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A Mathematical Model for the Optimization of Renewable Energy Systems †

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Abstract: The generation of energy from renewable sources is a fundamental aspect for the sustainable development of society, and several energy sources such as solar, biomass, biogas, and wind must be used to the maximum to meet existing needs. In Chile, there are villages that are off-grid. A real case study is presented in this research. To meet the needs of this village we have proposed a mathematical optimization model using a CPLEX optimizer to generate the necessary energy power while minimizing the cost of energy (*COE*). In this study, different scenarios have been evaluated with respect to the existing energy availabilities, for example, in different periods of the year, demonstrated in terms of economic costs, the viability of resources such as biomass and biogas, and the viability of the energy production of wind power given the associated high costs. Finally, the effect of the use of renewable energy in consideration of CO_2 emissions is studied in our research.

Keywords: mathematical programming; optimization model; energy system; renewable energy; cost of energy; greenhouse emissions

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1. Introduction

Nowadays, the use and implementation of renewable energy sources (RES) based on biogas, biomass, solar, and wind energy in a decentralized mode for energization (thermal energy and electricity) has been an active area of research in recent years, due to existing environmental problems and the increase in the cost of fuels, directly related to the production of electrical energy. These types of resources are an option to be considered by governments and companies dedicated to the generation of electrical energy, as primary sources. Renewable energy sources provide notable environmental, social and economic benefits. This is exposed in the "2030 Agenda for Sustainable Development" adopted by the United Nations [1]. There are currently around one billion people in the world who live without electricity, and the continent of Latin America is one of the most needy in this regard. Fortunately, in the last decade progress has been made in the use of renewable energy sources from wind energy, solar energy and water. Recently, the works presented by [2–5] have demonstrated such advances, specifically in electrical generation for different targets. However, there are obstacles that make it difficult for renewable energy resources to be competitive with conventional energy sources, because the energy supply of these renewable resources cannot be well managed according to demand.

To solve these problems, the definition of an Integrated Renewable Energy System (IRES) was suggested, which agrees with the energy conditions of villages with locally available renewable energy resources [6]. Currently, the concept of "smart" technologies on an RES has been implemented, and they are now called SIRESs (Smart Integrated Renewable Energy Systems), according to reference [6]. The authors of [7] introduced a methodology and an optimization model for an electricity supply chain that allows the variability in the RES supply to be reduced by optimally planning the supply chain operations. The methodology supports the identification of the optimal operation of the electricity supply chain by electricity decision makers, considering multiple objectives and supply chain designs, including innovative architectures.

In SIRESs, resources such as solar radiation and wind are considered stochastic and peculiar to a particular location [8,9]. There are other resources such as hydroelectricity and biomass, which are usually predictable, since they include seasonal variations and are specific to the place studied [10,11]. Certain loads present more variable characteristics than others, and some can be predicted with greater precision and reliability; furthermore, the conceptual models or design and implementation processes must encompass the factors involved and addressed in the algorithms and computational approaches.

As we mentioned above, a main goal of the 2030 Agenda, as well as a principle of the Energy Agenda in various regions of the world, is to raise the use of renewable energy sources for the energization of vulnerable areas and countries in terms of access to energy. In the case of Chile, the Ministry of Energy (MinEnergía) does not have a clear mechanism that defines the most appropriate configuration of renewable energy systems to be used in rural electrification projects from technical and economic perspectives.

This paper is an extended version of work published in [12]. The objective of the latter was to obtain only an optimization model. The current study presents an analysis and evaluation of the problem of sustainable energization, where the main objective is to determine the optimal operation strategy and determination of greenhouse emission reductions (CO_2 emission factor) for an off-grid village.

To meet this goal, a mathematical optimization model that defines an optimal renewable system is presented. Since the Ministry of Energy of Chile does not have a predictor that effectively shows the energy sources that should be used in rural off-grid areas, also based on the reduction of economic costs, the proposed model was implemented in CPLEX to be applied for the energization of an off-grid village of "La Mora", located in the Region of Valparaíso in Chile. The results of this study are used to design and plan an optimal system that provides an efficient supply of reliable energy and helps economically, minimizing the emissions of greenhouse gases in the real case addressed.

The remainder of the paper is organized as follows. A study of the literature regarding SIRES-oriented optimization systems and models is presented in Section 2. Section 3 describes the mathematical formulation and components of the optimization model. Results and discussion are given in Section 4, and Section 5 provides our conclusions and suggests further research lines.

2. Related Work

The Smart Integrated Renewable Energy Systems (SIRESs) are one the most variants of the well-known Integrated Renewable Energy Systems (IRESs). It is suitable for the sustainable development of remote and rural areas, and currently is an area of increasing interest to the scientific community, because the intelligent use of various renewable resources can be integrated by combining essential resources and needs with the objective of energization [6]. However, at the same time, the construction and cost of these systems need efficient planning, and this is where mathematical optimization models contribute to the efficiency of these systems.

