

Article

Integrated Renewable Energy System Based on IREOM Model and Spatial–Temporal Series for Isolated Rural Areas in the Region of Valparaiso, Chile

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Abstract: Providing energy to areas isolated from the electricity grid through the use of a smart integrated renewable energy system (SIREs) is proposed in this study for Valparaiso, Chile. The study analyzes the process of identifying the appropriate size of a SIREs considering technical and economic factors. An optimization model proposed in the literature was modified, and a subsequent spatial–temporal analysis of the different variables was conducted. The model comprises locally available renewable energy resources, such as biomass, biogas, wind power, solar photovoltaic, and thermal power. Furthermore, it was used to determine the energy potential of each of the isolated areas, identifying those areas in which the SIREs could be implemented as a sustainable solution. The design simulates the cost of the initial investment and energy generation in the chosen areas. The study also includes the selection of different system components and the use of the general model to determine the optimal combination of energy subsystems for isolated areas with the aim of minimizing the cost of energy generations. Finally, an economic evaluation showed that the use of a SIREs based mainly on solar energy supported by biomass, biogas, and mini-wind power costs approximately three times less than extending the electricity grid network.

Keywords: smart integrated renewable energy system; optimization model; off-grid electrification

1. Introduction

The use of renewable energy resources such as biomass, biogas, wind, and solar energy in a decentralized mode for the electricity supply has received considerable attention in recent years due to adverse environmental impacts and fuel cost escalation associated with conventional energy generation. These resources have enough potential to become important sources for power generation because of their environmental, social, and economic benefits in addition to public support and government incentives. All this is based on the Agenda 2030 for Sustainable Development, specifically Goal 7, according to the United Nations (UN) [1]. At present, there are approximately 1 billion people functioning without electricity, and 50% of them can be found in Sub-Saharan Africa alone. Fortunately, progress has been made in the past decade regarding the use of renewable electricity from water, solar,

and wind power. However, there are several barriers preventing renewable resources from being competitive against conventional energy sources in the current power market, as the supply of energy from these renewable resources cannot be regulated depending on the demand, and integration of these resources with grid network is not easy.

To overcome these problems, the concept of an integrated renewable energy system (IRES) has been propounded which matches the energy requirements of isolated zones far away from the utility grid having locally available renewable energy resources [2]. To keep up with developments in “smart” technologies, IRES was slightly modified and renamed SIRES to reflect the title of smart integrated renewable energy systems, in accordance with Reference [3].

A single technology approach, whether it be a solar photovoltaic energy home lighting system, wind, biomass, micro-hydropower, or any other system, is not adequate to meet the demands for long periods due to high cost of the systems as well as storage subsystems. To meet this challenge, locally available resources are either integrated or used in combination with conventional energy systems. The authors of [4] discussed a step-by-step approach for the adoption of technologies designed to exploit renewable energy sources at the rural level. In addition, an evaluation was made about the socioeconomic aspects of the introduction of solar (renewable) energy systems in rural areas in developing countries. The authors mentioned that the step-by-step approach discussed in this paper with the establishment of an energy center to provide energy for the basic needs of human existence and, later, the expansion of its functions to encompass agricultural and small-scale industrial needs appears to be a natural choice for developing countries to adopt.

Another similar study [5] presented an overview of the solar technologies of interest for use in developing countries and discussed rural energy needs and renewable technology options available to meet the requirements. Moreover, the authors analyzed the integrated system concepts and their advantages along with the economic and socioeconomic implications of introducing renewable energy systems in rural areas. The possibility of collaborative efforts between educational institutions in the US and in developing countries was outlined. Similarly, the authors of [6] described the role of renewable energy sources in meeting the energy needs of developing countries. The study showed the energy needs and unavailability of commercial fuels in rural zones increase the opportunity for the use of locally available renewable energy sources. Likewise, the paper emphasized that the final choice of the SIRES will depend on the particular site, village, region, available resources, country, application, need, and above all, the people and their customs.

On this matter, the Chilean authorities are working on the diversification of the energy base of the country, including in rural zones, and they have placed greater importance on renewable sources of energy. To take advantage of this potential, different actions are required, among which overcoming knowledge, economic, and regulatory barriers stands out. Renewable energies development in Chile is part of the 2050 Energy Agenda, a route that promotes, among its 38 guidelines, encouraging a high penetration of these energies in the country, using locally available resources, and taking advantage of energy development potential in production processes, among other recommendations [7].

Considering the 2050 Energy Agenda in the last few years, the National Commission for Energy (CNE), first, and then the Ministry of Energy (MINENERGIA) have worked in conjunction with the German Society for International Cooperation (GIZ) GmbH to propel lines of research destined towards bettering the knowledge of the potential for non-conventional renewable energy (NCRE) in Chile. Of note are prospection campaigns for wind and solar resources, as well as the studies developed and the refinement of tools for numerical modeling applied to the nation, which can be used to evaluate the behavior of renewable energy sources, with an ever-increasing spatial and temporal resolution [8,9].

Some of the resources, such as wind and solar radiation, are highly stochastic and characteristic of a determined site [8]. Others, such as biomass and hydro-energy, are more predictable, since they have a seasonal variation and are characteristic of the site studied [8]. Some loads are more variable than others, while some can be predicted with greater confidence; then, models or design procedures must take all these factors into account and be included in the calculation algorithms.

Some research has been carried out, directed towards the elaboration of models for designing SIRESSs. Examples of these are chronological simulation [10], linear programming [11,12], objective programming [13], and a probabilistic focus that considers the probability of loss of power supply (PPSP) [14]. Chronological simulation requires extensive databases on resources and loads that come from local needs, focusing on linear programming and objective programming and a deterministic use of average seasonal or annual values in their analysis. An interesting study was carried out using a knowledge-based approach; this design improves on previous studies in terms of the efficiency of the algorithm [15].

One of the techniques currently being used for a wide range of applications is temporal prediction, which is based on the order of magnitude of two temporal scales: the integration interval of a temporal series, and the maximum forecast horizon. In terms of the order of magnitude, according to Reference [16], this must be classified in a long-range prediction (annual horizons, with integration intervals varying between months and years), short-term prediction (daily horizons, with temporal series varying between minutes and hours), and ultrashort term (hourly horizons or less, with a temporal series varying between seconds and minutes). All these unified in the analysis of a region, and a study of the space obtained with a temporal series in different zones in the region, are called a spatial-temporal analysis. The creation of geographic information systems, with the spatial-temporal analyses of the region, will lead to being able to deduce energy behavior or potential [17]. According to Reference [18], the prediction that has been used most often is the short-term, with a quasi-stationary model, since it does not work with online data; however, due to the short time range of the temporal series, the behavior of any renewable system can be known very closely to what would happen in real time.

