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Small-Scale Solar-Powered Desalination Plants: A Sustainable Alternative Water-Energy Nexus to Obtain Water for Chile's Coastal Areas

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Abstract: The natural potential of Chile—solar energy and 8 km of coastline—make the implementation of small-scale reverse osmosis desalination plants (RODPs) in coastal areas energetically supported with photovoltaic systems (PVs) feasible. This work considers a survey of the plants in Chile. As a demonstration of a RODP, a technical/economic evaluation is carried out, analyzing four possible cases in which different energy configurations are proposed: electric grid, diesel generator, and photovoltaic systems, without or with batteries. Finally, the challenges and opportunities of these plants are presented. The results obtained indicate that there are 39 plants in operation, which produce an average permeate water flow of Qp 1715 m^3d^{-1}. Solar Explorer, and Homer Pro software are used for a plant that generates 8 m^3day^{-1} of permeate water, resulting in the conclusion that Case 3 is the most economically viable, as it has a useful life of 20 years and will have an annual solar contribution of more than 65%. The levelized cost of water production is 0.56 $USDm^{-3}$ (RODP/PV) and 0.02 $USDkW^{-1}h^{-1}$ was obtained for the LCOE. Finally, this case contributes to the mitigation of climate change.

Keywords: Chilean coastal zone; desalination; Homer Pro; solar photovoltaic energy; water-energy nexus

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1. Introduction

Resolution 64/292 of 2010, issued by the United Nations General Assembly, recognized water as a fundamental human right. This resolution invited the community and their respective government agencies to double their efforts to provide sufficient, safe, accessible, and affordable water and water facilities to the community [1]. In that sense, there is a great challenge to meeting the needs of humanity. Currently, less than 3% of water in the world is used for direct use, and 97% of the existing water, which is a greater proportion, has a high salinity, which cannot be used directly (Figure 1).

Therefore, in times when the lack of water is a global concern, it is necessary to seek new sources of supply for human consumption, irrigation, and industry, among other uses, with desalination technology considered a suitable alternative [3]. Through this technology, permeated water and reject water are obtained, the latter containing high concentrations of salts and other minerals [4]. Consistent with the new times, where the aim is to mitigate greenhouse gases, desalination technologies should be energetically supported by solar energy, to reduce the carbon footprint due to the energy consumption they require. In 2022, the United Nations indicated that it is necessary to reduce the emissions of these gases by almost half, by 2030 and to reach zero by 2050; for this, it is necessary to invest in alternative energy sources that are clean, accessible, affordable, sustainable, and reliable, such as non-conventional renewable energies (NCREs); therefore, the water-energy nexus is essential to address [5]. It is worth mentioning that GHG emissions from seawater desalination plants using thermal energy, are much higher than those powered by photovoltaic energy [6].

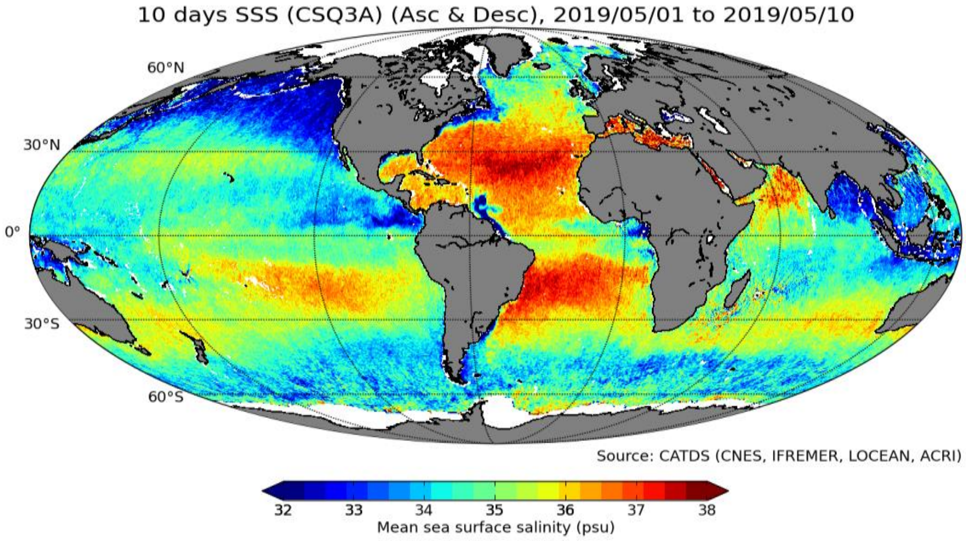

Figure 1. Salinity in the world. Source: [2].

A water-energy nexus approach is fundamental to reduce the negative externalities, with integrated planning, management, and governance of these resources [7]. Energy and water are vital elements in the security of states, socio-economic development, and sustainability of the planet. Energy production requires large volumes of water, and the infrastructure associated with water production and distribution requires large amounts of energy, mainly solar. Therefore, a detailed understanding of these interdependencies is critical to developing new technologies for water conservation and energy efficiency. Such interdependence and connection are known as the "nexus," which corresponds to the union of the issues addressed [8]. A large number of factors can affect the future of the water-energy nexus (WEN) [9], such as the water resource scarcity, energy availability, social demands, and the decisions on how to control the environmental impacts [10,11].

One of the first solar-powered reverse osmosis seawater desalination plants with a production capacity of 60,000 m^3d^{-1} was implemented in Saudi Arabia, in 2017, under the name Al Khafji (The first case to implement the water-energy nexus). It is important to note that this region has little freshwater resources worldwide, but is favored by high levels of solar radiation with yearly values of 2200 $kWhm^{-2}$ and extended daylight hours, which make it favorable for the production of renewable energy [12]. In terms of solar energy and the shortage of the water supply, these conditions resemble those found in northern Chile. There are also smaller plants, such as in Brazil, where it was proposed through the "Programa Agua Dulce" to increase the number of desalination plants powered by renewable energy and brackish water, in remote areas for low-income communities, considering the solar potential in the country's northern regions [13]. Notable is the fact that these plants are predominantly brackish-water plants. In Indonesia, a technical and economic study of a seawater PV-RO plant was completed. The levelized cost of water production utilizing this plant was roughly 9.0 $USDm^{-3}$, making it more cost-effective than the region's existing cost of drinking water. The plant has a capacity of 11.06 m^3d^{-1}, with a usable life of 25 years and an annual solar input of 84% [14].

In Chile, through different government initiatives, projects have been implemented to promote the use of renewable energies, to produce water for human use. At the COP25 water roundtable, it was recommended to study the development of techniques for the use of seawater, such as desalination for agricultural crops, mining, and drinking water for communities [15]. Chile has great natural resources; a great solar resource worldwide, as well as strong winds from the north to south, a wide coastline, and a geothermal resource from the Andes Mountains, which allow the development of technologies, based on non-conventional renewable energies, such as photovoltaic solar energy, wind energy, thermal energy, tidal, and geothermal energy [16]. Additionally, Chile is also considered a privileged country, with respect to the availability of water resources [17]; it has 76,407 km^2 of fresh water (between the glacier surface, north/south ice fields, lakes and lagoons, etc.), 8000 km of coastline, and 3,934,936 km^2 of maritime jurisdictional spaces [18]. The water shortage that has occurred in recent years is of particular concern. Despite being a country with an extensive coastline, there is a significant water crisis, which has led to the enactment of 10 decrees by the Ministerio de Obras Públicas (MOP) of Chile, in the year 2022. These documents declare that the area between the Atacama and the Aysén regions, are water scarcity zones, which, as of June 2022, correspond to the following affected regions: Coquimbo (4), the Metropolitan Region (1, 2, 3, 7, 8), Valparaíso (6, 9, 10), and Los Ríos (5), covering 79,214 km^2 and affecting 3,944,202 people who live in the rural areas [19].

In response to this issue, through the MOP's Rural Drinking Water Program (APR), community organizations can access drinking water services in quantity, quality, and continuity, following the current regulations [20]. The community can apply to the Subsecretaria de Pesca y Acuicultura (SUBPESCA) for projects. These projects are based on implementing desalination plants supported by photovoltaic solar energy. In Chile, there are 461 coastal communities that require technical and financial assistance for the conservation and sustainability of their fishing resources [21], and have water available for their basic services. According to Herrera-León, 2022, by 2015, a total of 2.51 m^3s^{-1} permeated water was produced through reverse osmosis desalination plants. However, this resulted in the generation of maximum greenhouse gas emissions of 253,782 tCO_2-eqyear^{-1}. For 2030, the same author considers a projected total desalinated water requirement of 11.25 m^3s^{-1}, producing 425,842 tCO_2-eqyear^{-1} [22].

Considering the above, through this work, it is expected to evaluate the water-energy nexus of small-scale desalination plants, supported by photovoltaic solar energy, as an alternative for sustainable development in the coastal areas of Chile. In addition, it addresses the lack of legislation and/or regulations that apply to both desalination plants and the waste products they produce, in order to contribute to the current public policies regarding water governance in Chile, through a comparison with other countries that produce permeated water.

This article is divided into five sections, which consider the methodology and existing desalination technologies. It also analyzes the water-energy nexus, a reverse osmosis (RO) desalination technology, and a photovoltaic (PV) system. Subsequently, small-scale desalination plants around the world are reported, considering the applicable regulatory framework and the costs, according to the specific energy consumption (SEC). In addition, a cadaster of small-scale desalination plants on the coasts of Chile is reported. Subsequently, through a technical-economic projection, an analysis of four cases is carried out, where different energy configurations are evaluated (electric grid (EG), diesel generator (DG), photovoltaic system (PV) without/with battery) that allow for sustaining the RODP, visualizing the potential, in terms of production and costs, and the environmental impact that this type of energization could have on the environment. It is worth mentioning that through this documentary study, it will be possible to identify the barriers and opportunities related to the effect produced on the population, considering the use of the water-energy nexus in coastal areas. Finally, the main conclusions and comments on the development of this article are presented.

2. Methods

The methodology used has a set of analysis schemes detailed below (Figure 2). Section 1 presents the water-energy nexus, considering the governance and macro-micro levels applicable to the desalination technology and a PV. Section 2 presents the main desalination technologies around the world, supported by solar PV, as well as some calculations relevant to this study. Section 3 reports the small-scale desalination plants in Chile and around the world, considering the applicable regulatory framework and the costs according to the specific energy consumption (SEC). Section 4 presents the results of a survey of the desalination plants in the coastal areas of Chile, through the review of multiple records and databases available at the Environmental Assessment Service, SEA [23], and the journalistic information issued by public and private organizations. Subsequently, an economic analysis of a reverse osmosis desalination plant (ROPD) that produces drinking water on a small scale is carried out. For this purpose, it is evaluated through four cases with different energy configurations, *Case 1: Electrical Grid; Case 2: Diesel Generator; Case 3: Photovoltaic system without battery; Case 4: Photovoltaic system with battery*, that allow for sustaining the plant. The following aspects are considered: costs and energy conditions through a technical-economic analysis, using the software Solar Explorer [24] and Homer Pro [25], allowing to simulate the engineering and economic feasibility of the microgrids or distributed energy systems that are off-grid or connected to an unreliable grid, considering the design of lower cost energy and electrical systems, as well as the risk mitigation.

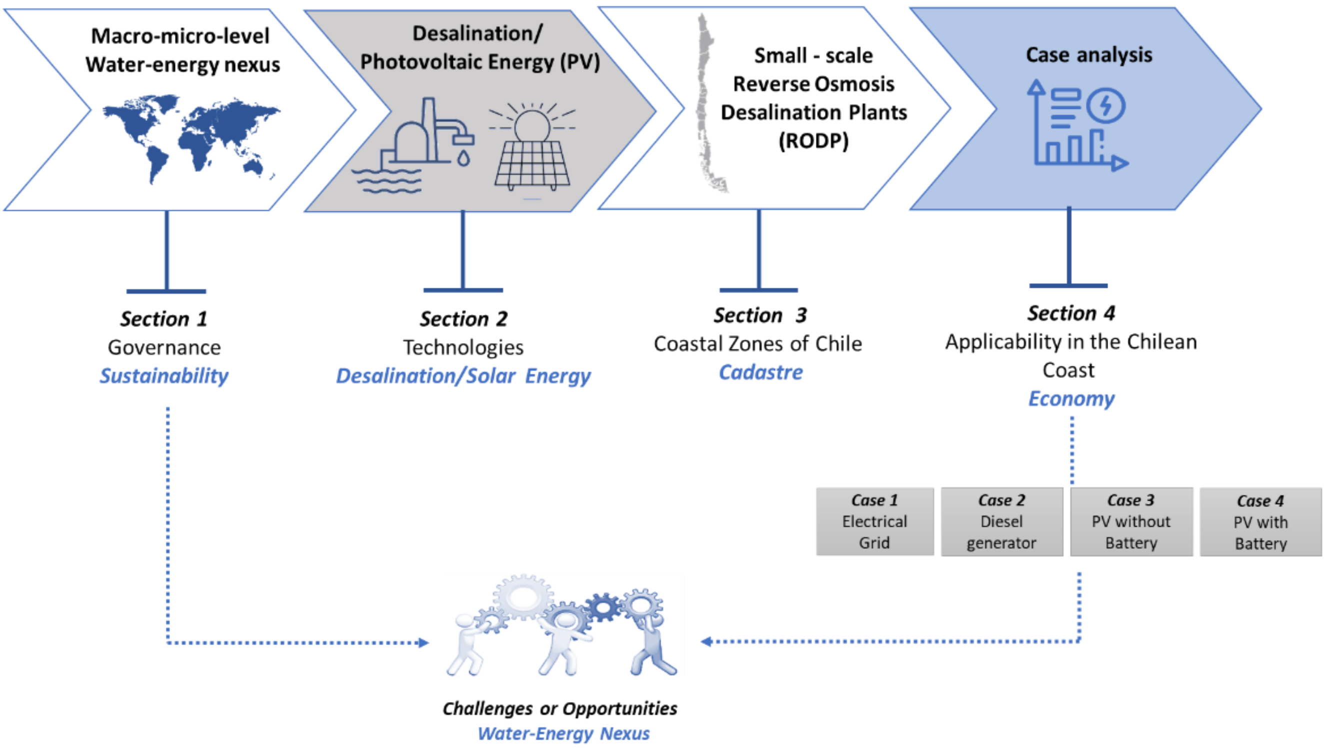

Figure 2. Methodology applied to the desalination plants cadaster, that apply to the water-energy nexus in Chile. (author's elaboration).

