h/year	200,931.84
DG 10 h/year	83,721.60
CAPEX WT	738,309.60
CAPEX PV	2,361,030.06

Cost-Effectiveness Ratio (CER)

The Cost-Effective Ratio (CER) is a metric used to assess the efficiency of an intervention or project and its costs. It is commonly used in economics, healthcare, and engineering to compare options' relative costs and benefits. The CER is calculated by dividing the cost of an intervention by the benefit it provides, which is usually measured in non-monetary terms, such as improved health outcomes, energy savings, or other measurable impacts. Equation (11) allows to compute the CER.

$$CER = \frac{Intervention\ Costs}{Benefits\ provided} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{o_t}{(1+r)^t}} \quad (11)$$

where C_t represents the operating and investment costs, and O_t, the benefits it produces, not necessarily thought in economic terms, in the case of Huichas Islands, this term could be considered in terms of the benefited population (1671 people), the tons of CO_2 that would stop being produced (189.99 ton/year) in case of using the photovoltaic and wind options, school days in case of not having water problems (180 days) and jobs generated by the photovoltaic and wind systems (approximately 5). r is considered as 12% hypothetically. Then, by replacing those values in each scenario, the results shown in Figure 10 were obtained.

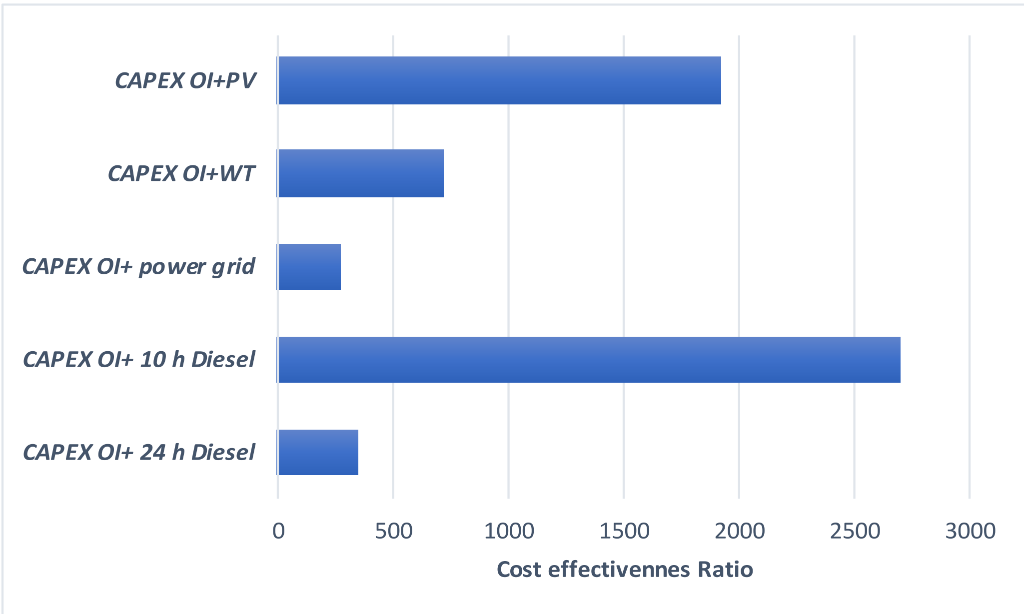


Figure 10. CERs for the five investment cases.

A lower cost-effectiveness ratio indicates a more efficient intervention, in the Figure 10, as it can be seen, the case of CAPEX OI + 24 h diesel, shows a better CER compared with renewable energy cases, because implicate and extensive intervention of the use of spaces in the Island, and also higher CAPEX.

4. Discussion

This study identified various shortcomings in the desalination system on Islas Huichas, resulting in reduced efficiency of the installed water generation system. Operational deficiencies can be rectified by adequately training the personnel responsible and redesigning the water intake and pretreatment system to achieve a Silt Density Index SDI of less than 5. The SDI is a measure used in desalination plants that employ reverse osmosis to evaluate the propensity of the feed water to cause fouling on the membranes. The SDI quantifies the number of suspended particles and colloids present in the water that can clog the pores of the membranes, reducing their efficiency and lifespan. To achieve the highest possible permeate quality, a membrane with high rejection is needed, and it should operate at the lowest possible recovery rate. The reason is that higher recovery rates lead to increased solute concentration on the feed side of the membrane, resulting in a more significant concentration difference and a consequent increase in solute flux, leading to lower quality permeate. If necessary, a double-pass system can be employed to obtain higher-quality permeate.