This topic was analyzed in [19], but it was applied to the first option of rural energy—the same as in [20], or [21], where the problem is focused on rural electrification by means of the geographic information system (GIS), directed towards the demonstration of value in the GIS methodology to develop the implantation of renewable energy in decentralized electrification in various pilot areas, the collection of data for its application in GIS, and the development of tools to determine the potential of renewable energy systems from initial data. The International Energy Agency, in [22], shows how the GIS provides detailed information about the type of possible energies that should be used in these communities, allowing comparative analysis among the costs of each possible system that could be used.

Several articles can be found dealing with the description of different models for the prediction of residential energy generation and consumption [23]. Two different approaches have been identified: Top-down and bottom-up. The top-down approach considers the residential sector as an energy dissipater and does not deal with final individual consumption, using the historical aggregated energy cost to determine the house-level energy consumption as a function of high-level variables, such as macroeconomic indicators, energy price, etc.

In other studies, spatial-temporal and spatial analyses have been used to evaluate renewable resources in any location, as [24] shows the wind potential in Malaysia on a nationwide scale. It comprises a spatial-temporal analysis of wind potential and a spatial analysis of wind power density (WPD) in Malaysia. The spatial-temporal analysis computed the spatial wind power density from the hourly wind map, computing the spatial distribution of the wind power density as a whole around Malaysia in a histogram. The total WPD for the whole of Malaysia was greater at higher heights or altitudes. The spatial wind data were interpolated from the point sources wind data by Kriging interpolation. The limitation of this model is that there are few measurements of wind speeds, covering only 1 year.

In Chile, a project was carried out to develop a solar explorer [25], allowing the analysis of surface solar radiation (GHI). The methodology employed to generate this database was based on the use of a radiative transfer model combined with information inferred from EAST GOES satellite cloudiness and local observations. The information provided by the solar explorer allows a preliminary assessment

of the solar resource for each of the geographical areas of the country where a SIRES system can be applied. Wind resources were assessed in [26], through the wind explorer, which provides information based on a numerical simulation of the atmosphere with an advanced model called weather research and forecasting (WRF). The WRF model has been used widely in the field of wind energy, both for characterization of the resource [27,28] and for generating predictions [29]. It appears in the guide on best practice recommendations for the development of mesoscale wind maps prepared by the World Bank Energy Sector Management Program Assistance (ESMAP) [8]. Several international suppliers who specialize in selling models use the WRF wind resource for the development of their commercial products (3Tier, Vortex).

As mentioned previously, a Goal of the 2030 Agenda for Sustainable Development presented by the United Nations, as well as a pillar of the 2050 Energy Agenda in Chile, consists of increasing the use of nonconventional renewable energies for energization of the country and vulnerable areas in terms of access to energy. In this way, ensuring universal access to affordable, reliable, and modern energy services is possible. Moreover, based on this, the proportion of the population with primary reliance on clean fuels and technology increases, as well as the share of renewable energy in the final total energy consumption. That is another objective of the 2050 Energy Agenda of Chile and 2030 Agenda for Sustainable Development for several countries.

The present study studied the decentralized option for the energization off-grid of a cluster of isolated villages of the Valparaiso Region in Chile. The objective was to find the suitable component sizes and an optimal operation strategy for the study area using the integrated renewable energy optimization model (IREOM). This model will be modified according to the necessities and spatiotemporal series of the study areas. The results obtained have been used to design and plan an optimal system ensuring reliable and economical power supply to the cluster of villages selected.

It is worth noting that from the reviewed literature, it can be seen that relevant contributions on this subject have been made. However, in some cases, the analyses have led to incomplete or inviable solutions from an economical and technical perspective. In the case of SIRES, some articles in the literature present the size and final configuration of the installation based on a time–space analysis, which considers the characteristics of a location in terms of its energy-related behavior. In this way, the present study allows to establish the most viable SIRES configuration to be applied in the energization of isolated villages.

2. Methodology

2.1. Study Area

The Chilean Ministry of Energy, through its Energy Equity and Access Division (DAEE), estimated that in 2010, electricity coverage in rural areas was 96% nationally and 95% in the region of Valparaiso.

According to this, approximately 20,000 rural homes in the country are isolated and without access to electricity. Figure 1 shows the geographic location of the study area, which is at latitude $33^{\circ}03'47''$ S and longitude $71^{\circ}38'22''$ W, with different altitudes above sea level. It has a surface area of 16.396 km^2 and an approximate population of 1,884,387 inhabitants, according to data from the National Statistics Institute (INE). Precise information on the fully isolated areas is vital in order to obtain an immediate solution. There are no concrete statistical data on these aspects; however, up-to-date information was obtained in conjunction with the Energy Regional Ministry of Energy Secretariat (SEREMI) of the region of Valparaiso, by requesting that all municipalities send frequent reports to be used to locate each sector in particular. Based on this, Table 1 shows the sectors that report families without access to electricity supply.

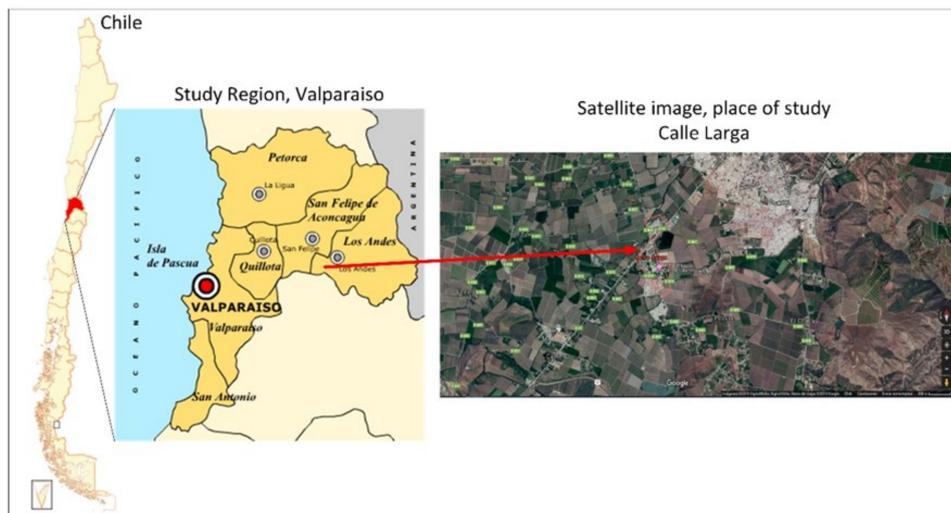


Figure 1. Location of the study area.