Finally, this method allows for evaluating the impact of the water-energy nexus applied to the coastal areas of Chile, thus identifying the existing challenges and opportunities and considering the installation of these small-scale plants in the coastal areas of Chile, supported by solar energy.

3. Water-Energy Nexus: Desalination Technology/Photovoltaic System

The interconnection between water and energy, known as the water-energy nexus (WEN), is a very relevant relationship for planning, as well as understanding the use of water and energy, both politically and technologically. Likewise, it also assists in the sustainability of the use of these vital resources [9,26]. Approximately 1.3 billion people do not have access to electricity, and 750 million people lack a source of safe drinking water [27]. According to the OECD, the energy sector needs 15% of the world's freshwater, and in Latin America, due to the increase in electric power, the need for water will triple by 2060 [26,27]. Most energy sources require water in the process of power generation. In addition, energy is required for the water collection, treatment, transport, and distribution.

For the generation of *water for energy as energy for water*, it is essential to consider that, in order to generate opportunities and solutions to water-energy problems, it is necessary to have a stronger interaction and agreements between governors and the people governed, aiming to elaborate the regulations that allow for generating changes in policies at a regional/national/global level, which would help to have a more equitable availability of these resources. They would also make it possible to regulate the production prices and costs related to implementing new technologies for an ampler distribution and availability to the community.

The United Nations World Water Development Reports and United Nations Development Program with "**The Value of Water**" and "**Water Governance**" respectively, indicate that, in the first report, "*recognizing, quantifying, and expressing the value of water and incorporating it into decision-making is fundamental to achieving sustainable and equitable water resources management and the SDGs of the 2030 Agenda*," and in the second, "*it is the systems of governance and administration that determine who gets a particular kind of water, when and in what way, and decide who is entitled to access to water and related services*". These systems are therefore not limited to "governments" alone but include local public authorities, the private sector, and civil society. In this sense, actions will be required that consider the following challenges [28,29]:

- Implementation of integrated approaches to water management at local, national, and global levels, always considering participatory decision-making;
- Providing safe drinking water in a manner that is affordable, accountable, and economically and environmentally sustainable, thus ensuring hygiene and sanitation services;
- Ensuring that regulations governing the distribution and disposal of water resources are always in place. Considering that the performance of public authorities is responsible for their sustainability over time;
- Strengthening the development of the skills and knowledge transfer.

Macro-micro levels applicable to the water (desalination)-energy (solar energy) nexus.

Regarding the preceding, we must ask ourselves:

Why should the water-energy nexus be considered for desalination plants that use solar energy?

The governance of the water-energy nexus is fundamental for countries to access these resources, which are so precious today. Water is considered the "*liquid gold of the planet*", essential for direct uses, such as irrigation, human consumption, industry, and indirect use to produce electricity. Desalination is a technology that allows for obtaining this vital element. In some parts of the world, combining renewable energy sources with the desalination technology is a cost-effective way of generating fresh water [30]. The most widely used technologies are solar photovoltaic energy and reverse osmosis desalination, which has the great potential to improve water sources in arid, semi-arid, and coastal areas, among others. Almost 1% of water desalination technology is powered by renewable energy [31].

The assessment of the nexus management is based on the use of seawater as the initial input that feeds the desalination plant. Two levels allow us to promote this interrelationship (Figure 3). First, the macro level, which includes the key actors for understanding the political, technological, social, economic, and environmental dimensions that intervene and influence the installation of a desalination plant supported by solar photovoltaic energy. In this sense, it is crucial to make an identification of the various factors, such as [32]:

- *Actors*: correspond to a social/community organization, a NGO, an association, a private company, a governmental institution (ministries/governments/municipalities), a university, among others, that participate in the nexus;
- *Geographical scale*: corresponds to the local urban-rural, regional, national, or global scope. In other words, it indicates the locality to which the stakeholder belongs;

- *Importance of the stakeholder participation*: In order to achieve the goals of a project involving the water-energy nexus, it must be determined whether the stakeholder will be considered throughout the process and how its intervention will be realized;
- *Work of the water-energy nexus*: this refers to the influence on the direct use, administrative, and regulatory functions, among others, of the components of the nexus.

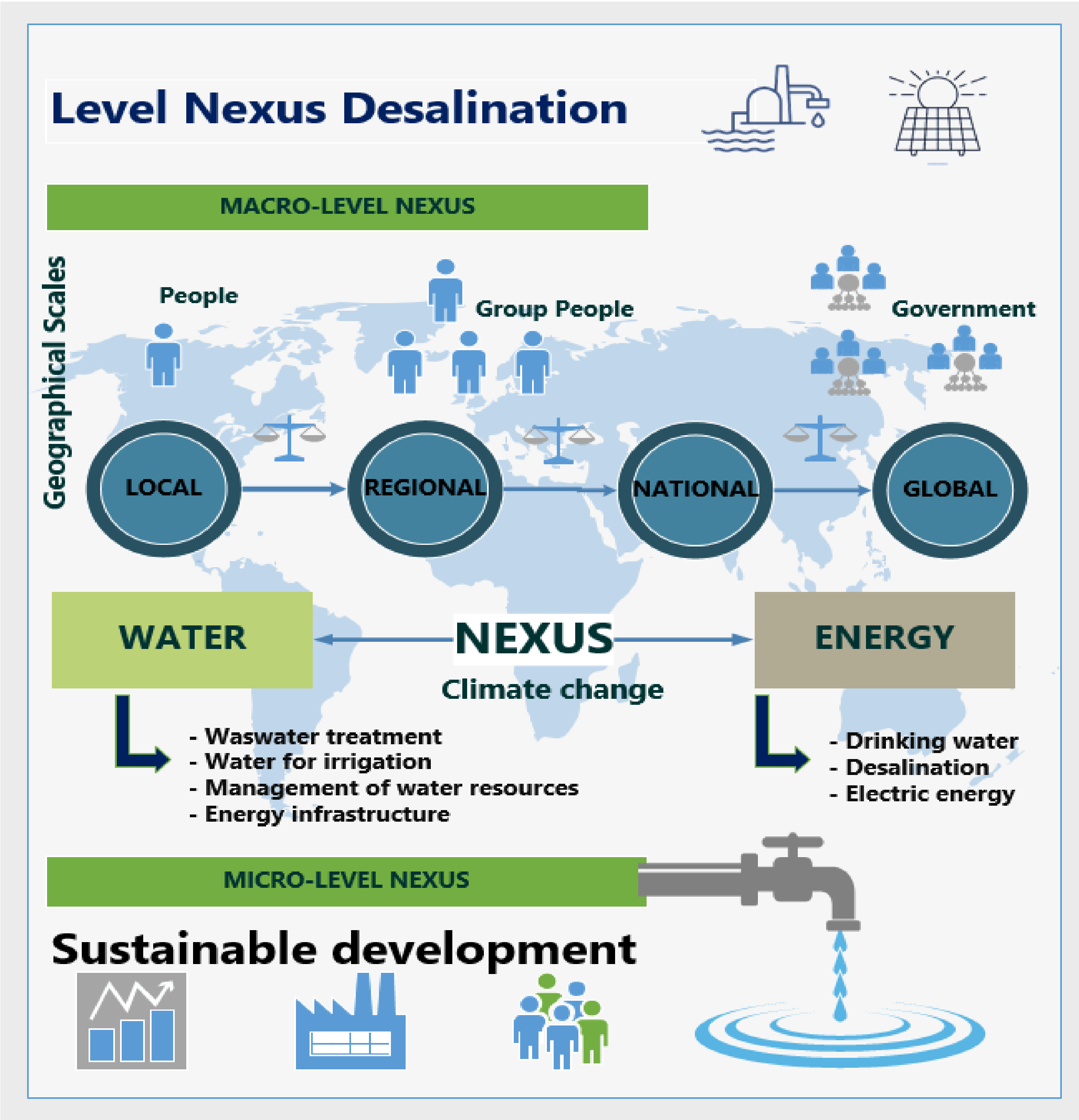

Figure 3. Macro-micro levels of the water-energy nexus, considering desalination (author's elaboration).

In addition, it should be considered that at the macro level, once the actor and its geographic location have been evaluated, this type of nexus can be determined. For this, there are several uses or applications of the water produced by the desalination process, such as reusing wastewater (brine), obtaining water for human consumption, water for irrigation, water for industrial processes, and for obtaining electricity.

At the micro level, applying suitable technologies, such as desalination-photovoltaics, can contribute to avoiding environmental deterioration, improve the quality of life of the communities, and to have a more significant social and economic benefit, which leads to the sustainable development by applying this water-energy nexus.

The following is a description of some key concepts of desalination and solar photovoltaic energy, which make up the nexus and together affect the design and implementation of a desalination plant supported by photovoltaic panels.

3.1. Conventional Desalination Technologies

Desalination is a technique that requires the removal of salt from seawater or brackish water, to obtain a resource suitable for human consumption, irrigation, or industrial uses. It is a technique that can significantly increase non-conventional water resources and solve the high demand for water [33,34]. From desalination, two products are obtained; first, a permeated water with a salt content of less than 500 mgL^{-1} from seawater (with a salt content in the order of 35,000 mgL^{-1}) or brackish water (with a salt content between 3000 and 25,000 mgL^{-1}), and second, a concentrated solution, known as ***brine***. Furthermore, it is classified, according to the technology, for desalination or feed water source [35]. There are several technologies currently developed to desalinate seawater. Although they have different characteristics, according to the type of energy, design, and production that each one requires, they all have the same objective: to reduce the concentration of dissolved salts in seawater or brackish water; this allows for distinguishing between processes that separate water from saltwater and those that perform the separation of salts from the solution, i.e., saltwater [36]. Table 1 below classifies the desalination processes.

The RO process is the most widely used worldwide. This process, through mechanical pressure, counteracts the natural osmotic pressure, causing water to flow from the area with the highest concentration of salts to the area with the lowest concentration, until pure water is obtained. Therefore, the higher the salinity of the water, the higher the osmotic pressure required to overcome it. For seawater desalination, a reverse osmosis plant consists of a seawater intake, followed by a physical and chemical pretreatment system, consisting of sand filters and activated carbon filters (physical); dosing (chemical) to regulate the pH of the feed water; and the addition of anti-scalants to prevent salt deposits on the membranes (Figure 4); and the reverse osmosis membrane racks to remove salts [36].

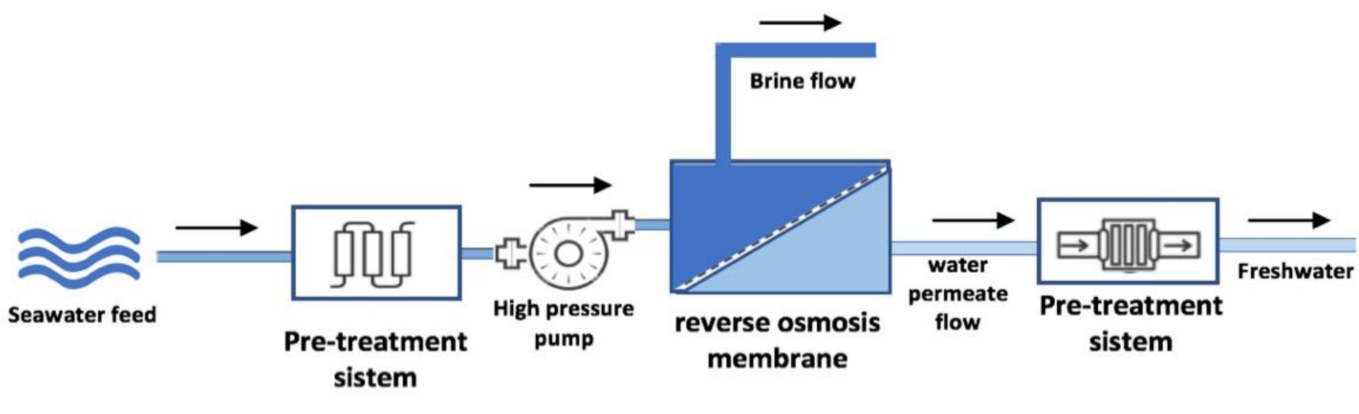

Figure 4. Reverse osmosis plant schematic diagram. (author's elaboration).

Table 1. Classification of the desalination process. Source: [31,35,37–40].