Another alternative for achieving higher-quality permeate is operating with low-temperature feedwater since lower feedwater temperature results in more membrane rejection, reducing salt passage. However, the drawback of this approach is the need for higher feed pressure, which increases the plant's energy consumption and system resizing.

The feedwater pretreatment system is as crucial as the membrane system in the freshwater generation process through reverse osmosis. It is responsible for reducing the elements present in the feedwater that lead to membrane fouling, which reduces membrane lifespan and system efficiency. Regardless of how well-designed and practical the pretreatment system is, membrane fouling is inevitable. It necessitates periodic cleaning of the membranes to remove fouling and restore membrane flow and rejection, extending their lifespan. With an inadequate pretreatment system, membrane fouling occurs frequently, necessitating more frequent cleaning. The above contributes to membrane degradation due to the temperature and pH at which cleaning is conducted and the chemicals used. Improving the feedwater pre-treatment system can also be studied as an alternative solution to improving the RO desalination plant with different pre-treatment scenarios [26].

Disposing of concentrate and cleaning solutions is a common challenge in land-based reverse osmosis plant design, as there is a risk of contaminating freshwater sources. Before disposal, the pH of the concentrate and cleaning solutions must be neutralized, eliminating the risk of environmental harm resulting from water discharge with high concentrations.

Another proposed solution for the RO treatment plant is installing a Supervisory, Control, and Acquisition System (SCADA) to monitor and improve the plant in real time. Implementing a SCADA system would enable more efficient management, early detection of issues, and process optimization, contributing to technical efficiency and cost-effectiveness.

Other alternatives to optimizing water consumption in the case studied are implementing water-independent homes [22] to reuse grey waters and modifying the tariff structure, such as the one proposed by [23], which can improve the economic resources to maintain the OI system on the island.

Finally, Table 6 was included to compare the advantages and disadvantages of the scenarios studied. The main parameter influencing the installation of renewable energy resources is the space utilization on the Island for Renewable energy.

Table 6. Comparative of the 5 scenarios proposed in this study related to the case study.

Scenario	**Advantages**	**Disadvantages**
Grid Power Scenario	Low cost associated to CAPEX	Dependence of onshore Grid system
Diessel Generator	Low CAPEX Low OPEX	Dependence on the fluctuations of the diesel prices CO_2 and non-emissions
Hybrid Diesel and 10% PV	Fuel consumption reduction Emission reduction	Extensive use of space for PV system installation An optimized control system is required
Hybrid and 10% WE	Fuel consumption reduction Emission reduction	Extensive use of space for PV system installation An optimized control system is required
100% PV	Low OPEX	High CAPEX Extensive use of space in the zone Intermittent energy Extensive use of batteries Low solar radiation during part of the year
100% WE	Low OPEX Abundant energy resources on the studied zone	High CAPEX Extensive use of space in the zone

5. Conclusions

The RO plant in Islas Huichas is known as the southernmost in the country. This has enabled the provision of drinking water to the community when water scarcity intensifies yearly during the summer.

Research has shown that it is possible to operate the RO plant 24 h/day by connecting it to the electricity grid, which reduces costs and increases water production. According to the AT3 tariff, the continued use of the plant costs a total of €5882.00 represents a saving of 15.7% compared to the current cost of using the plant with the APD200C generator for only 10 h/day, which is an expense of €6976.00. It is worth noting that the price per m^3 of water produced varies depending on the local electrical grid. Using the electrical grid costs €0.85/m^3 while using the APD200C generator costs €2.43/m^3. This means desalinating 1 m^3 of water with the electrical grid is 35.13% cheaper than using the generator. Those findings indicate that direct use of DG is the least advantageous option in the presented study.

The study evaluated the possibility of hybridizing the plant and found that wind energy is a good option due to the environmental conditions of the Aysén Region, which is known for its high wind speeds. Solar energy was also evaluated, but it has a high investment cost. Unlike the northern part of the country, it does not have optimal radiation levels due to its location. The study suggests it is feasible to hybridize the plant by implementing wind energy and contributing 10% of the energy through a wind turbine. This investment would cost €81,304.00 and it would save 2.4 h of electricity, which is a feasible amount compared to the investment made between 2012 and 2016 and the total cost of the RO plant.