Table 1. Rural sectors without access to the electricity grid as reported by the Energy Regional Ministry of Energy Secretariat (SEREMI) of the region of Valparaíso up to 4th January 2016.

	District	Sector	N° of Homes
1	Calle Larga	Álamo, Los Rosales, Patagual 1 and Patagual 2	25
2	Cartagena	El Turco, La Rudilla and Chacarillas	29
3	San Antonio	Rinconada de San Juan, Cuncumen-Valle Abajo and San Juan	6
4	Zapallar	Las Lomas, Cuesta Cavicolén and Los Perales.	10
5	Puchuncaví	El Rincón, Potrerillos and Chilecauquen.	6
6	Cabildo	Cerro Negro, Guayacan, La Mora y and Ciruelo.	32
7	Olmué	La Vega, Las Palmitas, Los Bellotos, Naváez, El Duraznillo, Farallones, Quevarada Alvarado, 21 de Mayo and La Palma	21
8	Papudo	Las Salinas and Pullaly	23
9	San Esteban	Baños el Barro	4
10	Santo Domingo	Fuente Rabia, Pagui Rosa, Bucalemu, Puente Yali and Santa Blanca	9

2.2. Resources and Load/Demand Assessment

The potential of NCRE is highly variable across different areas. The availability of the energy resources for each type of NCRE has its own variables, generally with degrees of uncertainty, such as the instability in solar potential depending on climate conditions, or the difficulty of long-term prediction of wind speeds. Therefore, it is not simple to analyze an energy resource or to choose the place where a SIREs can be installed. Nevertheless, there are statistical and physical methods that can give a general idea. To begin such an analysis, it is necessary to precisely identify the location of each sector on a macro level, since the behavior of the potential is almost the same throughout a single sector.

The potentials are based on the most common sources of NCRE present in the region, disregarding less developed technology that implies a much higher investment cost (such as geothermal, tidal, and wave energy). The potential energy sources include heat and photovoltaic solar energy, wind, biomass, and biogas. In the case of the energy generation potential of micro-pump hydraulic energy (MHP), the results obtained are inconclusive [30]. These were calculated in 2010, when the hydrological reality was completely different to today's situation. The values obtained lack detail in their seasonal fluctuations, which overlooks the real situation, in which there are variations depending on the time

of year and climate phenomena. The districts in the present study do not have rivers or reservoirs of any type to be used with MHP technology. Therefore, without detailed values on the sources of MHP, there would be a high degree of uncertainty in the potential of the energy source, and as such, it has been omitted from the present analysis.

The energy potential results are based on the spatial–temporal study of solar, wind, and traditional biomass energy, determining the daily contribution for each sector in the region at different times of the year [30]. Considering an installation that is fully dependent on NCRE, it is important to analyze the most critical month, which limits the design and size of the installation. The results obtained for the annual daily energy contribution and for the most critical month are shown in the following Figures 2 and 3.

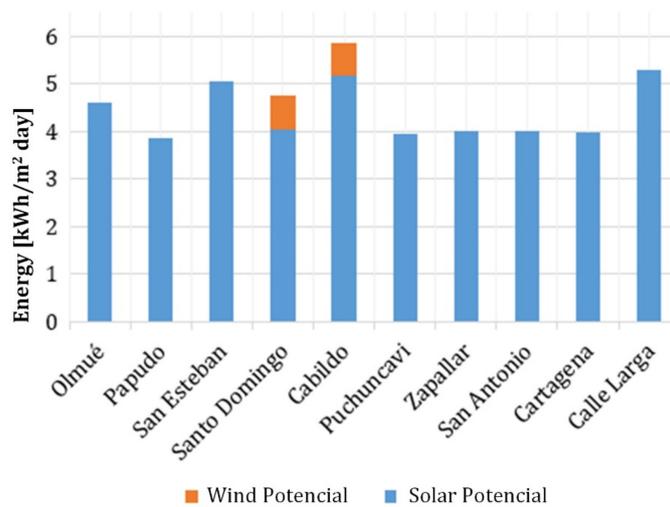


Figure 2. Average daily energy potential as a function of annual energy potential, by surface area and per sector.

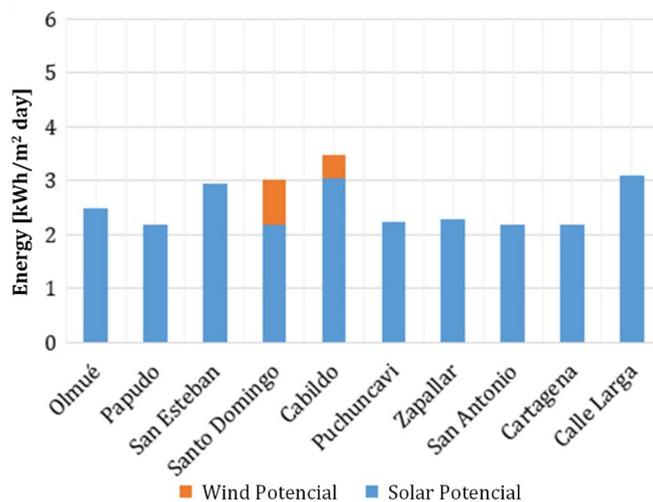


Figure 3. Average daily energy potential as a function of the monthly energy potential of the most critical month (i.e., June), for 1 m² of surface area and per sector.

Comparing sectors, it can be seen that the highest average annual energy contribution is in Cabildo, with 5.84 kWh/m² day (wind plus solar), followed by Calle Larga, with 5.29 kWh/m² day (solar only). Analyzing the most critical month, it can be seen that the most “optimal” sector for the installation of a SIREs is Cabildo, as it has a higher energy potential compared to the other sectors, with 3.5 kWh/m² day, followed by Calle Larga with 3.1 kWh/m² day and Santo Domingo with 3.0 kWh/m² day.

The biomass resource, including waste products from farming, foliage, and farm manure, was evaluated for each region in the country in a previous study [31] based on the different sources available. The biomass potential for electrical energy and heat production is shown in Figure 4, from which a total value of 13,675 MW was determined. The problem with this source of energy is that there are no individual studies for the sectors within the region.