Type of Process	Technology	Key Influential Parameter	Main Remarks	Energy Type	Energy Used kWhm^{-3}
Filtration	Electrodialysis (ED)	- Temperature and flow rate of the feed flow - Applied voltage - Initial feed composition - Membrane characteristics	- The ED process produces fresh water using electrical energy that ionizes the solution and salt ions that permeate through the membrane.	Electric	5.5
	Forward Osmosis (FO)	- Draw solution velocity - Membrane properties - Temperature of the draw solution - Osmotic pressure difference - Feed solution velocity	- FO uses the natural energy of osmotic pressure to separate water from dissolved solutes, through a semipermeable membrane. - Osmotic pressure is used to transport water across the membrane while retaining all dissolved solutes on the other side. - Concentration polarization and fouling are two main problems of the FO process. - The MD process is a hybrid membrane/thermal process that only allows for water vapor to permeate through the membrane, due to the hydrophobic characteristics of its membrane.	Electric	0.5
	Membrane Distillation (MD)	- Feed flow temperature - Mass flow rates - Module geometric parameters - Membrane properties	- Based on the water vapor collection method, MD modules are divided into four main categories: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD), and scavenged gas membrane distillation (SGMD). - Membrane wetting/fouling and temperature/concentration polarizations are the main problems in the MD desalination processes. - The required energy can be effectively supplied by solar energy.	Thermal	0.75

Table 1. *Cont.*

Type of Process	Technology	Key Influential Parameter	Main Remarks	Energy Type	Energy Used $kWhm^{-3}$
Thermal	Reverse Osmosis (RO)	- Temperature and flow rate of the feed flow - Applied voltage - Initial feed composition - Membrane characteristics - Feed pressure - Salt concentration of the feed flow	- Reverse osmosis is a water purification process driven by pressure, overcoming the osmotic pressure and obtaining fresh water, using a partially permeable membrane. - Although the reverse osmosis method is an energy-intensive desalination process, this technology is the most widely used worldwide, due to its high efficiency and comparatively low cost.	Electric	8.2
	Multistage Stage Flash (MSF) Distillation	- Top brine temperature - Number of stages - Temperature drop in each stage - Brine temperatures at the inlets and outlets	- In the MSF process, feed seawater is pressurized, heated, and discharged into a chamber with a slightly lower water saturation vapor pressure. A fraction of this water then turns to steam and condenses on the outer surface of the heat transfer pipe. - The temperature of each stage is kept below the saturation temperature of the water entering each stage, and mainly vacuum pressure is applied for this purpose.	Thermal	5.2
	Solar Still (SS)	- Solar intensity - Water depth - 4.71 Lm^{-2} of daily productivity - These solar stills can be further researched for commercialization, in order to achieve a faster penetration of this technology in society.	- Solar still uses direct solar radiation to desalinate saline water from the evaporation and condensation process. - It is mainly divided into active and passive categories. - Despite the low efficiency/productivity of fresh water, solar distillation technology is simple and suitable for remote areas.	Thermal	-

Table 1. *Cont.*

Type of Process	Technology	Key Influential Parameter	Main Remarks	Energy Type	Energy Used $kWhm^{-3}$
	HDH	- Mass flow ratio of the water to air - Top temperature of the cycle - Packing materials	- HDH is a desalination technology that mimics the natural rain cycle. - In the humidifier, water is sprayed into the air and then condenses into fresh water as it passes through the dehumidifier. - There are several configurations, depending on the heated fluid (water and/or air) and the type of fluid circulation (open or closed cycles). - Low temperature heat sources are used, such as solar energy and waste heat.	Electric	0.3
	MED	- Efficiency is higher, as the performance ratio is directly proportional to the number of effects, compared to MSF - Suitable for connecting to renewable energy resources that supply intermittent power - Has a high efficiency, simple operation, maintenance and economical features feasible, compared to MSF - Can work at a temperature lower than 70 °C	- In MED technology, seawater is preheated and then heated to evaporate in the first effect or steam evaporated. - Seawater that is not evaporated in the first effect, is fed into the second effect, where it is heated with steam from the first effect and evaporated further, and the process is repeated in subsequent effects at a reduced pressure and temperature.	Electric/Thermal	5.5–9

3.1.1. Brines

Desalination is a technique to address the problem of water shortages. However, it presents a disadvantage common to all applied techniques: obtaining a concentrated stream (brine) [41]. Brine is a product of the desalination processes [42], it is usually more saline than seawater (1.5 to 2.5 times) or brackish, it presents a temperature higher than that from the environment, and reflects most of its chemical constituents [43]. The main components of brine include, magnesium, sodium, potassium, calcium, chloride, sulfate, total dissolved solids, among other compounds [44]. The disposal of brine can potentially have a negative effect on the environment, degrading the physical, chemical, and biological characteristics of the receiving body [45,46]. These waters present temperature, density, and salinity values higher than the average level of the oceans. Furthermore, among the physical properties of brine, salinity and temperature are the most studied because they can affect the marine ecosystems. Generally, brine resulting from the reverse osmosis desalination processes can reach values of up to twice that of seawater (35,000 mgL^{-1}) [47]. Brine disposal depends on the location of the plant, the type of desalination plant, and the associated costs involved in its disposal. Among the available methods, there are alternatives, such as: *i. Injection of deep wells; ii. Discharge into surface water bodies; iii. Irrigation of high salinity tolerant plants; iv. Beneficial reuse of brine; v. Zero Liquid Discharge; vi. among others* [46]. The most commonly used method of these alternatives is seawater discharge, with 41% [3].

3.1.2. Desalination Plants and Their Impact on the Environment

Among the environmental aspects caused by desalination plants, a distinction can be made [48–50]:

Positive environmental aspects

i. Generates a water product, a relief for communities living in arid or semi-arid areas, that require water for irrigation, considering that 70% of the water in the world is used in agriculture;
ii. Provides available water for human consumption and sanitation. Considering that, according to the World Health Organization (WHO), a person requires 100 L of water per day to meet their basic needs. The current world population is approximately 7.9 billion people in the world;
iii. There would be fewer greenhouse gases if the desalination plants were electrically supported with solar photovoltaic energy. Seawater treatment plants do not generate a significant volume of pollutants. The problem is due to the higher energy consumption; the excess energy consumed can transform fossil fuels into CO_2, SO_x, NO_x, and other suspended particles;
iv. Generate a lower environmental impact if the brine is reused in agriculture, such as in the cultivation of halophyte plants or for aquaculture shrimp farming, among other uses;
v. Allows the brine to be used, extracting the chemical elements, such as Cu, Na, K, Mg, among others;
vi. When brine management and treatment are not intended to produce fresh water but to have a permeated water that is generally not required to meet drinking water quality. As a result, brine treatments can be more affordable and suitable for the end use.

Negative environmental aspects

A saline residue is generated that is environmentally damaging, considering that currently, 58% of reverse osmosis desalination is used worldwide, providing approximately 50% of the permeated water available for human consumption and irrigation. Nevertheless, the other 50% of the saline waste generated, causes more environmental pollution than benefits. The situation could change if countries were to generate updated environmental norms or regulations, considering that climate change is a global problem.

i. The desalination process consumes considerable energy, resulting from the use of fossil fuel energy sources, causing considerable greenhouse gas emissions and affecting the environment;
ii. Another problem with desalination plants is the impact generated by the brine when it is directly disposed of in marine systems, which causes alterations such as:
    - Water inlets for processing in desalination plants can trap marine organisms, affecting marine fauna and flora;
    - The outfalls of liquid waste from the desalination plants are channeled directly into the sea, causing high seawater temperatures and salinity;
    - Chemicals used for corrosion prevention, water pretreatment, and water cleaning are also disposed of through marine outfalls.

3.1.3. Calculations for the Desalination Plants

The desalination process produces a permeated water, concentrated water, and brine (Figure 5). In this process, it is possible to estimate and know the brine quantities produced by the plant for final disposal. The amount depends on factors, such as the type of technology used, and the water feed, among other factors.

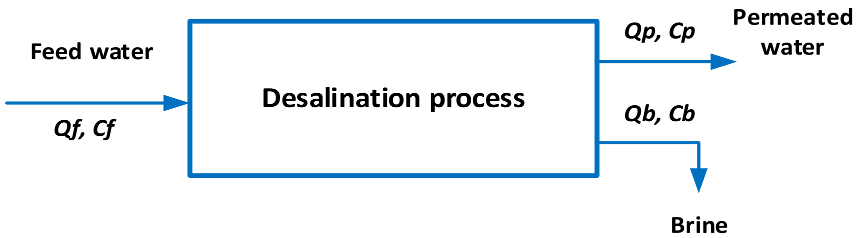

Figure 5. Desalination process diagram (author's elaboration).

The waters that participate in this type of desalination process are i. *Feed water*: a solution that enters the desalination system to be treated, it can be brackish or seawater (Qf) and is pressurized, with a solute concentration Cf; ii. *Permeated water*: water that passes through the membrane and is collected (Qp) with a solute concentration Cp, but requires adjustment to be potable or for irrigation use; and iii. *Brine*: a solution that does not pass through the membrane (Qb) and is enriched with the rejected highly saline solute (brine, Cb). Considering the waters described above and involved in the calculation of the desalination processes (Table 2), they are described below:

Table 2. Desalination process estimates. Source: [51].

Item	Equation	Definition
Charge balance (Qf)	Qf = Qp + Qb (1)	Corresponds to the production of permeated water plus reject water, in proportions of 50% and 50%, respectively, in the case of reverse osmosis.
Rejection factor (R)	R = (Cf − Cp)/Cf × 100 (2)	Corresponds to the rejection of salts from the membranes and in a membrane system, it is the factor that determines the final quality of the permeated water of a distillation system.
Salt passage (SP)	SP (%) = 100 − R (3)	It corresponds to the ratio between the salt concentration of the product and the feed, measured as a percentage.
Conversion (Y)	Y (%) = Qp/Qf ∗ 100 (4)	It corresponds to the percentage ratio between the permeated flow rate and the water flow rate entering the desalination process.
Concentration factor (CF)	CF = 100/(100 − Y) (5)	Corresponds to the number of times the brine is concentrated with respect to the feed water.

3.2. Solar Energy

Solar energy is the energy that comes from the sun; it is a type of non-conventional renewable energy (NCRE), where the sun's radiation can be used for photovoltaic conversion, to obtain electricity. In photovoltaic technology, global solar radiation is directly converted into electricity by the photoelectric effect [52]. A PV system is composed of panels or modules, which may be fixed or tracked, a control and power conditioning system, and sometimes an energy storage system (batteries), and may or may not be connected to the grid.

The inclusion of renewable energies in desalination garners significant interest, since it can cut energy expenditures by 60% of the specific energy consumption of reverse osmosis [53].

To determine how much PV capacity a RODP requires, the calculations below must be performed:

3.2.1. Calculation of the Solar Peak Hour (SPH)

The SPH equates to a theoretical period of time, equal to the hours during which the sun produces the greatest amount of irradiance on a specific surface. One SPH is equal to one $kWhm^{-2}$, meaning that it is the energy received from the sun, packaged into one-hour increments, with each "package" getting 1000 Whm^{-2} [54].

$$\text{SPH year} = \frac{\text{H}}{\text{Istc}} \tag{6}$$

where: H: the average daily solar radiation of the studied site, $kWhm^{-2}$, Wh; SPH: solar peak hour, h; Istc: solar irradiance, 1 kWm^{-2}.

3.2.2. Calculating the Number of Photovoltaic Panels and Batteries

To determine the energy demand of a RODP through a photovoltaic (PV) system with storage batteries, a charge regulator, and an inverter. To assure the adequate amount of energy for the plant's proper operation, the following equation will be used [55]:

$$\text{Number of panels} = \frac{\text{TE}}{\text{Ppeak, panel} * \eta\text{inverter} * \text{SPH}} \tag{7}$$

where: TE: total energy demanded, Whd^{-1}; SPH: solar peak hour, h; Ppeak, panel: power generated by the selected solar module, in W; ηinverter: inverter efficiency, in %.

Once the number of solar panels to be utilized in the desalination system has been identified, the number of batteries necessary for the correct storage of the generated energy may be computed. This is achieved by Equations (8) and (9) [55].

$$\text{Ahr} = \frac{\text{TE}}{\text{Fe} * \text{Vs}} \tag{8}$$

where: Ahr: average daily capacity, Ah; TE: total energy demand, Wh; Vs: output voltage depending on the panel connection; Fe: efficiency factor = 0.9.

$$\text{N}^\circ \text{ of batteries} = \frac{\text{Ahr} * \text{DA}}{\text{Ldes} * \text{Pdes}} \tag{9}$$

where: Ldes: battery voltage discharge limit, Ah; DA: days of autonomy, in days; Pdes: battery depth of discharge, in %.

3.2.3. Load Controller Calculation

For the safety of the equipment, such as the inverter, batteries, and photovoltaic panels, it is important to determine the minimum current capacity of the charge regulator, which is calculated by Equation (10) [55]:

$$\mathrm{Ic} = \mathrm{Is} * \mathrm{Fs} \tag{10}$$

where: Ic: is the controller current, A; Is: the output current depending on the connection of the panels; and Fs: is the safety factor.

3.2.4. Current Inverter Calculation

To ensure the appropriate operation, the power given to the power inverter must be adequate to support the power consumed by the pump, the charge controller, and the sensors. The inverter's capacity is computed using Equation (11) [55].

$$\mathrm{PI} = \mathrm{PT} * \mathrm{Fs} \tag{11}$$

where: PI: current inverter power, W; PT: total power demand, W; Fs: safety factor, 2.

3.2.5. Homer Pro

Homer Pro is software that can simulate the engineering and economic feasibility of the microgrids or the distributed energy systems that are off-grid or connected to an unreliable grid, as well as to build the least expensive energy and power systems and risk mitigation techniques [25]. Users can create standalone and networked systems to examine the performance, based on the technology feasibility and resource availability, as well as use the software's knowledge on the most cost-effective combination of conventional and renewable energy, storage, and grid resources (where available). Homer Pro, moreover, takes the given system configuration, the capital and the maintenance costs of the various system components, and the size of each component into account, in order to maximize the net capital cost of the overall system, while satisfying the load requirements [25]. In order to initiate a simulation with Homer Pro, a baseline system architecture is required, depending on the case study.

3.3. Calculations Applicable to the Desalination-Photovoltaic Nexus

3.3.1. Calculation of the Osmotic Pressure in the Desalination

The RO process of saline water involves the separation or filtration by semi-permeable membranes, where the feed water is pressurized to overcome the osmotic pressure. The membrane allows the feed water to be separated into two streams: desalinated or permeated water, which contains between 1% and 15% of its initial salt content; and the brine stream, which is rejected at a high pressure. In the reverse osmosis desalination, the pressure ranges from 54.281 to 78.954 atm (797 to 1160 psi), depending on the salt concentration, feed water temperature, and membrane type [56].

The osmotic pressure of a solution can be calculated by the Van't Hoff equation (Equation (12)):

$$\mathrm{Op} = \mathrm{i} * \mathrm{M} * \mathrm{R} * \mathrm{T} \tag{12}$$

where: Op: osmotic pressure is expressed in units of atm; i: the factor of the Van't Hoff, expressed as the degree of dissociation of the solute; M: molar concentration of the solution, expressed in mol L^{-1}; R: gas constant, equal to 0.082 $atmL^{-1}mol^{-1}K^{-1}$; T: temperature, expressed in K.