In addition to the long-term economic savings, wind energy positively impacts environmental conservation. It aligns with governmental trends that promote the implementation of renewable energy. The calculation shows that 8 of these wind turbines could be implemented in the future, ultimately replacing the energy obtained through diesel burning. This would cost €738,309.00 representing 39.81% of what was invested between 2012 and 2016. It would also reduce the emission of 188.99 tons of CO_2 annually produced by the diesel plant, positively impacting the environment.

Future work aims to study the technical issues related to implementing the hybrid wind power system and evaluate a SCADA system for monitoring and controlling the RO plant in real time.

Author Contributions: Conceptualization, B.B. and V.C.; methodology, B.B. and V.C.; software, R.G. and V.C.; validation, J.A., M.M., R.G. and V.C.; formal analysis, B.B. and V.C.; investigation, B.B., J.A. and V.C.; resources, B.B. and R.G.; data curation, B.B., M.M. and V.C.; writing—original draft preparation, B.B., R.G. and V.C.; writing—review and editing, J.A., V.C. and R.G.; visualization, B.B., J.A. and M.M.; supervision, V.C.; project administration, V.C.; funding acquisition, B.B. and R.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: Not applicable.

Data Availability Statement: If data of this research are required, please do not hesitate to contact the corresponding author.

Conflicts of Interest: Author Benjamín Borquez was employed by the company CMC Engineering. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Fayyaz, S.; Khadem Masjedi, S.; Kazemi, A.; Khaki, E.; Moeinaddini, M.; Irving Olsen, S. Life cycle assessment of reverse osmosis for high-salinity seawater desalination process: Potable and industrial water production. *J. Clean. Prod.* **2023**, *382*, 135299. [CrossRef]
2. Funcionamiento e Impacto Ambiental del Proceso de Desalinización de Agua de Mar, Biblioteca del Congreso Nacional de Chile. Available online: https://www.bcn.cl/asesoriasparlamentarias/detalle_documento.html?id=28413 (accessed on 10 December 2023).
3. Jung, M.; Yaqub, M.; Lee, W. Optimization of chemical cleaning of discarded reverse osmosis membranes for reuse. *Membr. Water Treat.* **2021**, *12*, 1–9. [CrossRef]
4. Okampo, E.J.; Nwulu, N. Optimisation of renewable energy powered reverse osmosis desalination systems: A state-of-the-art review. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110712. [CrossRef]
5. Shalaby, S.M.; Sharshir, S.W.; Kabeel, A.E.; Kandeal, A.W.; Abosheiasha, H.F.; Abdelgaied, M.; Hamed, M.H.; Yang, N. Reverse osmosis desalination systems powered by solar energy: Preheating techniques and brine disposal challenges—A detailed review. *Energy Convers. Manag.* **2022**, *251*, 114971. [CrossRef]
6. Alawad, S.M.; Mansour, R.B.; Al-Sulaiman, F.A.; Rehman, S. Renewable energy systems for water desalination applications: A comprehensive review. *Energy Convers. Manag.* **2023**, *286*, 117035. [CrossRef]
7. Zakariazadeh, A.; Ahshan, R.; Al Abri, R.; Al-Abri, M. Renewable energy integration in sustainable water systems: A review. *Clean. Eng. Technol.* **2024**, *18*, 100722. [CrossRef]
8. Nurjanah, I.; Chang, T.-T.; You, S.-J.; Huang, C.-Y.; Sean, W.-Y. Reverse osmosis integrated with renewable energy as sustaina-ble technology: A review. *Desalination* **2024**, *581*, 117590. [CrossRef]
9. Econssa Chile. Los Desafíos de la Gestión de Proyectos de Desalinización de Aguas. Marzo de 2016. Available online: https://www.camara.cl/verDoc.aspx?prmid=45932&prmtipo=documentocomision (accessed on 19 March 2024).
10. Ministerio de Obras Públicas, Atlas del Agua Chile 2016. 2015. Available online: https://bibliotecadigital.ciren.cl/items/5f46898c-f9e5-4d97-936b-a1e9f0dcecde (accessed on 12 January 2024).