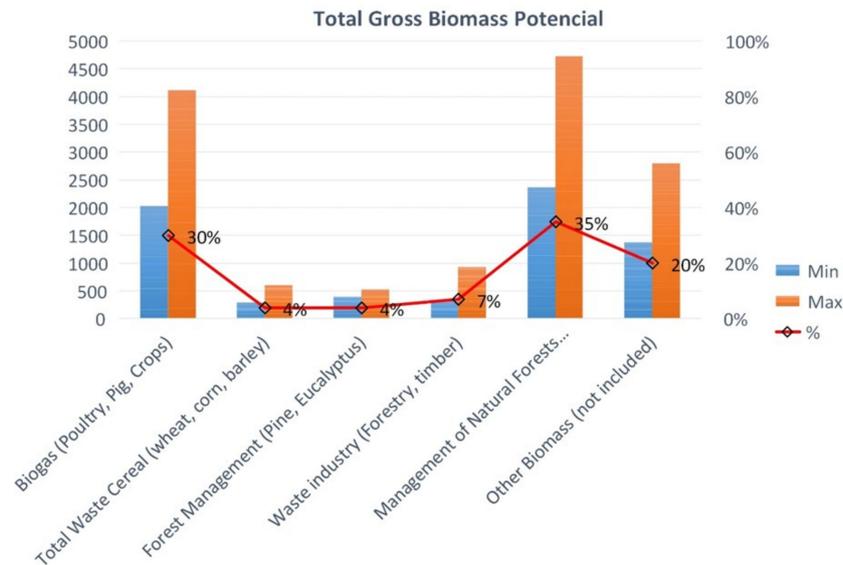


Figure 4. Gross potential in Chile per Biomass Source. From data of [31].

According to these results, there are three methods of energization by different sectors in which the final evaluation will be carried out:

- 1st Method—Wind + Solar (Photovoltaic and thermal) + Biomass (biogas), Sector Cabildo;
- 2nd Method—Wind + Solar (Photovoltaic and thermal), Sector Santo Domingo;
- 3rd Method—Solar (Photovoltaic and thermal), Sector Calle Larga and Cabildo.

In order to evaluate the most economical solution, it is necessary to determine the size of the installation and compare the profitability of a mixture, such as Cabildo, where there are three potential energies to be used, though solar is the highest. In Santo Domingo, two energy sources (solar and wind) are usable, but wind is considerably higher than the other sectors, and in the case of Calle Larga, there is only a high degree of solar potential. It can be stated that one of the two main sectors may be capable of the application and implementation of a SIREs.

2.3. Average Energy Consumption of an Isolate Home in a Rural Area and Disconnected from the Grid

The energy consumption of any home is naturally divided into the types of energy used: Electricity consumption for electrical appliances and other electrical items and thermal consumption, mainly used for cooking and sanitary hot water (SHW). The energy contribution required of a SIREs needs to be known to the highest degree of accuracy possible to avoid an energy deficit or inadequate design of the installation. The proposed case is of a single-family home comprising four people.

2.3.1. Electrical Energy Consumption

Reference is made to a prior study of consumption in rural and isolated sectors [32], which proposes two cases:

- Basic rural housing with four inhabitants: Basic electrical appliances;
- Equipped rural housing with four inhabitants: Common electrical appliances.

Table 2 shows the electricity consumption of homes isolated from the grid of the types “basic” and “equipped”, determined by studies that present the updated version of the aforementioned Chilean standard.

Table 2. Electricity consumption for homes isolated from the grid of the types “basic” and “equipped” updated from Reference [32].

Variable	Potential	Number of Appliances in a Basic Home	Number of Appliances in an Equipped Home	Daily Use	Energy Needed “Basic”	Energy Needed “Equipped”
Unit	(W)	(u)	(u)	(h)	(kWh/day)	(kWh/day)
Total	865.0	5.0	14.0	36.5	1.0	3.64

2.3.2. Energy Consumption for Cooking

It is not a simple task to determine the energy consumed by a home over a period of time, as this depends on several variables, such as the number of inhabitants, the type of food, and socioeconomic factors. Table 3 shows a summary of a prior study [33] carried out throughout the country. It calculated the energy consumption per socioeconomic level (A, B, C1, C2, C3, and D) and climate area, including annual energy consumption for cooking.

Table 3. Monthly energy consumption for cooking, by socioeconomic level and on a national scale [kWh].

Socioeconomic Level	Nacional	A, B, C1	C2	C3	D
Energy unit	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
Annual consumption per home	78.3	70	70	59.9	63

This was used to calculate the energy consumption for the present study, using the level C3, for an “equipped rural home” and level D for a “basic rural home”, which has been presented in Table 4, since these are isolated rural areas and have low socioeconomic levels.

Table 4. Energy consumption for sanitary hot water (SHW) for single-family homes with four inhabitants.

Sector	Average Annual Daily Heat Demand (kWh Day)	Sector	Average Annual Daily Heat Demand (kWh Day)
Olmué	5.63	Puchuncaví	5.21
Papudo	5.14	Zapallar	5.25
San Esteban	6.70	San Antonio	5.34
Santo Domingo	5.30	Cartagena	5.34
Cabildo	5.94	Calle Larga	5.66

2.3.3. SHW Consumption and the Energy Needed

SHW consumption per home is relative and mainly depends on the number of people that live there, considering a home (single family) or a population (multifamily), sector and the temperature of the water supplied. In order to calculate SHW consumption and the energy needed to heat the water to the required temperature, it is necessary to determine some values before calculating. These are obtained from the technical Chilean norms on low temperature thermal solar collectors [34]. The case in question is a single-family home with four inhabitants, and the results in Table 4 were obtained using Reference [34].

3. Model Configuration

Once the sources of NCRE in each sector had been analyzed, a case was proposed for which an energy solution could be found. The SIREs aims to make full use of the NCRE resources available in the sector in a clean, self-sustainable way while remaining as economically viable as possible. Though the ideal SIREs would use all sources of NCRE in order to diversify the energy matrix and not be fully dependent on one source, in most cases, this is not possible. The design will depend on the energy potential of the site and the profitability of exploiting that energy. Figure 5 evaluates cases using one or two sources of energy, which is more viable than attempting to integrate all of them. Analyzing the potential separately can help to find out whether there is a wide economic gap in the use of one compared to another if the financial costs are similar. Then, integration would undoubtedly be possible, as [35] proposes.