3.3.2. Calculation of the Energy for Desalination

The formula used by Estevan and Garcia, 2007, for small-scale plants, can be applied to this estimation. Considering that a solution's osmotic pressure (Op) corresponds to the pressure necessary to start the RO process. Furthermore, the minimum energy required to extract 1 m^3 of permeated water (Wmin) from a solution by an ideal RO device, will be according to Equation (13) [56]:

$$\text{Wmin} = 0.02815 * \text{Op} \quad (13)$$

where, Wmin: minimum energy required to extract 1 m^3 of permeated water, kWh; Op: osmotic pressure feed solution, atmm^{-3}; 0.02815 conversion factor kWhatm^{-1}m^{-3}.

3.3.3. Specific Energy Consumption for the RO Process

The specific energy consumption (SEC), defined as the ratio of the freshwater yield to the electrical energy input, is expressed in kWh per m^3 of permeable water [57]. For the desalination, according to Delgado-Torres and Garcia-Rodriguez, 2022, "*the daily freshwater production from a given power generation profile, depends on the rated capacity and the specific energy consumption (SEC)*" [58]. Therefore, the SEC allows for evaluating the performance of the membrane desalination process and the contributions of the different sections of the plant, such as the high-pressure pumps, reverse osmosis membrane trains, and energy recovery devices, among others [59]. The calculation can be performed using the following equation:

$$\text{SEC} = \frac{\text{Wtotal}}{\text{Qp}} \quad (14)$$

where, Qp: total permeated flow rate; Wtotal : sum of the losses of each component of the system, kWhm^{-3}. SECf membrane filtration resistance; SECr friction losses, retentate; SECp friction losses, permeated; SECmin osmotic pressure; SECcp concentration polarization, and SECinef pump and ERD inefficiency, for further details review [59].

As an illustration of the losses associated with the RO process for sea water, according to Karabelas et al. (2018), the SECtotal for this type of facility would be:

$$\text{SECtotal} = \text{SECf} + \text{SECr} + \text{SECp} + \text{SECmin} + \text{SECcp} + \text{SECinef} =$$

$$0.574 + 0.057 + 0.0012 + 1.200 + 0.057 + 0.485 = 2.374 \text{ kWhm}^{-3}$$

4. Worldwide Desalination and the Chilean Desalination Program

Globally, as of 2019, there were 15,906 desalination plants in operation, producing 95 million m^3d^{-1} of desalinated water for human use, with 48% of their production concentrated in the Middle East and North African region. The desalination plants in Figure 6 produce over 90% of the world's desalinated water, considering large plants, 10,000 m^3d^{-1} operating with different feedwater sources and technologies [60]. In South America, Chile is one of the countries that currently has 85 medium and small-scale desalination plants throughout the territory, providing permeated water for sectors, such as mining (22%), sanitary (15%), thermoelectric (6%), among others (Figure 7), with rural drinking water as the sector with the most plants (49%). Regarding the total number of existing plants at the national level, 91.76% use reverse osmosis technology, 3.53% correspond to the mechanical vapor compression (MVC) technology, 1.18% to PV, and for 3.53%, there is no information available, concerning the technology used [61].

Currently, the use of seawater from the desalination plants for the production of desalinated water, in the mining industry, for example, has an additional cost to the conventional value of the water produced by the sanitary plants (fresh water), which causes a narrow margin between the price of the product and the operating costs. Additionally, the cost of supplying water at high altitudes must be added to this cost. When comparing the price of freshwater vs. desalinated water at 4000 m in altitude, there is a difference of 1000% in their costs, considering that the value of fresh water is about USD 0.4 m^{-3}, compared to USD 4.0 m^{-3} for desalinated water obtained by the desalination process [62].

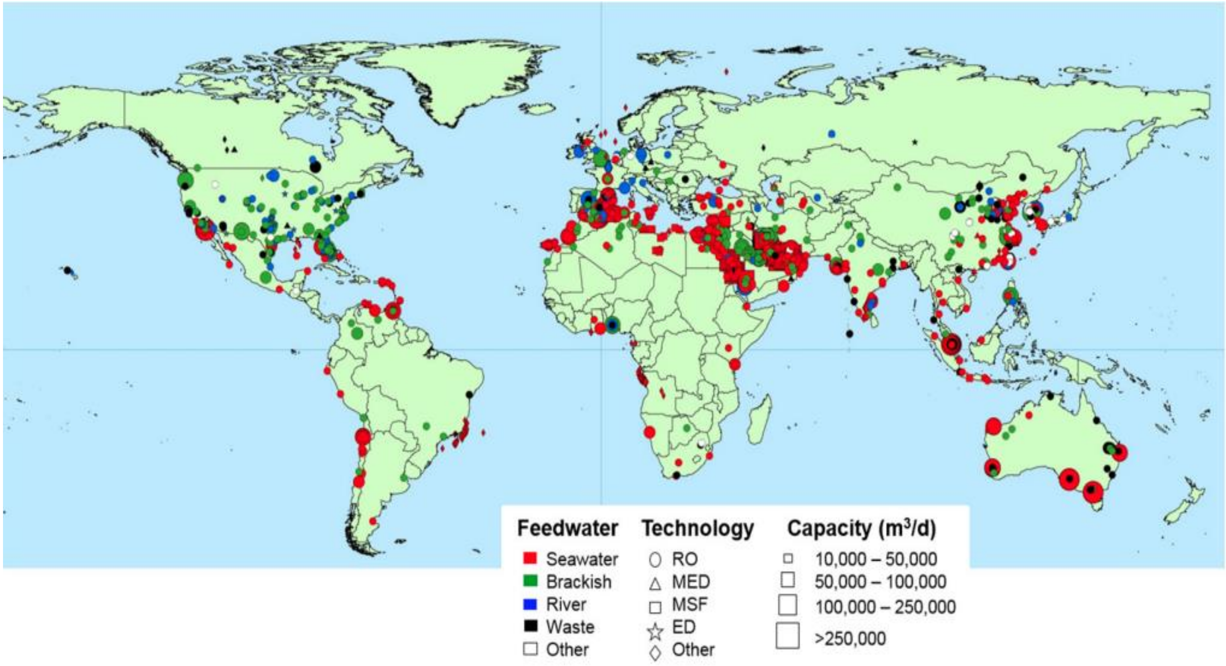

Figure 6. Desalination plants worldwide 2020. Source: © Elsevier [60].

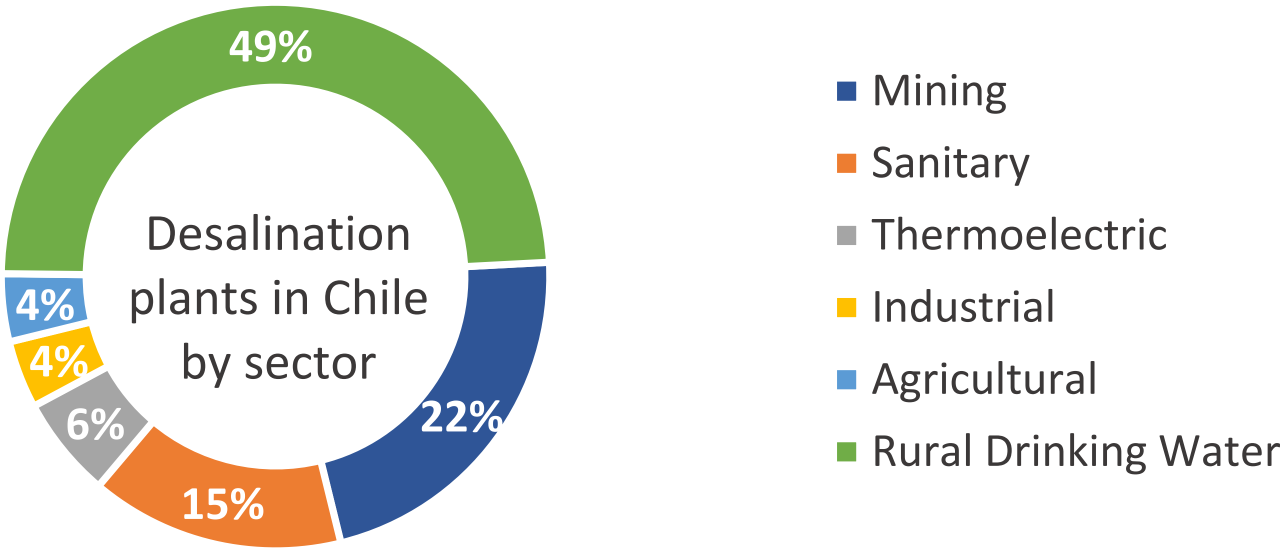

Figure 7. Percentage of the desalination plants in Chile by sector, 2020. Source: [61].

4.1. Solar Potential Worldwide and in Chile

The greatest solar potential in the world is found in North America, areas in Africa, Oceania, parts of Asia, and markedly in Chile, specifically in the Atacama Desert, with an average solar radiation of 2957 kWh $m^{-2}year^{-2}$ (Figure 8), representing an opportunity to use this energy for different technologies, such as photovoltaic, solar thermal technologies, and solar water treatment, among others [42]. Consequently, reverse osmosis desalination plants supported by photovoltaic solar energy are now promoted and implemented.

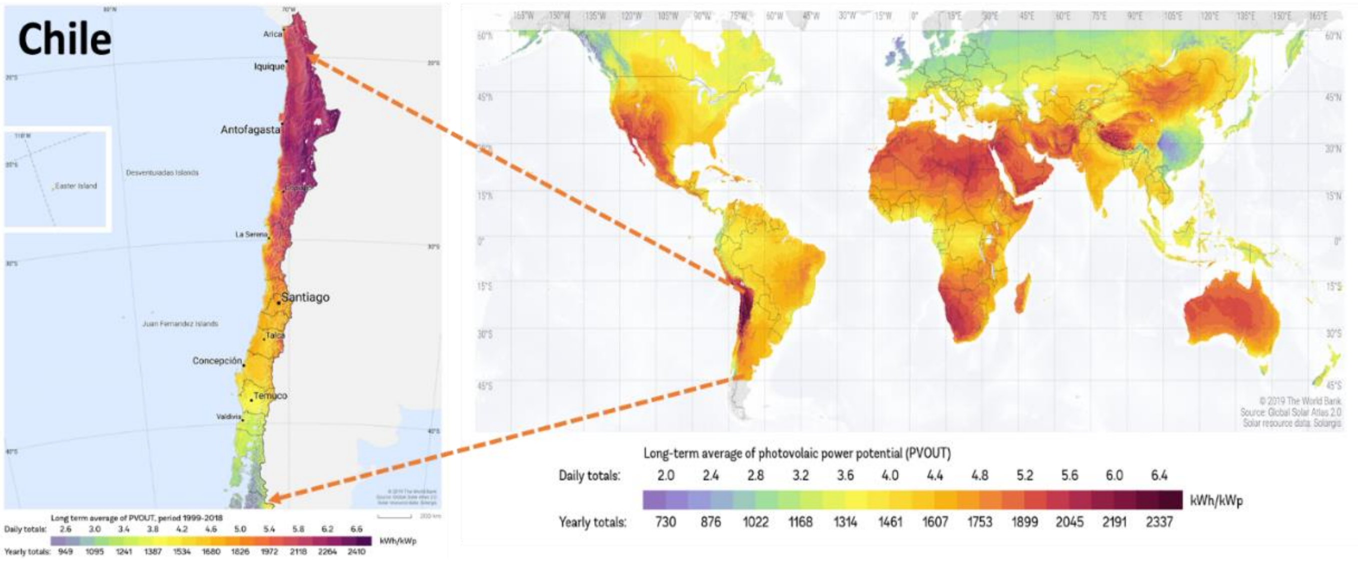

Figure 8. Solar photovoltaic resource map of the world and Chile. Source: [63].

Chile is depicted as a long and wide country with diverse microclimates and a great solar potential (Figure 9). On the one hand, the northern zone (XV: Arica and Parinacota Region; I: Tarapacá Region; II: Antofagasta Region; III: Atacama Region; IV: Coquimbo Region) has a high solar radiation, temperatures, and desert areas. On the other hand, the southern zone (XVI: Ñuble Region; VIII: Bio-Bio Region; IX: Araucanía Region; XIV: Los Ríos Region; X: Los Lagos Region; XI: Aysén Region; XII: Magallanes Region) has a low solar radiation and temperature; however, the winds increase considerably. The central zone (V: Valparaiso Region; RM: Metropolitan Region; VI: O'Higgins Region; VII: Maule Region), meanwhile, is an intermediate zone between the north and south, distinguished by its crops.

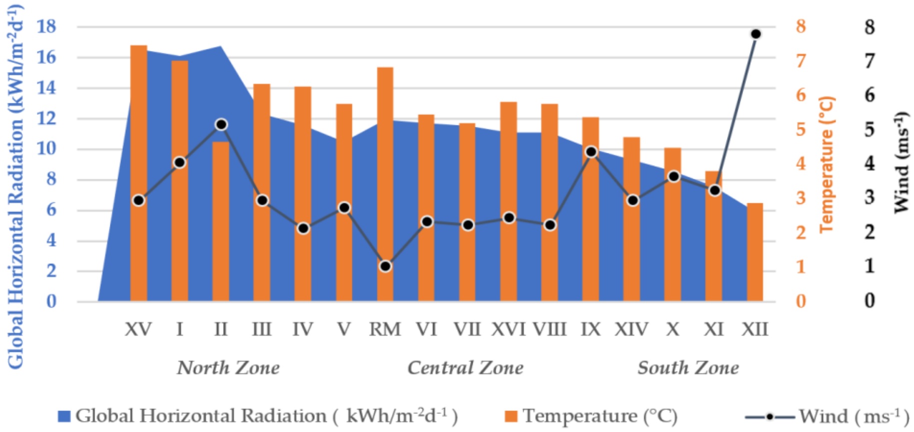

Figure 9. Solar radiation, temperature and wind by region, in Chile 2022. (author's elaboration).