There is literature that focuses on mathematical models for the design of SIRESs. Some of these investigations are comprised of simulations [13,14], linear programming [15–17], objective programming [18,19], optimized analysis and planning for power generation [20], and a probabilistic approach that takes into account the probability of power leakage [21]. A chronological simulation demands large amounts of data on resources and loads that are obtained from local requirements, oriented towards linear programming (LP) and objective programming (OP) and a deterministic use of annual or seasonal average values in its analysis [22]. A knowledge-based procedure was performed, and this procedure improved on previous research in terms of the advantages of the algorithm [23–25]. In [26], the authors presented an attempt to develop an integrated renewable energy system for power generation using solar and wind resources. Hybridization of solar and wind systems was performed to supply isolated loads, and the model was implemented in MATLAB/SIMULINK, offering promising results. Likewise, the authors of [27] provided Smart Hybrid Home Power Systems for isolated customers who have an off-grid power connection to ensure that energy was efficiently produced. They proposed an itemized simulation system in which the solar energy factor was considered the main source. The system also includes energy storage devices to guarantee safe energy recovery and distribution. The results indicated that the proposed system meets the goals defined for an intelligent energy management system. In [28], a framework based on a dynamic Mixed-Integer Linear Programming (MILP) model integrated coal-fired, NaS batteries with energy storage, natural gas power plants, and solar, and wind energy to meet demand. The authors took into account the economic goals and constraints to supply an efficient power balance. In [29], the authors presented the design of an online algorithm that shared the cost of energy among residents in a cooperative community. The problem was formulated as a stochastic constrained problem, and the objective was to minimize the time-average cost in the community, including the cost of purchasing electricity from the main grid and the cost of charging and discharging energy storage systems. In the same way, the authors of [30] proposed an improved brain storm optimization algorithm to solve the optimization problem in a hybrid renewable energy system. The objective of the proposed algorithm was the minimization of the annualized costs of the system, the total fuel emissions, and the loss of power supply probability.

Concerning hybrid systems (HS) based on renewable energy, several authors have studied hybridization and conducted comparative analyses of this type of system outside the electrical network [31–36]. Principally, the analysis of solar photovoltaic (PV) energy and wind hybrids was shown to be a solution that most reduces the use of traditional energy sources. These alternative sources of energy have many notable rewards, such as the cost of energy and feasibility. The cost-effectiveness and stability of these sources is possible due to their complementary nature, compared to that of independent energy systems. In these papers, the resulting analyses showed that hybrid system configurations were the most suitable technological and economic solutions concerning the *COE*, maximum renewable penetration, renewable fraction, operating cost, levelized cost, emissions, and mean electrical efficiency. It should be pointed out that the power supply problem has been solved in regions where it is possible to extend the electrical grid in combination with renewable resources. In [37], the authors present a study on the maximization of energy efficiency within a heterogeneous network that includes various types of networks, in addition to renewable energy sources, and the information and energy data were coordinated synchronously between base stations. In addition, in [38], it was reported that a control system based on the management and administration of energy within a home can be programmed efficiently and can integrate an RES. The optimization approach used was a genetic algorithm based on swarms of binary particles that are driven by the wind, managing to program single and multiple electrical appliances and energy cost calculations.

Furthermore, the authors of [39] indicated that renewable energy systems are a reasonable and profitable solution in locations where electrification is extremely difficult. In [40], the authors proposed efficient charge–discharge schedules of energy storage systems (ESSs) based on the price of renewable energy. The development of an approach that integrates a genetic algorithm (GA) and a dynamic programming (DP) algorithm was proposed. In addition, the authors of [41–43] were oriented towards the implementation of mathematical models for the optimal sizing of hybrid renewable energy systems that satisfy the energy needs in load sectors. The main objective of these studies was to minimize the total cost of generation and the cost of energy using different optimization approaches. Considering the expected energy is not supplied and the optimization power factor, the optimum system feasibility was investigated. Similarly, in [44], the techno-economic feasibility of off-grid cellular base stations powered by integrated renewable energy was investigated, taking into account the stochastic behavior of RES generation and the rise of traffic in intricate areas in Bangladesh. There are some examples devoted to the analysis of the temporal and spatial space, so as to evaluate and manage renewable resources in an efficient way. In [45], a real case is shown in Malaysia on a national scale, related to wind energy. The previous study was oriented towards a spatial and temporal analysis directed to wind energy and a spatial analysis and observation of the fluidity of wind energy in Malaysia was reported. In [46], a study on surface solar radiation was included within the scope of a research project carried out in Chile. Based on these studies, it was found that SIRES is a feasible solution to the energization of rural villages.