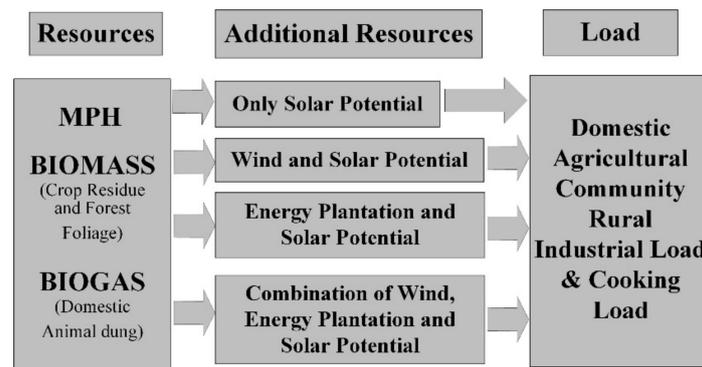


Figure 5. Different energy scenarios, depending on the study area. Reported by Uttarakhand, India. Reproduced with permission from [36], [Renewable Energy], published by [Elsevier], [2010].

After obtaining the total values for energy potential, the installation site was analyzed and defined by choosing the area with the highest total potential. Once the site was defined, a model similar to Figure 6 was proposed and which was able to mathematically describe the behavior of the SIREs and satisfy the criteria in accordance with the availability of sources of NCRE identified in the previous potential analysis. This prior analysis determined which sources to include in the model. However, the model must be able to optimize the development of the installation, placing more or less importance on the difference sources of NCRE.

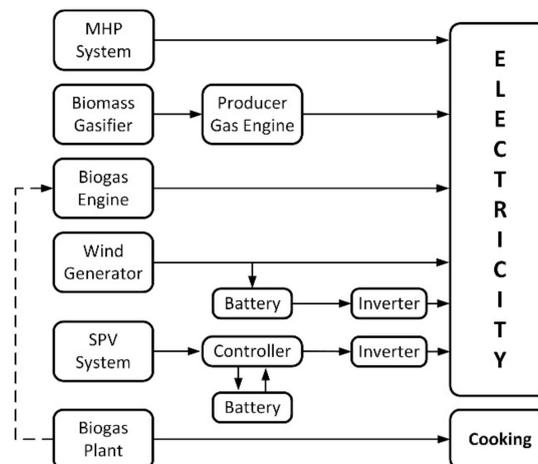


Figure 6. Configuration of the integrated renewable energy optimization model (IREOM). Reproduced with permission from [37], [Renewable Energy], published by [Elsevier], [2011].

Figure 6 shows the optimal configuration of a SIREs implemented in India and published in References [37,38], where the researchers modeled and used the integrated renewable energy optimization model (IREOM). The proposed IREOM was designed to integrate the locally available renewable energy systems. Each system has its advantages and limitations. The system supplies continuous energy, while the wind energy and the PV solar system produced or stored energy to be used continuously. The use of biomass (from crop waste products and forest foliage) as a source of energy in rural areas produced little information on electricity generation for groups of remote villages using an integrated renewable energy system and on the size of the biomass gasifier, although biomass is a prominent source of energy in rural areas in Chile. For the case of the present study, MHP is not considered for the reasons explained above. The other energy sources are similar, only varying in their potential, as is logical considering the geographical location and climate of the area. A biomass gasifier is used continuously during a short period of time and is mostly operated when the load exceeds the system capacity of wind and solar energy.

The IREOM model can therefore be planned and designed to overcome intermittent behavior. In this model, all the energy systems are interdependent, and their size varies when a small change is made to the model. The different sets of sizes of the systems are analyzed to obtain the optimal solution, and the model developed is able to provide an optimized combination of the sizes of the renewable energy systems for a given load profile. The study analyzed the different load profiles and different proposals to select the best option from the optimized solutions.

The optimization of the proposed IREOM has three submodels: Energy conversion systems, reliability, and the economic submodel. A brief description of each submodel is presented in detail in the study [37]. For the present study, the MHP submodel should be discarded and replaced by a submodel for the use of thermal solar energy (solar thermal collectors—STC), which is used to produce SHW. As has been previously reported, the MHP potential depends on the climate variables and the availability of water reservoirs at the villages selected. Therefore, without detailed values on the sources of MHP, there would be a high degree of uncertainty in the potential of the energy source, and as such, it has been considered negligible. The equations programmed for the STC system are shown later in Section 3.

Moreover, a traditional hot water boiler (THW) was included in the IREOM in order to provide hot water on winter days. The start-up of THW occurs at times that the STC system can operate offline. The gas supply for the THW system was implemented by means of the biogas plant, with the aim of ensuring the production of sanitary hot water.

The other modifications of IREOM are considered minor. These changes do not include big modifications of the original IREOM. Just the data of the equipment available in the Chilean market for each renewable energy sources used have been added, as well as an update on the variables that influence on the economic analysis, such as the current price of equipment and government subsidies. Based on the above description, the IREOM Modified is represented in Figure 7, in which the changes are shaded.

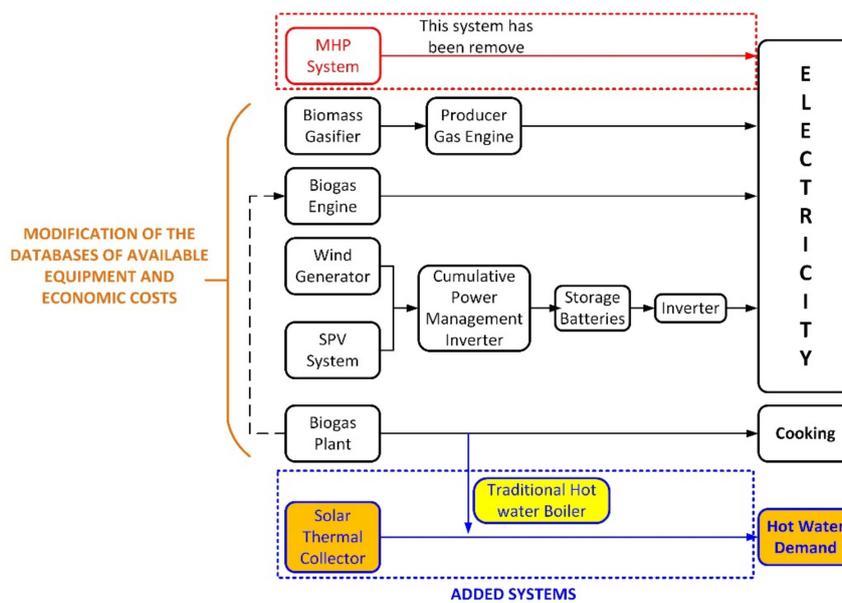


Figure 7. Configuration of the modified IREOM model.