4.2. Small-Scale Desalination Plants in Chile and Around the World

Small-scale desalination plants are considered to be those that produce permeated water $< 0 = 2160\ m^3d^{-1}$. For medium and large-scale plants, they consider flows greater than $2160\ m^3d^{-1}$or greater than $43{,}200\ m^3d^{-1}$, respectively [64]. Depending on the location, technology, and size of the plant, desalinated water costs vary and are expected to decrease in the future. In relation to the costs of desalination plants with RO technology, they are usually reduced due to the development of the membrane coupled with the application of energy recovery systems, or the use of renewable energies. Therefore, the nexus between RO and photovoltaic technology is a solution to be considered, mainly in the sectors where water scarcity problems are a matter of concern and where there is limited or no electricity, such as in the rural areas, fishing coves, highlands, and isolated areas [65]. Consequently, depending on the location, technology, and size of the plant, desalinated water costs vary and are expected to decrease in the future. Currently, the cost of producing desalinated water by the seawater RO process, is approximately USD 0.60 m^{-3}. According to Hamdan, 2021 [66], RODP plants offer a possible decentralized solution to provide citizens with safe, fresh water, generated from brackish and seawater aquifers, considering energy sustenance through a PV (Table 3).

Table 3. Permeated water production costs in some PV-supported RODP locations in the world. Source: [16,67].

Technology	Location	Capacity m^3d^{-1}	Salinity mgL^{-1}	Specific Energy Consumption $kWhm^{-3}$	Cost USD m^{-3}
PV-RO without battery	Australia	0.4	5000	1.86	10–12
PV-RO with biodiesel	India	0.5	SW *	-	-
PV-RO with battery	West Bank	10	2680	2.30	3.17
PV-RO with battery	Indonesia	12	3500	8.00	3.68
PV-RO	UAE	20	SW *	7.33	6.87
PV-RO with diesel	UAE	20	SW *	7.73	7.39
Wind-diesel-battery	Turkey	24	SW *	4.38	2.20
PV-RO with battery	KSA	100	SW *	6.30	4.55
PV-RO with battery	KSA	100	SW *	5.70	4.55
PV-RO grid	UAE	200	SW *	6.99	2.06
RO	Chile	-	3500	3.50	-

* SW—24,000–42,000 mgL^{-1}.

The incorporation of small-scale PV systems into the RODPs is seen as a promising technology [68]. Small-scale, direct-coupled, variable-speed PV-RO systems are technically viable, according to Jones (2016), but the flow rates, pressures, and membrane recovery rates must be regulated, to prevent the membrane degradation or fouling. It also demonstrates that in certain regions of Africa, Australia, the Middle East, and North and South America [69], a PV-RO water purification system is less expensive than a diesel-RO system.

The RODPs in Chile's coastal areas were financed by public agencies, such as the Instituto Nacional de Desarrollo Sustentable de la Pesca Artesanal y de la Acuicultura de Pequeña Escala (INDESPA), Subsecretaría de Pesca y Acuicultura (SUBPESCA), as well as the Ministerio de Obras Públicas (MOP), the Dirección de Obras Hidráulicas (DOH), and other key macro-level stakeholders in the water-energy nexus. These funds of approximately USD 100,000, were awarded through a bidding process to beneficiaries in the fishing sector, such as fishermen's organizations or artisanal shellfish gatherers, registered with SERNAPESCA, throughout the country. The aim was for these organizations to implement small-scale desalination plants to provide drinking water through seawater extraction (Figure 10). These plants would allow them to improve the quality of their production processes and encourage them to move towards productive di-versification, adding value to their products and better services, marketing their goods according to the regulations of the Ministry of Health. The plants are located in the coastal areas and are supported energetically by photovoltaic solar energy, which is environmentally friendly. Additionally, most desalination plants were installed in containers, to avoid damage to their infrastructure due to tidal waves and salt corrosion. This modular system is easy to handle so that the beneficiaries can use them efficiently.

As stated in a press release from INDESPA (SUBPESCA, 2021), "*At the national level, the government has supported, during the last few years—through SUBPESCA and INDESPA—the implementation of about 30 desalination plants that deliver—each one—between six thousand and ten thousand liters of water per day, contributing to improving the productivity conditions and quality of life of coastal communities*" [70].

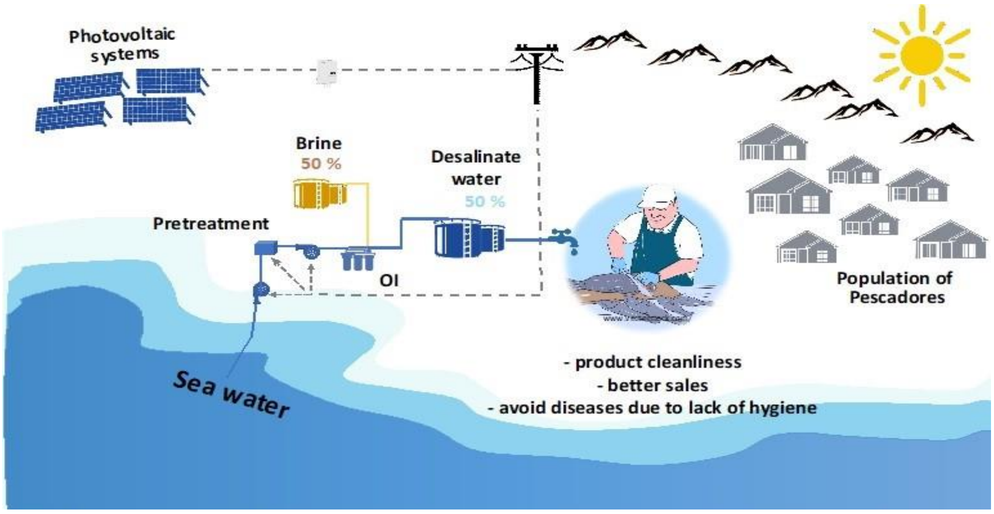

Figure 10. Diagram of the desalination plant and the benefits in the coastal areas. (author's elaboration).

The population benefiting from these initiatives is estimated at approximately 12,367 people living in the coastal areas.

4.3. Legislative and Regulatory Framework Governing Desalination Plants in Chile

According to the Climate Change Bill (PLCC), in its Bulletin No. 13.191-12 [71], Chile is highly exposed to the effects of climate change, considering that it meets six of the nine vulnerability criteria established by the United Nations Framework Convention on Climate Change (UNFCCC) [72], i.e., **1. low altitude coastal areas; 2. arid and semi-arid areas**, areas with forest cover and areas exposed to forest deterioration; 3. **areas prone to natural disasters**; 4. **areas exposed to drought and desertification**; 5. **areas of high urban air pollution**; and, 6. **areas of fragile ecosystems, including mountain ecosystems**. Considering the above, both the coastal areas of continental and insular Chile would meet at least one of these vulnerability criteria. Consequently, to reduce or mitigate this problem, implementing means, such as desalination technologies, energetically supported by a solar photovoltaic system, would reduce greenhouse gases and decrease the environmental impact.

Campero (2021), suggests that from the perspective of political ecology and critical geography, desalination is important because of its potential impact on water governance, inequalities, livelihoods, and ecosystems [73]. In the same year, the Chilean government announced a series of initiatives related to the problem of water scarcity, including the reform of the Water Code, to ensure human consumption and promote the access to new water sources, including: *i. reuse of rainwater, ii. artificial recharge of aquifers, and iii. desalination, among others* [74].

In Chile, however, neither the operation of the desalination plants nor the final disposal of brine is governed by any rules. Since 2011, efforts have been made to manage a law in the Chamber of Deputies that has been presented as an initiative empowering the state to create desalination plants (Bulletin No. 9862-33) [75], as well as a measure on the use of seawater for desalination (Bulletin No. 11,608-09 of 2018) [3]. Currently, the Environmental Evaluation Service (EES) is the public entity with the authority to assess whether or not a project can be implemented. In order to accomplish this, prior to the execution of a project, it must assess whether: *i. it complies with existing environmental regulations and/or ii. it addresses the potential for substantial environmental repercussions*. The "Environmental Impact Assessment System" (EIAS) is a management tool that allows projects to be reviewed for their environmental impact and to see if they follow the rules. It also encourages and makes it easier for citizens to take part in the review of projects [18]. However, the EES lacks particular laws pertaining to desalination plants. Meanwhile, the Dirección General del Territorio Marítimo y de Marina Mercante, DIRECTEMAR, of the Chilean

Navy is the only agency that has developed a ***Guide for the environmental assessment of industrial desalination projects in the jurisdiction of the maritime authority***, taking into account the jurisdiction of the Maritime Authority, and whose purpose is to define the basic requirements that the Environmental Impact Assessment (EIA) or the Environmental Impact State Assessment (EISA) must satisfy [76].

For the implementation and start-up of a large, medium, or small-scale desalination plant requiring ground, well, or sea water, a report with the project's description must be submitted to the EIAS to evaluate whether an Environmental Impact Assessment (EIA) or an Environmental Impact Statement (EIS) must be submitted, in order to obtain an Environmental Qualification Resolution, which approves the project to be executed. These procedures usually take a long time, delaying the construction and start-up of this type variety of plants.

Therefore, as described in this section, the main impacts of desalination plants and the environmental factors that should be considered in an EIA, are given below [77]:

- *Effect on land use*: Desalination plants are located near the coastline, where recreational or tourist use of the land is replaced by the installation of an industrial plant. This could have an impact on the coastal soil;
- *Impact on the marine environment*: This can be caused by the uptake of seawater or brine discharge (water quality) into the marine ecosystem, on the seafloor, or by the currents generated by the outfalls. Through discharge into the sea, infiltration or evaporation in ponds located on land;
- *Aqueduct routes*: The use of pipelines to carry seawater and the resulting brine can cause damage to marine ecosystems, causing sediment resuspension and the modification of coastal dynamics, burying benthic communities sensitive to changes in sedimentation. Furthermore, leaks from these pipelines can cause salt to enter the aquifers, affecting the marine flora and fauna;
- *Noise impact*: This impact is produced when desalination plants utilize high-pressure pumps and turbines, to recover electricity, which generates environmental noise;
- *High energy consumption*: Gas emissions, such as nitrogen oxide and carbon dioxide, as a result of the high amount of energy required for desalination;
- *Social impact*: The availability of freshwater produced by the desalination plants (after treatment to make it suitable for human consumption) in areas with shortages, allows the population to grow. Furthermore, the new uses of the territory may cause an imbalance in neighboring and indigenous communities, affecting tourism and reducing the economy of the local communities, causing a negative visual impact due to the installation of large plants, among other aspects.

Some of the rules that apply to building and running a desalination plant have to do with air pollution, noise, toxic chemicals, electricity, fuel, roads and transportation, land use planning, cultural heritage, and natural resources. Some of the rules that apply to building and running a desalination plant have to do with air pollution, noise, toxic chemicals, electricity, fuel, roads and transportation, land use planning, cultural heritage, and natural resources.

In relation to the international regulations, it is worth mentioning that Brazil has made progress in programs to promote desalination, mainly of brackish water on a small scale, but its development is still incipient, especially in seawater-fed plants. According to Moreira 2022, this progress is subject to technical, economic, and political issues. In addition to the price of permeated water, technological development, government incentives, and other variables affect the growth of this sector [13].

The regulations applicable to the construction and commissioning of a desalination plant include those pertaining to the atmospheric emissions, noise, hazardous substances, electricity and fuel, roads and transportation, land use planning, cultural heritage, natural resources, and those described in Table 4 [78].

Table 4. Regulations or programs applicable to the desalination plants in the world and Chile [3,78].

Country/State	Applicable to	National Regulation	Maximun Limited
Brazil	Promotes and manages the implementation of desalination units to serve low-income populations in remote communities in the Brazilian semi-arid region.	Agua Doce, a permanent public policy aimed at ensuring access to good-quality water for human consumption, since 1994.	
Chile	Effluent standards.	Environmental norms, established in the Supreme Decree N° 90/01.	Discharge of liquid wastes into marine waters inside the coastal protection zone. Discharge of liquid waste into marine water outside of the coastal protection zone.
Mexico	General specifications and requirements for desalination plants, considering the discharge of wastewater into the sea, the quality of wastewater, and the discharge of wastewater on sea beaches, as well as the infiltration or injection of reject water into wells.	"PROY-NOM-013-CON AGUA/SEMANAT-2015: establishes the specifications and requirements for the intake and discharge works, that must be met in the desalination plants or processes that generate brackish or saline rejection water."	pH 6–9 SST 20 mgL^{-1} DQO 100 mgL^{-1} Total phosphorus 5 mgL^{-1} Copper 6 mgL^{-1} Cadmium 0.4 mgL^{-1} Among others
Kingdom of Saudi Arabia	Comply with guidelines in the discharge permit. For the direct discharge: water desalination plants.	The Public Environmental Law (Royal Decree No. M/34, 2001) guidelines for the concentrations in the discharge and at the edge of the mixing zone (size on a case by case basis). General Environmental Regulations and Rules for the Implementation Guidelines for the Classification of Industrial and Development Projects. Key Principles for the Environmental Assessment of the Project.	Chlorine only (residual) 0.5 mgL^{-1}.
Countries bordering the Mediterranean Sea (France, Greece, Israel, Italy, Lebanon, Libya, Malta, Morocco, Monaco, Syria, Tunisia, Turkey, and Yugoslavia)	Agreement limiting the physicochemical discharge rates (salt, chlorine, temperature, etc.) and requiring an environmental impact study.	Benaissa et al., 2017. BTelluric Protocol to the Barcelona Convention Annex I: A1; B Annex II: A13 "Substances which, although not of a toxic nature, may be harmful to the marine environment or hinder any legitimate use of the sea, as a result of the quantities discharged."	Does not report the maximum allowable limit. Does not report the maximum allowable limit.
Spain	A wastewater treatment plant when any of the following situations occurs: i. The capacity of the plant exceeds 150,000 in population equivalents. ii. When the discharge of the effluent affects an aquatic environment, classified as sensitive. iii. When the location of the effluent discharge is close to the human supply intakes upstream, in the case of a river.	Royal Decree 1302/1986, Group 8. Hydraulic engineering and water management projects.	
United States, California	All desalination facilities discharging brine into ocean waters, including facilities that commingle brine and wastewate.	Water Quality Control Plan for the Ocean Waters of California, Effective 7 April 2016 Clean Water Act, National Pollutant Discharge Elimination System Permit Program, National Environmental Policy Act.	Discharges shall not exceed a daily maximum of 2.0 parts per thousand (ppt) above the natural background salinity. Considering seawater salinity is 35,000 ppm.