11. DOH, «Informe Final De Investigación Especial N° 446-2016 Dirección De Obras Portuarias Región De Aysén Del General Carlos Ibáñez Del Campo—Octubre 2016», Dirección de Obras Hidráulicas Región de Aysén del General Carlos Ibáñez del Campo, Report 446/2016, jul. 2016. Available online: https://www.dropbox.com/scl/fi/7ndzbgpz5cpde3x0v78qk/INFORME-FINAL-DE-INVESTIGACION-ESPECIAL-N-446-DE-2016.pdf?rlkey=mn6ad919sovhr3cc5r1ppuhl2&dl=0 (accessed on 19 March 2024).
12. Herrera-León, S.; Cruz, C.; Negrete, M.; Chacana, J.; Cisternas, L.A.; Kraslawski, A. Impact of seawater desalination and wastewater treatment on water stress levels and greenhouse gas emissions: The case of Chile. *Sci. Total Environ.* **2022**, *818*, 151853. [CrossRef] [PubMed]
13. Osorio, B.B. *Proyecto de Optimización de Planta de Ósmosis Inversa*; Universidad Austral de Chile: Valdivia, Chile, 2022.
14. Ritchie, H.; Roser, M.; Rosado, P. CO_2 and Greenhouse Gas Emissions. *Our World Data* **2020**. Available online: https://ourworldindata.org/co2-and-greenhouse-gas-emissions#article-citation (accessed on 11 February 2024).
15. UNESCO, Desalación de agua de mar mediante sistema Osmosis Inversa y Energía Fotovoltaica para provisión de agua potable en Isla Damas, Región de Coquimbo 2019. ISBN 978-92-9089-192-5 . Available online: https://unesdoc.unesco.org/ark:/48223/pf0000230987 (accessed on 25 January 2024).
16. Instituto Libertad. Las Energías Renovables No Convencionales En Chile, sep. 2018. Available online: https://www.senado.cl/appsenado/index.php?mo=transparencia&ac=doctoInformeAseso-ria&id=2613#:~:text=generaci%C3%B3n%20renovables%20no%20conventiona-les.,dependiendo%20su%20forma%20de%20explotaci%C3%B3n (accessed on 12 February 2024).
17. Radiación global horizontal–Región de Aysén del General Carlos Ibáñez del Campo. Available online: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://mma.gob.cl/wp-content/uploads/2019/05/politica-energetica-aysen-2050.pdf&ved=2ahUKEwjArtP61Z6KAxXtb_UHHXE_GDAQFnoECBIQAQ&usg=AOvVaw2cOOsUxd_ckMPfnD2K3rfZ (accessed on 13 January 2024).
18. Aravena, J.C.O. Laboratorio De Energías Renovables Para El Fomento De La Transición Energética Sostenible En La Región De Aysén. Master's Thesis, Universidad de Chile, Patagonia, Chile, 2017. [CrossRef]
19. Cabrera, E.; Estrela, T.; Lora, J. Pasado, presente y futuro de la desalación en España. *Ing. Agua* **2019**, *23*, 199. [CrossRef]
20. Enapac, la Planta Desalinizadora Sustentable Aprobada en Chile y más Grande de la Región, 27 de septiembre de 2018. Available online: https://www.emol.com/noticias/Economia/2018/09/27/922021/Enapac-la-planta-desalinizadora-sustentable-aprobada-en-Chile-y-mas-grande-de-la-region.html (accessed on 2 April 2024).
21. Gallegos, I.R.H. Análisis De Factibilidad Para La Instalación De Un Sistema De Energía Limpia Mediante Celdas Fotovoltaicas Para La Alimentación Eléctrica Del Edificio 4 En El Itslv. CIATEQ (Thesis), México 2017. Available online: https://ciateq.repositorioinstitucional.mx/jspui/bitstream/1020/97/1/HernandezGallegosRodolfo%20MMANAV%202017.pdf (accessed on 22 February 2024).
22. NAMA Chile. Índice de Precios de Sistemas Fotovoltaicos (FV) conectados a la red de distribución comercializados en Chile, versión 2019, NAMA Chile. 2019. Available online: http://www.minenergia.cl/archivos_bajar/2020/02/Factsheet_IP_FV_Final.pdf (accessed on 15 March 2024).
23. Burton, T. (Ed.) *Wind Energy: Handbook*; Wiley: Chichester, UK, 2009.
24. Explorador Eolico. Available online: https://eolico.minenergia.cl/exploracion (accessed on 19 December 2023).

25. Letcher, T.M. (Ed.) *Wind Energy Engineering: A Handbook for Onshore and Offshore Wind Turbines*, 2nd ed.; Academic Press: London, UK; San Diego, CA, USA; Cambridge, MA, USA, 2023.
26. Ramírez, Y.; Cisternas, L.A.; Kraslawski, A. Application of House of Quality in assessment of seawater pretreatment technologies. *J. Clean. Prod.* **2017**, *148*, 223–232. [CrossRef]