Mathematical Model for Solar Thermal Collectors (STC)

In order to modify the IREOM and model the size of the STC system, two methods were used:

- Chilean standards on sizing and calculation equations from the F-Chart method [39];
- Software for solar fraction calculations from [40].

In the case of the F-Chart method, the solar contribution of a system and its mean yield can be calculated using monthly mean values of different variables (water demand, water network temperature, solar radiation, and mean daytime temperature). This is then used to define two nondimensional parameters, $D1_i$ and $D2_i$, related to the ratio between daily energy absorbed by the collector and daily heat demand for month i , and the ratio between energy lost from the collector and the daily heat demand for month i , respectively. These parameters are used in the calculation of the correlation factor of the F-Chart method, f_i , using the following empirical expression (Equation (1)) and the development algorithm in accordance with [41]:

$$f_i = 1.029 * D1_i - 0.065 * D2_i - 0.245 * D1_i^2 + 0.0018 * D2_i^2 + 0.0215 * D1_i^3 \quad (1)$$

Since the present problem is an isolated system, the aim is to cover the entire demand, meaning that the solar fraction will tend to 1, thus theoretically giving the number of panels necessary to cover all demand, since each panel provides a percentage of the solar fraction. Dividing the total by the percentage provided per panel will give the number of panels needed, as shown in Equation (2):

$$N^\circ \text{ panels} = \frac{f_{total}}{f_{per \text{ panel}}} = \frac{1}{f_{per \text{ panel}}} \quad (2)$$

The installed surface area of the STCs (A) with solar thermal collectors is expressed in m^2 and is the sum of the areas of each collector belonging to a single system. The total area of the panels is directly related to the volume of the accumulation deposit (V) accumulated in the tanks, based on the amount of flow circulating and the SHW production capacity. The values of V and A must comply with the following condition:

$$40 \leq \frac{V}{A} \leq 180. \quad (3)$$

Parameter $D1_i$ is calculated through the multiplication the optical efficiency of the solar collector η_0 in %; the mean daily solar radiation on the inclined surface for month i , $R_{Gd\ inc\ i}$ in MJ/m²; the correction factor of the collector–interchanger, according to Chilean standards [41], $FC_{int} = 0.95$; and the modifier of angle of incidence, according to Reference [41], $MAI = 0.96$; divided by the daily thermal energy demand for heating water for month i , $D_{ed\ i}$, in MJ/day, according the Equation (4), for each month of the year:

$$D1_i = \frac{A * \eta_0 * MAI * FC_{int} * R_{Gd\ inc\ i}}{D_{ed\ i} * 100}, \quad (4)$$

Parameter $D2_i$, is calculated in following way for each month of the year:

$$D2_i = \frac{A * UL * FC_{int} * (100 - T_{ami}) * FC_{acm} * FC_{ACS} * \Delta t}{D_{ed\ i} * 100}, \quad (5)$$

where:

- Δt : Daily operation time in hours (h),
- UL : Global loss factor (W/m²·K), proposed in Reference [42]:

$$UL = K1 + 30K2, \quad (6)$$

- $K1$ and $K2$ are the coefficients of the collection efficiency equation, according to standard [35],
- FC_{acm} : Accumulation factor [41]:

$$\left(\frac{V}{75 * A} \right)^{(-0,25)}, \quad (7)$$

- FC_{ACS} : Correction factor per temperature [41]:

$$FC_{ACS} = \left(\frac{11,6 + 1,18T_{ACS,min} + 3,86T_{Redi} - 2,32T_{amb}}{100 - T_{amb}} \right), \quad (8)$$

in which:

- $T_{Red\ i}$: Mean monthly temperature of water network, for month i , for the district, in °C.
- $T_{amb\ i}$: Mean monthly outside temperature, for month i , for the district, in °C.
- $T_{ACS,min} = 45$ °C, minimum working temperature [41].

Finally, the adjusted energy contribution [Pi] is the percentage of the final energy contribution in comparison to the demand, and it is calculated as follows:

- If $fi < 0$, then $Pi = 0$
- If $fi > 1$, then $Pi = 1$
- If $fi > 0$ and $fi < 1$, then $Pi = fi$

There are months in which the theoretical energy contribution of inclined solar radiation is higher than the energy demand on the system, making the solar fraction more than 1. Nevertheless, this case is not possible in reality, since the size calculation is as a function of demand, and the use of a percentage more than 100% would affect the real and annual average contribution used by the system. With the methods explained with F-chart and Ministry of energy (MINENERGIA) Software, the necessary area of absorption to satisfy heat demand for SHW using the proposed STC is calculated, and the results are shown in Figure 8.

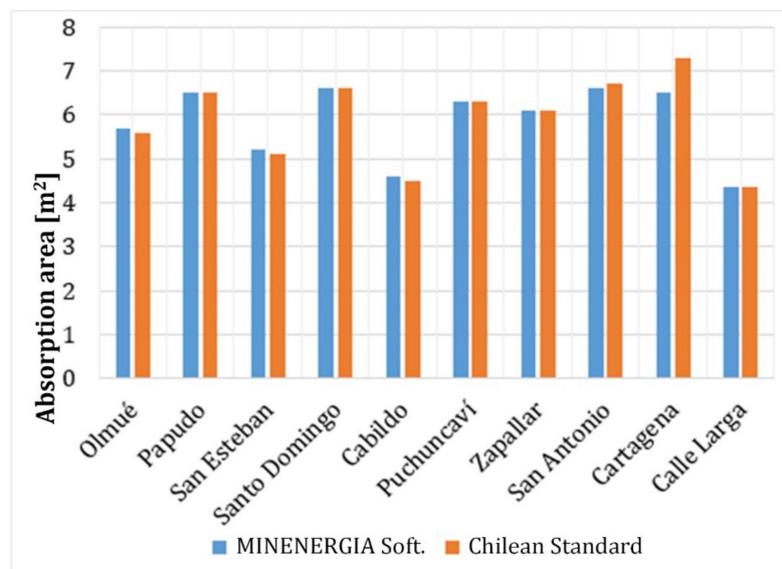


Figure 8. Comparison of two calculation methods for the value of absorption surface area in m^2 needed to cover 90% of demand in the most critical month.