Although there is no specific regulatory framework for desalination plants in Chile, there is in some other countries, such as Mexico, where the regulation "*PROY-NOM-013-CON AGUA/SEMARNAT-2015: establishes the specifications and requirements for the intake and discharge works that must be met in the desalination plants or processes that generate brackish or saline rejection water*", where only some parameters are regulated [3,79].

5. Results

5.1. Chilean Cadaster of Small-Scale Desalination Facilities

The present study presents the results obtained from a survey of the desalination plants nationwide, which mainly correspond to rural drinking water systems for human consumption, with the purpose of benefiting fishermen or shellfish harvesters in the coastal areas of Chile. These plants have been financed mostly through competitive funds from INDESPA, SUBPESCA, as mentioned above. Currently, there are six plants in the pipe-line and 49 desalination plants (small to medium scale) in operation, which produce a total of 117,273 m^3d^{-1} permeated water. These plants are located in the different regions of Chile, from the north to the south, and Region IV and Region V are the ones that deliver the largest amount of permeated water.

Currently, there are 39 small-scale plants, which produce a total of 1715 m^3d^{-1}, from a feed flow of 3430 m^3d^{-1}, considering a Y of 50% (Figure 11).

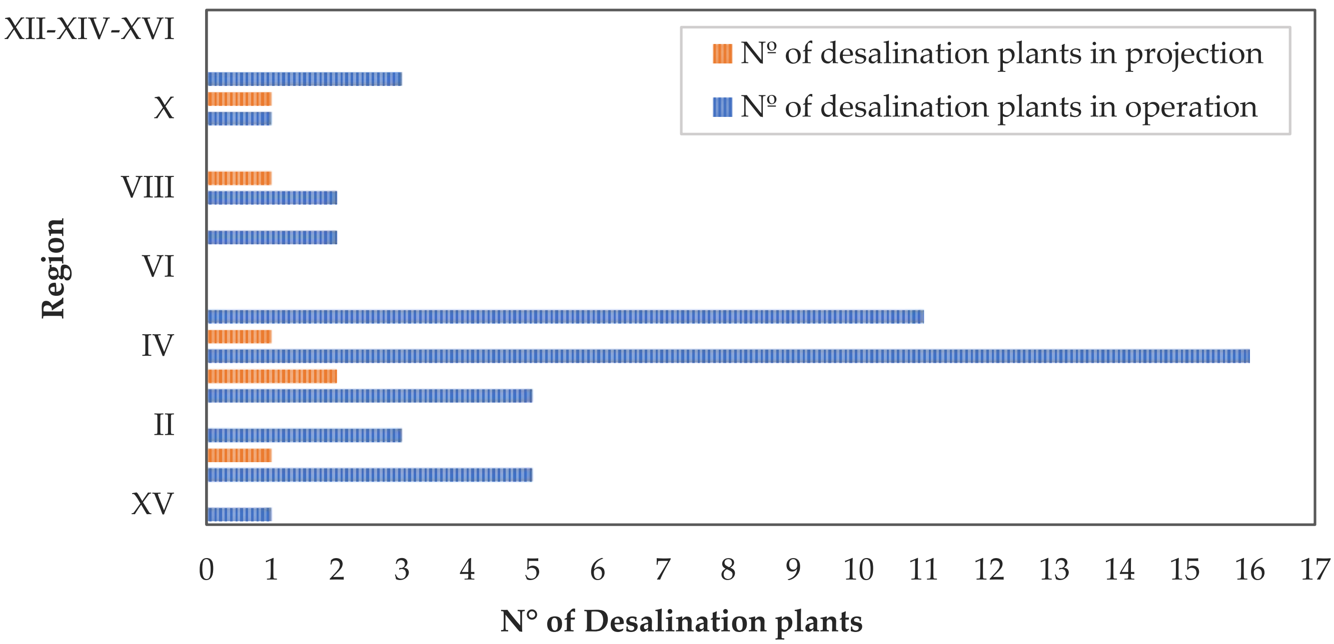

Figure 11. Diagram of the desalination plants and benefits in the coastal areas. (author's elaboration).

Among the sampled plants, 98% correspond to RO technologies and 2% to other technologies. It is worth mentioning that 100% are plants supported energetically by photovoltaic panels. Furthermore, the calculations applicable to the desalination plants were considered in Section 3.3, to obtain the Qb and Qf data for the different small-scale plants that exist, per region, in Chile. Likewise, there are calculations for the salt passage (SP), conversion (Y), and concentration factor (CF). For these calculations, the rejection factor of the plants is assumed to be 50% (Table 5). From the total of the small-scale plants registered, a Qf of 3430 m^3d^{-1} and a Qp = Qb of 1715 m^3d^{-1} are obtained.

Table 5. Calculations applied to the small-scale desalination plants in Chile, by region (author's elaboration).

Region	Qf m^3d^{-1}	Qp m^3d^{-1}	Qb m^3d^{-1}	R %	SP %	Y %	CF
XV	226	113	113	50	50	50	2
I	80	40	40	50	50	50	2
II	185	92	92	50	50	50	2
III	62	31	31	50	50	50	2
IV	158	79	79	50	50	50	2
V	1369	684	684	50	50	50	2
VI *	0	0	0	0	0	0	0
VII	1028	514	514	50	50	50	2
VIII	260	130	130	50	50	50	2
IX *	0	0	0	0	0	0	0
X	6.04	3.02	3.02	50	50	50	2
XI	56	28	28	50	50	50	2
XII-XIV-XVI *	0	0	0	0	0	0	0

* Regions VI, IX, X, X, XII, XIV, and XVI do not have small-scale desalination plants.

5.2. Localization

A small-scale RODP supported by a PV was considered as a case study, a plant located in Caleta Pan de Azúcar, Atacama Region (III), with a latitude of −26.142 and a longitude of −70.662 degrees (Figure 12). This plant produces 8 m^3d^{-1} of potable water supplied by an 8 kW PV, that was used as the primary source of electricity. This plant was implemented by Nature Energy SpA, with a useful life of 25 years [80].

Figure 12. Satellite location of Caleta Pan de Azúcar. Source: [24].

The solar resource and weather conditions at the project site were collected with Solar Explorer (Figures 13 and 14). The most relevant data for the economic and technical evaluations of the project under study are the annual radiation with: global horizontal 4.90 $kWhm^{-2}d^{-1}$, global inclined (According to latitude) 5.05 $kWhm^{-2}d^{-1}$, direct normal 5.11 $kWhm^{-2}d^{-1}$, diffuse horizontal 1.66 $kWhm^{-2}d^{-1}$ [24].

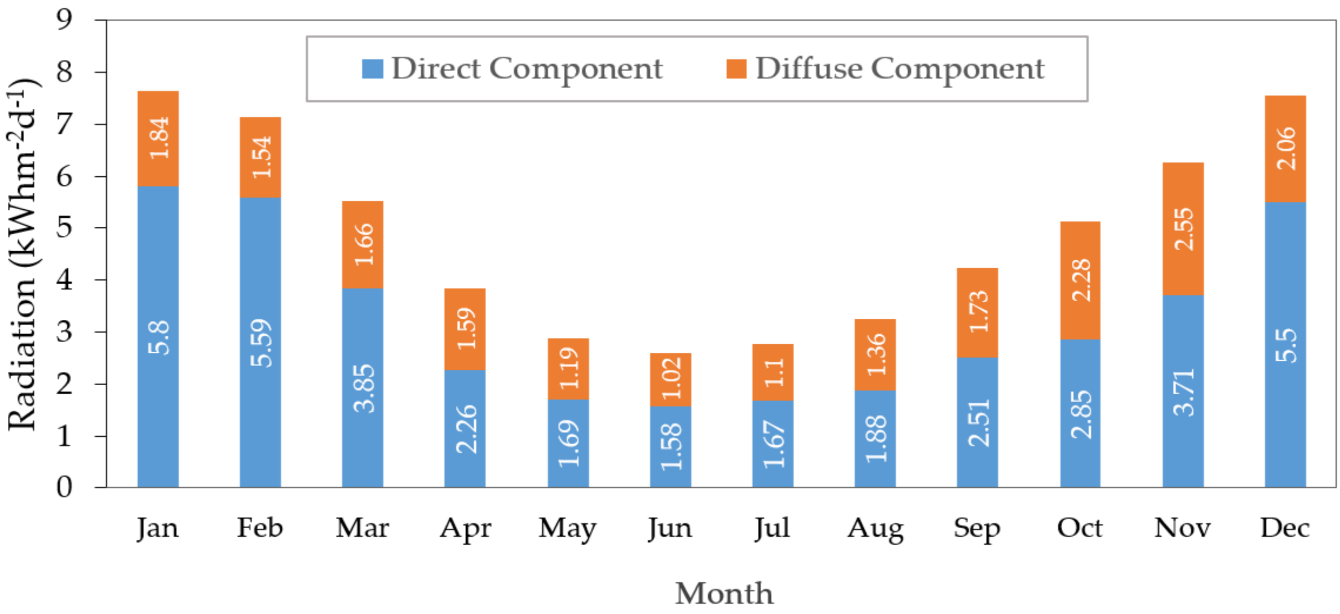

Figure 13. Global horizontal radiation of the location of the Caleta Pan de Azúcar drinking water desalination plant. Source: [24].

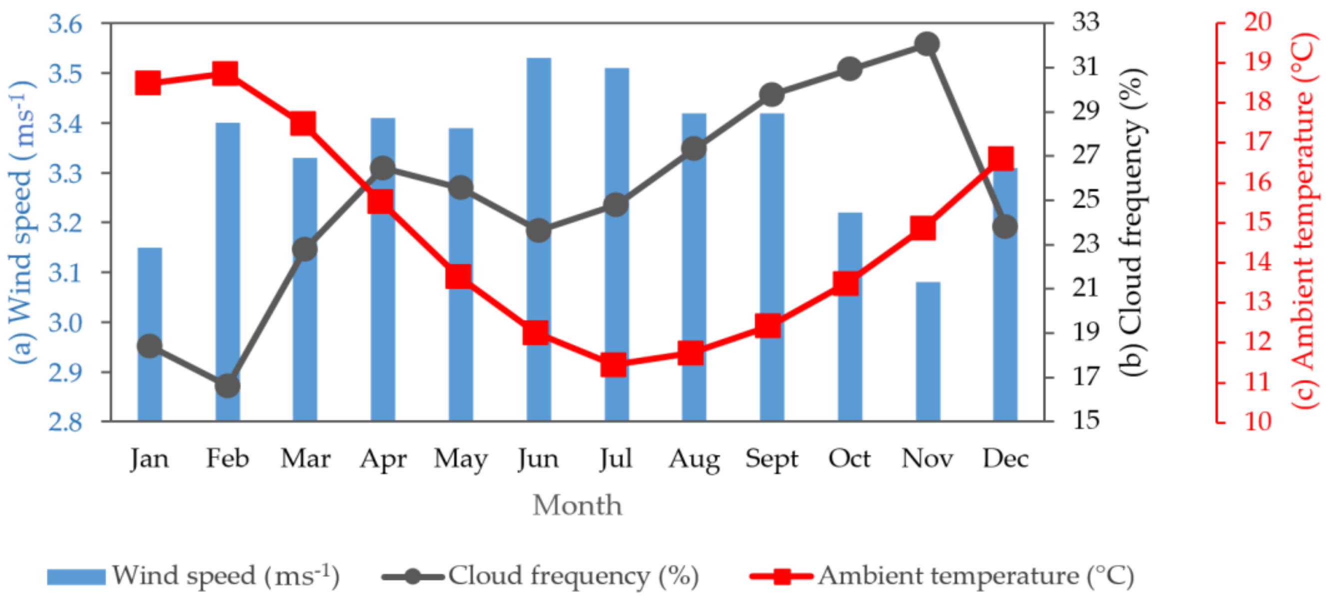

Figure 14. Meteorological conditions at the Caleta Pan de Azúcar drinking water desalination plant. (**a**) Wind speed, (**b**) Frequency of clouds, (**c**) Ambient temperature. Source: [19].

The average monthly seawater temperature of the planned location, for the implementation of the reverse osmosis plant, is between 14 °C and 19.2 °C. Moreover, the average water temperature in Chañaral, in winter, reaches 18.5 °C, in spring, 17 °C, in summer, the average temperature rises to 14.3 °C, and in autumn, it is 15 °C [81].

5.3. Characteristics of the RODP

The technical specifications of the RODP with the input parameters and their fixed values for running the case study are shown in Table 6.

Table 6. The technical specifications of the RODP.

RODP Plant Information	Value	Units
Model of the reverse osmosis membrane	4040 VONTRON *	
Number of membranes	2	-
Raw water pump		
Power	0.75	kW
Voltage	220	V
Frequency	50	Hz
Pressure pump		
Power	1.5	kW
Voltage	220	V
Minimum salt rejection	99.7	%
Freshwater nominal flow	45.7	m^3d^{-1}
Maximum operating pressure	600	psi
Maximum recovery rate	15	%
Maximum water temperature	45	°C
Brackish water pH range	3–10	-
System power	2.25	kW

Note *: Membrane, Importadora RC. https://importadorarc.cl/, accessed on 8 november 2022.

In this study, the conditions of the seawater that feeds the desalination plant are considered to have a salinity of 35,000 mg L^{-1} at 25°C, and for these values, it has a Van't Hoff factor of 1.82 [56]. Furthermore, considering that the density of seawater with these characteristics is 1.0233 kgL^{-1}, and that the molecular weight of sodium chloride is 58.44, a molar concentration of water of 0.613 mol L^{-1} is obtained [56]. The osmotic pressure is calculated by Van't Hoff's law, according to Equation (6), resulting in Op = 27.31 atm. This result indicates that to initiate the reverse osmosis process, a pressure higher than this value is required for the seawater flow to begin to cross the membrane [56]. The maintenance of this pressure will be the only energy input necessary, to obtain a pure water flow in the system under consideration. By means of this pressure, the minimum energy required to extract 1 m^3 of permeated water can be obtained. Considering Equation (7), the corresponding energy is 0.769 kWh.