4. Results and Discussion

As discussed above, the objective of this study is to determine the size and technical–economic viability for the feasibility of implementing an integrated renewable energy system in the region of Valparaíso, for which a modified IREOM was used in order to satisfy the energy demands (electrical and heat energy) in specific isolated areas, Cabildo and Calle Larga. The system sizes for the different sources of renewable energy have been considered in accordance with the manufacturer’s specifications, and the four seasons were taken in account, and the resulting required loads were calculated.

4.1. Solar Thermal Collectors (STC)

It is highly difficult to select the most optimal model and type of technology for the STC, since the working conditions in each sector are variable. Engineering criteria help to avoid evaluation of each of the technologies for each type of operation and each of the sectors, as this would be too expensive and time-consuming. However, there are factors that can be differentiated, such as water hardness, inclined solar radiation, minimum temperatures, cloud cover percentage, etc. Based on this, it was found with the IREOM modified model that the best solution is to use a heat pipe type STC. According to this, the STC (Table 5) obtained at both zones studies of Cabildo and Calle Larga are practically identical.

Table 5. Technology used for solar thermal collectors (STC).

Supplier	ESOL
Brand	Prisma Solar
Technology	Heat pipe STC
Optical efficiency (η_0)	71.4%
Linear loss	$1.08 \left(\frac{W}{m^2} \cdot K \right)$
Collection area	2.84 (m^2)

4.2. Tube Biodigester for Biogas Production

As well as contributing to SHW production, biogas is also used as fuel in cooking, meaning that the final heat demand is the sum of the energy deficit from producing SHW and the total to cover the heat demand for cooking. The data available on this resource are mainly based on bovine manure,

which can be used to ensure at least a minimum production to satisfy heat demand. Plant waste has a better production factor, which introduces an additional percentage to the biogas generation. The final size necessary for the biodigester to ensure biogas demand obtained from the IREOM Modified Model is shown in Table 6.

Table 6. Dimensions and operational characteristics of the biodigester.

Variable	Roll Width (m)	Circumference (m)	Radius (m)	Diameter (m)	Area (m)	Length (m)	Volume (m)
DIMENSION	1.5	3	0.48	0.96	0.72	6.15	4.45
	Daily bovine manure (kg/day)	Dilution ratio	Production factor (bovine) (m ³ /kg)	Load retention time (days)		Biogas production (m ³ /day)	
OPERATION	15.8	1:4	0.04	45		0.632	

4.3. Installation of Solar Photovoltaic (PV) for Electricity Consumption

The design must be able to take sufficient safeguards and also accumulate energy depending on the climate conditions of the sector, based on an analysis of cloud cover and precipitation, as these can affect the correct functioning of a photovoltaic panel. Based on this, a König Sonne polycrystalline PV panel with a maximum potential of 300 W should be used. The number of modules necessary for the three sectors in the most critical month is presented in the Table 7.

Table 7. Summary of results for the number of photovoltaics (PVs), days of autonomy, and pairs of batteries, by sector for the most critical month.

Sector	Calle Larga	Cabildo	Santo Domingo
Number of PV	4	4	6
Days of autonomy	3	3	4
N° of pairs of batteries	3	3	4

From the results above, since Cabildo and Calle Larga have the highest level of radiation, they need a lower number of modules, in this case four. Under this same criterion as with the case of PV, the results obtained for the number of pairs of batteries and days of autonomy are as follows in Table 7.

4.4. Installation of Wind Energy

In order to analyze the real energy potential of the sector, it is necessary to use a base aerogenerator, since the behavior changes with the technology and characteristics of the device. Therefore, the operational characteristics of the wind turbine must be considered. The way in which the energy generation from the turbine was determined involved a combination of energy potential of the sector and the capacity of the aerogenerator to make use of this potential based on the operational characteristics. The main criterion for the selection of the turbine was the cost–potential ratio, which is certified by the Office of the Superintendent of Electricity and Fuel in Chile (SEC), since there are no laws that financially support the purchase of these devices. It was found that the base aerogenerator to be used is the Boreas 150, which has a nominal power of 120 W (12 m/s). The daily electrical energy contribution for each sector varies by month, unlike the electricity demand, which remains constant throughout the year. Since the energy contribution has been quantified, it is possible to determine the number of Boreas 150 turbines that are needed to satisfy the demand in each month. The results of this are shown below:

According to the results shown in Table 8 at the Cabildo zone, there is a high concentration of wind in summer months, a time when there is also maximum solar power. This leads to a poor distribution of NCRE resources, meaning that in the most critical month, a total of 20 wind turbines

are needed, along with four PVs due to the decrease in solar radiation. However, when looking at the best place to install the SIREs, the result is based on the economic evaluation more than the energy performance. Moreover, there is not enough landscape for these many turbines to occupy.

Table 8. Number of Boreas 150 turbines to satisfy the total electricity demand in the sector of Cabildo, by month.

Month	Number of Turbines	Month	Number of Turbines
January	10	July	20
February	10	August	20
March	13	September	13
April	13	October	13
May	13	November	13
June	20	December	10

4.5. Biomass Gasifier Power

The size of the biomass gasification system is mainly considered for biomass materials such as tree branches, forest foliage, and harvest byproducts. Based on the information obtained from manufacturers, a biomass gasification system using wood varies from 4 to 250 kW. Normally, a biomass gasification system is considered to function for 2 to 4 h a day with the daily available amount of biomass. The biomass gasification system in question for a wood-based system, for the total number of homes isolated from the electricity grid, is 2.5 kW [42].

4.6. Approximate Cost Generation Equipment, Reserve Equipment, and Installation

In order to compare the energy production costs of different NCRE technologies, it is necessary to standardize the parameters. One way is to use the parameter \$/kWh, or the cost of producing 1.0 kWh, including all costs. The lowest value for this parameter for each technology would then give the most economical energy production and, therefore, the most recommendable. However, the costs are approximated, since it is not possible to determine the detailed cost of the components of each installation. Based on this, the unit costs per device and the total costs of providing energy for each type of NCRE technology and for each sector are shown in Table 9.

Table 9. Cost of SHW production using an STC, evaluated in Chilean pesos (CLP) and the ratio \$/kWh to energy production, in the sector of Cabildo and Calle Larga.