5.4. Cases Analysis and Simulation

Although small-scale RODP plants are almost entirely supported by PV, it should be noted that coastal communities typically do not have access to or do not have continuous electrical grid service; therefore, they must seek alternative energy sources, such as the use of a diesel generator or PV with batteries. In this regard, it is proposed to explore four energy assistance options for RODPs:

- Case 1: electricity supplied straight from the grid at the cost of a free client with a contract;
- Case 2: power generation using a generator, considering the cost of fossil fuel;
- Case 3: electricity supplied by a photovoltaic facility without battery energy storage;
- Case 4: the provision of electricity via a photovoltaic facility with energy storage in the batteries.

Assuming that 50% of the permeate water is obtained from the 16 $m^{-3}d^{-1}$ of seawater, as indicated in Section 5.2, a seawater requirement is assumed for the RODP in all the cases evaluated at 20 years. For the simulation of the technical-economic evaluation of the cases, the following technical specifications were considered in Table 7:

Table 7. Technical specifications of each component, according to the case study.

	Properties	Value	Units
		Case 1	
EG	Type of electrical network	BT1	
	Tariff sector	STxB-1-A *	
	Electric company	Emelat	
		Case 2	
DG	Model (Brand)	HYG7750E (Hyundai) [a]	
	Feeding	Gasoline	
	Voltage	220	V
	Rated energy (Maximum energy)	5000 (5500)	W
	Frequency	50	Hz
	Tank capacity	25	L
	Lifetime	15,000	hr
		Case 3	
PV without Battery	***Solar module***		
	Module type (Brand)	Poli SPLITMAX (Trinasolar) [b]	
	Nominal Power	335	Wp
	Cell orientation	144 polycrystalline cells (6 × 24)	
	Module cover	AR Coated tempered glass	
	Temperature coefficient of the solar module	−0.41	%°C^{-1}
	NOCT	44 (±2)	°C
	Maximum efficiency	17.4	%
	Module dimensions	2000 × 992 × 40	mm
	Weight	23	kg
	Inverter		
	Model (Brand)	7–8 (Single Phase Inverter, Solis) [c]	
	Input DC		
	Recommended max. PV power	12	kW
	Max. input voltage	600	V
	Rated voltage (Start-up voltage)	330 (120)	V
	MPPT voltage range	90–520	V
	Max. input current	12.5/25	A
	Max. short circuit current	19.5/30	A
	Output AC		
	Max. output power	8	kW
	Rated grid frequency	50/60	Hz
	Max. output current	34.8	A
	Inverter efficiency	98.1	%
	Photovoltaic generator		
	No. solar module	24	-
	Array type	Fixed inclined plane	
	Tilt	20	degrees
	Azimuth (Orientation)	0 (North oriented)	degrees
		Case 4	
PV with Battery	***Solar module***	Same Case 3	USD
	Inverter	Same Case 3	USD
	Battery bank		
	Model (Brand)	Battery-Box Premium HVM (BYD) [d]	
	Battery Module	HVM (2.76 kWh, 51.2 V, 38 kg)	
	Number of Modules	5	-
	Usable Energy	13.8	kWh
	Max output current (peak output current)	50 (75)	A
	Nominal voltage	256	V
	Operating voltage	200–300	V
	Dimensions	1411 × 585 × 298	mm
	Weight	205	kg
	SmartSolar Charge Control		
	Model (Brand)	MPPT 250/85 (Victron energy) [e]	
	Efficiency	99	%
	Voltage	12/24/48 (Auto Select)	V
	Max. PV short circuit current	70	A
	Operating temperature	(−30, 60)	°C
	Battery terminals	35	mm^2/AWG2
		Small-scale RODP	
RODP	Model of reverse osmosis membrane	4040 VONTRON	
	System power	2.25	kW
	Minimum salt rejection	99.7	%

* Electricity tariff type, www.CGE.cl, accessed on 8 november 2022. [a] Generator set, Sodimac. www.sodimac.cl/, accessed on 28 october 2022; [b] Solar module, Solartex. www.solartex.cl/, accessed on 28 october 2022; [c] Inverter, Ginglong. www.ginlong.com, accessed on 28 october 2022; [d] Battery Bank, Solar Top Store. www.solartopstore.com, accessed on 3 november 2022; [e] SmartSolar Charge Control, Victron Energy MPPT. www.naturaenergy.cl, accessed on 30 october 2022.

5.4.1. Simulation in Homer Pro

In this study, the four systems are modeled and analyzed as potential alternatives for the RODP's sustainable electricity production. The technical specifications given in the previous sections are considered for this analysis. Similarly, solar radiation and meteorological data (Solar Explorer software) from the location of the RODP in Caleta de Pan de Azcar, Region III, are used to perform various types of simulations using Homer Pro software, such as a simulation of the hourly electric energy production profile for each case study mentioned previously in the research.

EG: Homer Pro compares a grid-connected system using the grid electricity price as an input parameter. **DG**: According to the manufacturer's statistics, the Homer Pro models' fuel consumption is a function of the RODP electrical load. In contrast to PV systems, diesel and EG systems presume demand-based operating at a constant speed. **PV**: Homer Pro estimates the incident solar radiation, based on the provided horizontal radiation statistics, latitude, season of the year, time of day, and orientation of the PV system. It then estimates the temperature and power output of the PV system cell on an hourly basis; using this information, it is possible to establish an hourly power production profile, scale it to meet the system power demands, and determine the ideal PV system size with or without batteries, for the RODP. Notably, the PV system with a battery bank will only be utilized in the event of a power outage or during nighttime operations.

Case Configuration

To perform the simulation with HOMER Pro, the base architecture of the EG-RODP (Case 1), DG-RODP (Case 2), PV-RODP without a battery bank (Case 3) and PV-RODP with a battery bank (Case 4) is determined, as shown in Figure 15. In addition, it considers the electrical consumption concentrated in the RODP required for the pressurization of the saline water flow (Figure 16), the water treatment processes (pretreatment and post-treatment), and the energization of the pumps for the water circulation [56].

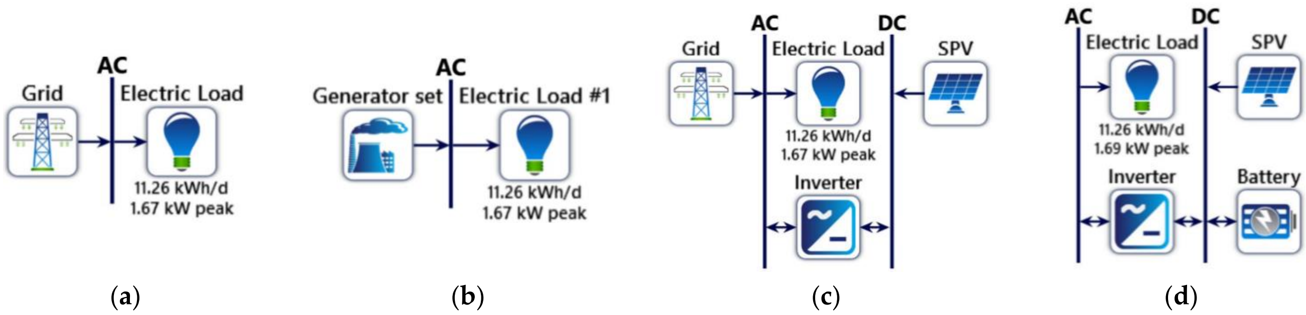

Figure 15. Configurations: (**a**) Case 1, (**b**) Case 2, (**c**) Case 3, and (**d**) Case 4. Source: Homer Pro simulation. (Author's elaboration).

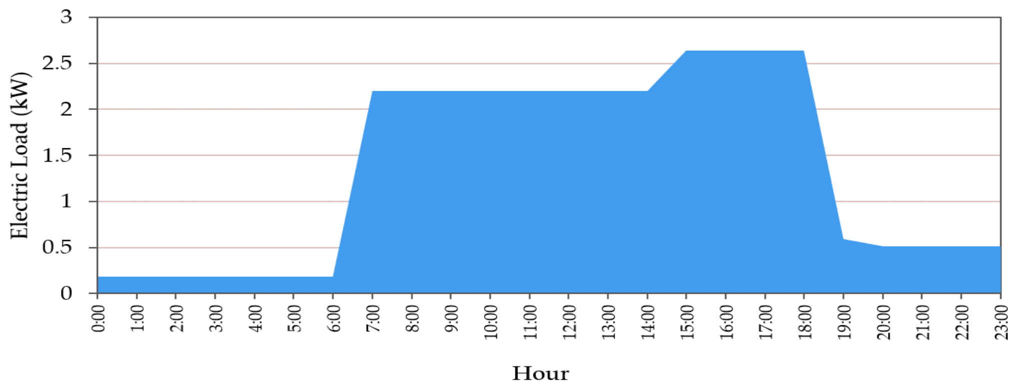

Figure 16. RODP daily consumption. Source: Adapted from Homer Pro.

The software also provides different categories, in terms of project costs, such as initial capital costs, capacity costs, replacement costs, operation and maintenance (O&M) costs, allowing the tracking of the system's installation costs under study. Each component's associated costs are shown in Section 5.4. *Cases analysis and simulation*, on the case configuration.

For the O&M costs of the PV, maintenance is included every 6 to 12 months: *i.* monthly cleaning of the solar modules (12 USD); *ii.* replacement of the inverter equivalent to its cost (between 10 and 17 years) if the product no longer works (within the warranty); and *iii.* replacement of the damaged modules at year 25 (maximum number of years of operation of the typical solar module). Regarding the RODP, the expenses associated with the O&M cost are approximately USD 1500. The values were subjected to the cost analysis of the Homer Pro program. The results are shown in Table 8.

Table 8. Costs associated with the EG, DG, PV, and RODP, depending on the case of analysis.

	Properties	**Value**	**Units**
		Case 1	
EG	Consumer price	0.161	USD/kW^{-1}h^{-1}
	Injection price	0.079	USD/kW^{-1}h^{-1}
		Case 2	
DG	Initial capital	798.4	USD
	Replacement	798.4	L hr^{-1}kW^{-1}
	O&M	0.274	USD/hr^{-1} of operation
	Fuel price	1.24	USD/L^{-1}
	Lifetime	15,000	hr
		Case 3	
PV without Battery	Solar module	146.6 *	USD
	Inverter	1631.6 *	USD
	Photovoltaic structure installation	184.4 *	USD
	2 Victron MPPT Smart Solar 85A 250V controllers	2251.5	USD
		Caso 4	
PV with Battery	Solar module	146.6 *	USD
	Inverter	1631.6 *	USD
	Photovoltaic structure installation **	184.4 *	USD
	2 Victron MPPT Smart Solar 85A 250V controllers	2251.5	USD
	Battery bank	9372.9	USD
	Battery O&M	100	USD/year^{-1}
	PV O&M	144	USD/year^{-1}
	Inverter O&M	50	USD/year^{-1}
		Small-scale RODP	
RODP	Investment cost	10,396.6	USD
	Cost of O&M	2.7% of cost of capital	

Note *: VAT included; **: Photovoltaic structure installation, Nature Energy. www.naturaenergy.cl accessed on 6 November 2022.

For the post-simulation technical evaluation of the RODP-PV, a PV capacity of 8 kW, an electrical generation capacity of 11,060 kWh year^{-1} with a useful life of 20 years and a seawater RODP production capacity of 8 m^{3}d^{-1}, with a power of 2.25 kW, a useful life of 15 years and an efficiency of 70–80%, are considered. Therefore, once the base architecture of the system is obtained and with all the input information associated with each component, we proceed to run the corresponding simulations. This will allow for comparing both the theoretical and simulated data.

Regarding the injection and consumption prices, in Case 1, the annual cost of electricity varies on the kind of residential consumption in the Chañaral commune, with the BT1 tariff being the most prevalent CGE, 2022. This tariff is applicable if the client has a low voltage supply and a connected power of less than 10 kW, which is greater than the 8 kW needed by the RODP plant. In Chile, Law No. 21,185 established a temporary system for stabilizing the electricity costs for customers subject to tariff regulations; hence, as of July 2019, the retroactive tariffs are still in effect and the cost of the supply has not changed [82].

Technical and Economic Analyses of the Cases

With the execution of the previously defined PV system simulation in Homer Pro, it is feasible to determine the equivalent sunshine hours (Equation (6)), as depicted in the graph below:

The highest sunshine hours are achieved in the summer months and the lowest, in the winter months. Moreover, the variation of the equivalent hours of sunshine is directly related to the amount of solar radiation reaching the Caleta Pan de Azúcar, Chañaral, as shown in Figure 17.

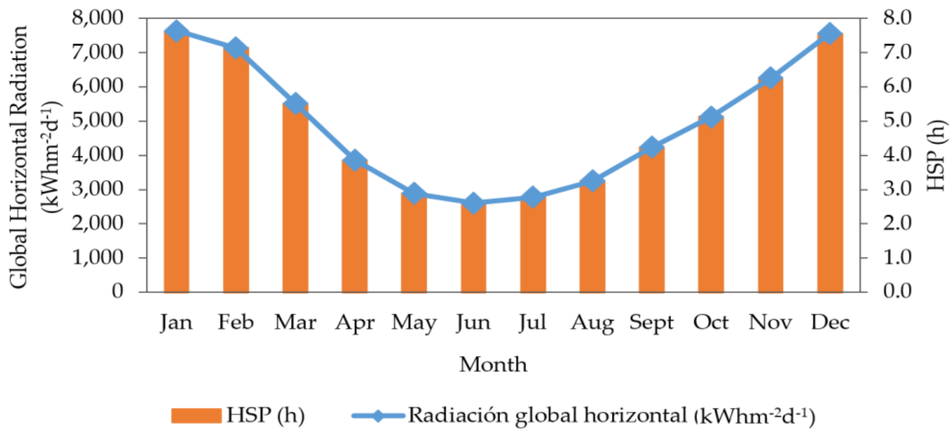

Figure 17. Relation between the global horizontal radiation and HSP. Source: author's elaboration.

Table 9 shows the simulation results of the annual and monthly performance of the desalination plant, in the Homer Pro software, once the models described in section "Case configuration" are applied for the different comparisons of technologies integrated into the seawater RODP, assuming the costs associated with each system (Table 8) and investment costs associated with each case study.

According to Table 9, the differences that exist in the monthly production of permeate water are not significant, since the daily water production is the same throughout the year (i.e., 8 m^3d^{-1}). In addition, the specific energy consumption of the RODP does not vary throughout the year, due to the fact that the variation in seawater temperature is not significant (monthly average, between 14 °C and 19.2 °C). Moreover, the highest monthly electricity consumption of the RO unit occurs in August (364 kWh), and this consumption is used to size the surface of the PV array for Cases 3 and 4 (number of PV panels).

In Case 1, to energize the RODP by means of EG, the monthly average electricity consumption costs are USD 55.1, likewise, this EG would allow for supplying the entire electricity demand of the desalination plant (Tables 9 and 10). In Case 2, the energy source is from a DG, it can be noted that the operating cost and total investment cost increase by 23.4% (Table 10) and 92% (which is the highest among all of the case studies), respectively. Moreover, for Case 3, by using solar energy as a renewable energy source, the PV would be supported by the grid electricity, as long as the electricity generated by the PV subsystem is not enough to cover the electricity needed for the daily operation of the

RODP (32.1 kWhd^{-1}), or in case of a PV failure. The annual generation of EG from the PV subsystem is 12,024 kWh and the annual supply of electric power from the public grid is about 1018 kWh, the cost of which is USD 163.9. For Case 4, by implementing the use of a battery bank integrated into the PV-RODP system without the dependence on the grid, it can be observed that the surplus energy from the PV can be stored for use during night hours, if required, as it is in the month of January when the maximum amount of electric energy is stored (30.7 MWh). The monthly solar contribution to the energy consumption of the PV-RODP plant is between 48% (in June) and 100% (in January), with an annual contribution of approximately 90%.

Table 9. Summary of the investment costs associated with each case study.

Component	Capital USD	Replacement USD	O&M USD	Fuel USD	Salvage USD	Total USD	LCOE USD
Case 1 (EG)	0.0	0.0	7661.1	0.0	0.0	7661.1	0.16
Case 2 (DG)	1516.9	9725.6	52,811.3	32,668.6	(154.75)	96,567.7	2.03
Case 3 (Grid + PV without Battery)	5303.1	1336.6	(3415.9)	0.0	(499.3)	2724.5	
Inverter	1631.6	525.7	540.9	0.0	82.4	2615.9	0.02
PV	3671.5	810.9	1596.9	0.0	416.9	5662.4	
Grid	0.0	0.0	(5553.8)	0.0	0.0	(5553.8)	
Case 4 (PV with Battery)	34,089.5	14,048.6	2571.4	0.0	(246.3)	50,463.2	
Inverter	1672.4	538.8	509.1	0.0	(246.3)	2474.1	
PV	3671.5	0.0	1466.2	0.0	$0.0	5137.7	1.24
Battery	28,745.7	13,509.8	596.0	0.0	$0.0	42,851.5	

Note: The use of parentheses indicates negative values.

Moreover, an important point to consider is the value representing the levelized cost of water (LCOW), produced by the PV-RO plant. This value can be estimated in a simplified approach using Equation (15) [83]:

$$\mathrm{LCOW} = \frac{(\mathrm{Ico} + \alpha) + \mathrm{Cops}}{\mathrm{Qp, annual}} \tag{15}$$

where Cops is the operating cost of the desalination plant per year (USD 280.7), Qp, annual is the quantity of water produced per year (2920 m^3), and Ico is the initial investment expenditure (i.e., the capital investment of USD 10,396.6). The capital amortization factor, α, is calculated using the Equation (16), which is approximately 0.13.

$$\alpha = \frac{\mathrm{i}(1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}} - 1} \tag{16}$$

Thus, the LCOW is about USD/0.56 m^{-3}. This water production cost is much lower than the sale price of water per capacity of the drinking water distribution system by the company Nueva Atacama S.A. in Caleta Pan de Azúcar (Chañaral), whose value is 2.11 (USD/m^{-3}), the main option available for the region [82].

It is noteworthy that the implementation of a PV-RO desalination plant can be cost-effective, compared to the drinking water available for the company **Nueva Atacama S.A**, in the Chañaral region. In addition to the economic advantages, the use of a PV-RODP significantly reduces the CO_2 emissions associated with seawater desalination, using RO plants that rely on electricity obtained from fossil fuels. It is worth mentioning, that the estimated LCOW is based on a conservative PV (e.g., PV module efficiency of 17.4); therefore, a lower LCOW could be obtained with more accessible system sizing and economic input data. Therefore, these results show that the production of permeate water, by means of a PV-RODP connected to the EG, is economically viable and environmentally friendly, making its implementation in the study region favorable.

Table 10. Monthly permeated water and energy consumption associated with the RODP seawater plant with a capacity of 8 m^3d^{-1} at Caleta Pan de Azúcar, Chile.

Month	Permeated Water m^3	RO Unit Energy Consumption kWh	Case 1 (RODP + EG)		Case 2 (RODP + GE)			Case 3 (RODP + PV + Grid)			Case 4 (RODP + PV + Battery)	
			Net Energy Purchased to the Grid kWh	Energy Charge USD	Generator Set Output Power kWh	Fuel Consumption L	Fuel Consumption Expense USD	PV Power Output kWh	Grid Purchases kWh	Grid Purchases USD	PV Power Output kWh	Battery Energy Content kWh
Jan	248	341	341	54.9	477.8	191.8	237.8	1386.6	47.7	7.7	1386.6	30,693.9
Feb	224	305	305	49.1	429.6	172.9	214.4	1262.3	45.4	7.3	1262.3	27,712.8
Mar	248	360	360	58.0	496.2	196.2	243.3	1180.6	73.6	11.9	1180.6	30,268.1
Apr	240	339	339	54.6	471.2	187.9	233.0	870.0	93.2	15.0	869.9	28,865.2
May	248	342	342	55.1	480.1	192.5	238.6	731.4	108.2	17.4	731.4	28,897.5
Jun	240	341	341	54.9	473.1	188.4	233.6	665.6	122.6	19.7	665.6	27,188.4
Jul	248	346	346	55.6	483.3	193.3	239.7	726.6	115.6	18.6	726.6	29,377.6
Aug	*248*	364	364	58.6	499.9	197.2	244.6	787.7	116.3	18.7	787.7	28,154.2
Sept	240	343	343	55.2	474.7	188.7	234.0	910.1	92.0	14.8	910.1	28,241.0
Oct	248	344	344	55.4	481.9	192.9	239.2	1031.3	72.7	11.7	1031.3	30,261.6
Nov	240	334	334	53.8	467.4	187.1	232.0	1126.4	72.4	11.7	1126.4	29,237.5
Dec	248	348	348	56.1	485.6	194.0	240.6	1345.4	58.4	9.4	1345.4	30,596.9
Annual Average	***2920***	***4109***	***4109***	***661.6***	***5720.8***	***2282.8***	***2830.6***	***12,024.0***	***1018.1***	***163.9***	***12,023.9***	***349,494.7***

6. Discussion and Comments

This work shows that the water-energy nexus is vital for the sustainable development of resilient communities. Integrating RO desalination technologies with a photovoltaic (PV) system is an effective solution in coastal areas, where seawater is a resource that, when treated by the RO process, can be converted into drinking water (after conditioning) and benefit these communities in their productive activities. Through the cadaster, it was determined that there are 49 plants (RODP), of which 39 are in operation, and of these, 48% produce less than 8 m^3d^{-1}. The volume of water produced (flow) by the 39 RODPs is 1715 m^3d^{-1}, and considering that the optimal volume of water per person is 0.1 m^3d^{-1} (according to the WHO), it would cover the drinking water demand for 17,150 people, which is sufficient for consumption and use in the production of marine products for the 12,367 people living in these areas, where the RODPs were implemented.

In Caleta Pan de Azucar, a techno-economic evaluation of a small-scale, grid-connected and off-grid RODP with and without a battery system, revealed that its implementation is feasible. The desalination plant can cover part of the water demand, with a solar contribution of more than 65% throughout the year (65–100%). The levelized cost of permeate water production using PV-RODP without a battery bank is about USD 0.56 m^{-3}, which is much more cost effective than the current cost of potable water in Chañaral (~USD 2.11 m^{-3} for potable water). The payback period for this desalination plant is about 5.4 years, considering a useful life of 20 years.

Additionally, as an example of the operation of these plants, a production of 8 m^3d^{-1} permeated water was considered, and the importance of the origin of the energy resource (PV) used by these plants was evaluated, as well as the technical-economic aspects. For this simulation, we considered the use of fossil fuels, such as grid electricity (Case 1), diesel generator (Case 2), and we also considered the analysis of a PV power system with and without bacteria (Case 3 and Case 4, respectively). Based on the above, the result corresponding to the total investment cost (capital, replacement, O&M, fuel, and salvage) of using fossil fuels indicates that Case 1 has advantages over Case 2, the former being 48.8% more expensive than the latter; and, with respect to the use of renewable energy sources, Case 3 has advantages over Case 4, the former being 26.6% more expensive than the latter. One of the main advantages of the PV-RODP nexus, is that it does not produce GHGs, which contributes to mitigating climate change. In short, a grid-connected PV-RODP desalination plant can help solve the water shortage in the region's coastal zone in a cost-effective and environmentally friendly way.

Due to the high cost of the PV systems, RO desalination with conventional energy was primarily limited to small-scale applications in distant locations. A study of six cases between 1991 and 2003 reveals that permeate water production costs range between USD 8 and USD 29 m^{-3} for 120 and 12 m^3d^{-1} production capacity, without a PV system [84]. When compared to the data from this study, the 8 m^3d^{-1} has a value of USD 0.56 m^{-3}.

Regarding governance, the fact that the plants are implemented with funds from governmental organizations of the macro-level water-energy nexus, is remarkable, confirming the importance of these entities in promoting and encouraging this type of initiative to support regions where there is a significant shortage of drinking water, and for small communities to have access to easy-to-operate technologies (modular and autonomous).

The implementation of the small-scale desalination plants in the coastal areas of Chile was assessed by identifying the existing challenges and opportunities, considering the economic, social, and environmental factors (Table 11).

Table 11. Identification of the challenges and opportunities related to the implementation of small-scale RODPs in Chile. (author's elaboration).

	Challenges	Opportunities
Environmental	• *Community empowerment regarding the use of solar-powered water treatment technologies. Development of a regulatory and legislative framework for the deployment of small-scale desalination plants.* • *Creation of a regulatory and legislative framework for implementing small-scale desalination plants.* • *Implement adequate designs that consume the least amount of energy and generate the least possible environmental impact.* • *Saline waste must be treated and reused so that it is not returned to the sea, thus avoiding ocean pollution.*	• *Chile's solar potential, especially in the Atacama Desert, is considerably more favorable than in other parts of the world.* • *Having sunny days almost all year round in the northern zone allows for the implementation of technology that uses solar energy in its processes.* • *The implementation of desalination plants avoids the depletion of aquifers from the underground and surface sources.* • *Use of seawater as a power source for desalination plants, considering that Chile has 8000 km of coastline.* • *The implementation area of a modular plant (in a container) is minimal, so it is not required to intervene in large areas.* • *Reduced carbon footprint by powering the desalination plant with photovoltaic solar energy.*
Economic	• *Prioritize desalination plants powered by renewable energy sources, as they will also allow for lower operating costs in coastal areas.* • *Lack of decentralized offers. There are few companies at the regional level that offer installation services for small-scale desalination plants, supported by photovoltaic panels in Chile.* • *Investment in the maintenance and monitoring of desalination plants and photovoltaic systems.* • *The cost required for a seawater harvesting system is low, compared to large-scale plants.* • *A maritime concession is required, which implies a cost to obtain the necessary permits.*	• *Fishers add value to their products.* • *Productive diversification is encouraged.* • *Sustainable economic development of artisanal fisheries.* • *The potential of artisanal fishing coves benefits from being poles of economic, gastronomic, and tourism development.* • *The operation of seawater desalination plants is generally in modular systems that do not require a large surface area and therefore reduce costs.* • *There is autonomy in using the desalination plant, requiring only one operator.*
Social	• *Training the end users is vital for the increased autonomy, which is essential for the operation of the desalination and photovoltaic plant.*	• *Improve the quality of life of local fishers and their families in coastal settlements.* • *Providing water for human use is essential, to avoid diseases.* • *Enables communities to face periods of scarcity with better resilience.* • *Avoiding the depopulation of coastal localities.*

7. Conclusions

The study results reveal the importance of obtaining water through desalination plants in coastal areas, considering the technological advantages and the improvement in the quality of life of fishers and shellfish gatherers in the sectors where these plants are installed. According to the cadaster, only 8.4% of the 461 existing coves in Chile have a desalination plant in operation.

The simulation with Homer Pro shows that Case 3 (PV-ROPD-Grid) is the most economically viable, as it has a useful life of 20 years and will have an annual solar contribution of more than 65%. Considering that the EG should be utilized in the event that the PV system fails, scenario 2 is the least viable study case, as its total investment cost is 53% higher than all other cases of analysis. This is mostly due to the high cost of acquiring diesel fuel a fossil fuel that is extremely polluting after use) for the generator, making it the least profitable alternative.

Therefore, the levelized cost of water production using the RODP/PV was USD 0.56 m^{-3}. Likewise, the LCOE was USD 0.02 $kW^{-1}h^{-1}$ for a permeated water generation capacity of 8 m^3d^{-1}. Notably, this levelized cost is considerably less than the USD 9 m^{-3} for a RO/PV plant with identical characteristics to the one analyzed in this study, but located in Indonesia with a production capacity of 11 m^3d^{-1}. Additionally, the use of this type of plant in areas with a shortage of potable water, such as at Caleta Pan de Azúcar, mitigates the greenhouse gas emissions associated with seawater desalination. The new design is both economically and ecologically beneficial.

This work contributes to macro-level actors, i.e., to set a precedence for public policies in the face of recognized uncertainties. The implementation of small-scale desalination plants must be normalized and legalized as a priority in the near future.

Finally, the availability of seawater and solar radiation in Chile is a great opportunity, which confirms that the water-energy nexus will considerably improve the sustainable development in coastal areas, contributing to the productive sector and minimizing the effects of climate change.

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