Energy Generation Method	Ratio (\$/kWh)	
	Cabildo	Calle Larga
Electricity from PVPs	183	240
Electricity from Wind Turbines	301	271
SHW production from STC technology	92	122
Biogas production for cooking and SHW	7.7	7.7

Another important value that is independent from the investment in equipment for energy generation is the cost of workers certified by SEC who will carry out the installation of electronic equipment, as well as individuals to install the solar thermal systems:

- Cost of electrical installation: \$600,000 Chilean pesos
- Cost thermal installation: \$400,000 Chilean pesos

4.7. Selection of Technology to Be Used and the Sector of Installation of the SIRES

In Table 9, the costs of providing energy to the study zones are compared, using different technologies and the results obtained from the IREOM modified model. This analysis shows that the wind resource is not economically viable in comparison to photovoltaic power. The results performed that Cabildo has better indices (\$/kWh) than Calle Larga, since its main advantage is its solar resource. As such, Cabildo was chosen as the most optimal sector for the SIRES installation, mainly due to its higher solar resources, biomass, and the contribution of wind power using aerogenerators to diversify the energy matrix, considering the low cost of each unit. Therefore, the SIRES will be defined as shown in Figure 9, and the details of the components are presented in Table 10:

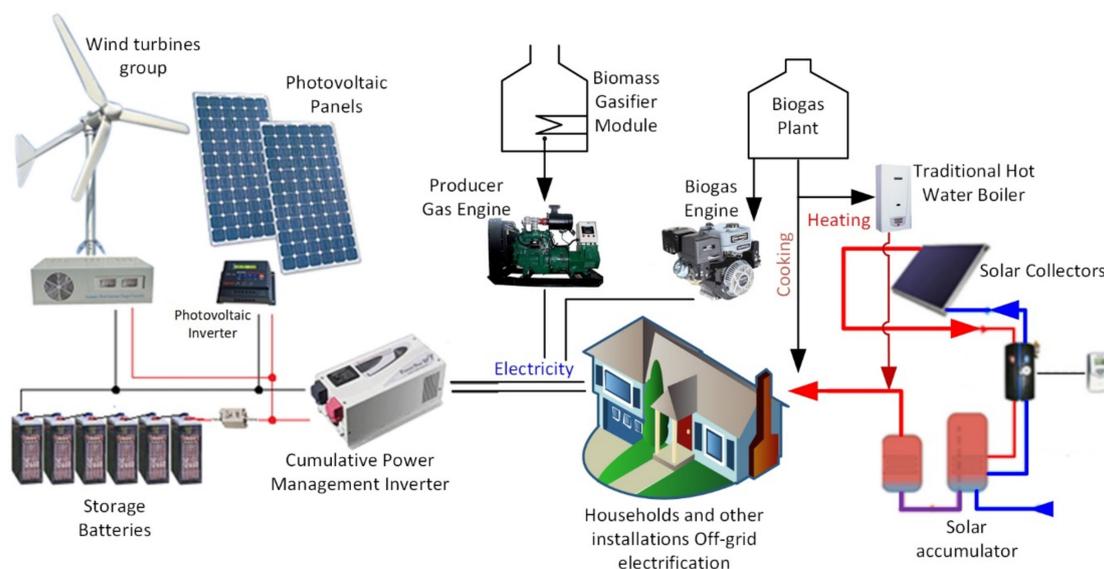


Figure 9. Simplified diagram of the resulting smart integrated renewable energy system (SIRES) to supply energy at a sector of Cabildo.

Table 10. Equipment that makes up the smart integrated renewable energy system (SIRES).

Equipment	Model	Units
PVP	ESOL	3
Biomass gasifier	-	1
Wind turbine + controller	Boreas 120 W	3
Inverter	Koning Sonne	1
Controller	Chisol	1
Structure	Gensolar	4
Batteries	Vision	6
Black cable	20 cm	2
Black cable	50 cm	1
Red cable	50 cm	1
Cabinet	Chisol	1

The final cost of the SIRES was compared with the cost of extending the current electricity grid in the Region of Valparaiso in Chile. Table 11 shows the calculations, which were carried out using referential costs from the Ministry of Energy for extending the electricity grid for each region in the country [43].

Table 11. Comparison of costs, in Chilean pesos.

Cost of Extending the Electricity Grid	\$ 9,969,716
Cost of SIRES	\$ 4,045,130
Cost of SEC technicians	\$ 1,000,000
Difference	\$ 4,924,586

The difference between extending the electricity grid and installing the SIRES is \$4,924,586 Chilean pesos, making the latter option considerably more economical, though to determine if it is profitable, it would be necessary to perform a long-term analysis, comparing possible solutions and considering aggregated costs over the life-span of the equipment.

5. Conclusions

An integrated renewable energy system was designed through the use of a modified version of an IREOM optimization model. The system consists of biogas, wind, and solar energy for the study area in question. The main changes included in the IREOM model consist of programming a module for solar thermal energy, as well as a supplementary traditional hot water boiler to ensure hot water supply. In addition, the module of MHP system was eliminated due to hydraulic resources being negligible. Other minor modifications on the IREOM model regarded the equipment available for each renewable energy source used. For the economic analysis, it was necessary to take into account the current price of equipment and government subsidies of Chile. From these changes, the modified IREOM model optimized different options in renewable systems on the basis of economic cost and the reliability index when the specific conditions of the site and seasonal loads are known.

Regarding the Sustainable Development Strategy 2015–2030 and the specific Goal 7, these criteria were important to establish the SIRES more adequately for the villages selected, because the use of clean technologies and sustainable energy allows to reduce the amount of greenhouse gases which cause climate change and have harmful impacts on people's well-being and the environment. Moreover, countries such as Chile can accelerate the transition to an affordable, reliable, and sustainable energy system by investing in renewable energy resources and adopting clean energy technologies and infrastructure.

Of all the villages analyzed in this study, Cabildo was found to have the highest potential for NCRE standardized to a surface area of 1 m², at a value of 5.84 kWh/m² day for the most critical month. This can be broken down to 0.4 kWh/m² day for the wind resource and 5.44 kWh/m² day for solar power. It was found that the SIRES would have solar thermal energy as its main source of NCRE, followed by solar photovoltaic, with a small contribution from biogas, a biomass gasifier, and wind power. Taking into account that the total energy required for a house located in Cabildo is equivalent to 3557 kWh per year, it can be highlighted that the integration percentages for each of the energy generators are: 49.5% STC, 22% PV, 18.5% biogas, 5% biomass gasifier, and 5% wind.

The use of the proposed SIRES is vastly more economical than providing energy to the sector using traditional fuels or extending the connection to the electricity grid. The total investment required for the basic engineering of the SIRES is CLP \$4,045,130. This is equivalent to approximately 40% less than the investment required to extend the national grid. Of all the sources of energy integrated into the SIRES, the most economical is the energy generated by the heat pipe biodigester, with a cost of 7.7 \$/kWh, almost 10 times less than the other technologies.

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