3. Mathematical Formulation

This section presents a model design, mathematical submodels and formulas, and the mathematical optimization model.

3.1. Model Design (SIRES)

In developing countries, such as Chile, it is common to find this type of small towns or villages outside the electricity grid. In a study proposed by [9], these villages can be connected or energized by establishing a point of energy center and establishing a distribution line that clusters to all houses. Given the local conditions of the territory and the availability of the permit, the renewable resources can be integrated with solar energy, oil and other units of energy conversion (e.g., biomass gasifiers and agricultural residues), similar to the one presented in the paper of [47].

The proposed system includes biomass (crop residues, tree foliage, etc.), solar energy (thermal and photovoltaic), wind energy, and biogas (for cooking, electrification and hot water). The biogas is produced from pigs, cattle and sheep, and is used for cooking and, later, the generation of electrical energy and water heating, while solar thermal energy is proposed to only be used for hot water, and other renewable energy sources are only to be used for electricity generation [12]. In Figure 1, we can see these resources used for energy production, for example, cooking and hot water.

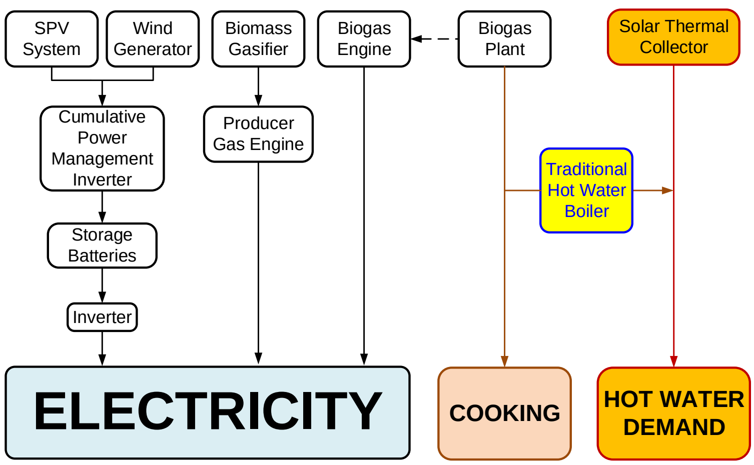

Figure 1. Diagram of the Smart Integrated Renewable Energy System (SIRES), based on [12].

3.2. Mathematical Submodels

The mathematical model of optimization is designed to merge renewable energy systems available in a given location, taking into account the advantages and limitations of each system. Solar and wind energy are used according to daily availability and are stored over a short period of time. Biomass gasifiers have continuous utility for a short period. Therefore, through the optimization model, it is possible to obtain a design that overcomes the intermittent behaviors of the different energy sources. We see renewable energy systems as independent components, taking into account that their size varies if any change occurs in the model.

We present two sub-models, one of them for energy conversion systems and another that helps to reduce costs. Several previous investigations present detailed mathematical models that take into account the biomass, biogas, wind and solar resources [16,23], and the formulas for the production of the electrical energy from these systems are represented in Table 1.

Table 1. Description of each of the submodel expressions for the electrical power.

Authors	Energy Systems	Equations
Li et al. [35]	Solar Photovoltaic (PV)	$I_s = I_bF_b + I_dF_d + F_r(I_b + I_d)$ • I_s: total solar radiation (kWh/m^2). • $\{I_b; I_d\}$: direct irradiation and diffuse solar radiation (kWh/m^2). • $\{F_b; F_d; F_r\}$: tilt factors for the beam, diffuse and reflected parts of solar radiation.
Huang et al. [48]	Solar Power Generation (SPV)	$P_{PV} = R_{pv}I_sA$ • P_{PV}: power generation from the PV system (kWh). • R_{pv}: system efficiency. • A: available panel area.
Babatunde et al. [49]	Wind Energy (WES)	$P_{WT} = P_wA_wR_W$ • P_{WT}: electric power obteined by a wind turbine (kWh). • P_w: power of the wind generator. • A_w: total swept area. • R_w: overall efficiency of the gearbox, generator and associated.
Hamilton et al. [17] Kanase-Patil et al. [47]	Biomass Gasifier (BM)	$P_{BM} = R_g(\phi_w - \phi_B)$ • P_{BM}: biomass gasifier power (kWh). • R_g: overall efficiency of the gasifier system, including the efficiency of biomass to producer gas conversion, internal combustion engine and generator. • ϕ_w: biomass available in an instant (kg). • ϕ_B: biomass required per hour.

Table 1. *Cont.*

Authors	Energy Systems	Equations
Chang et al. [14]	Biogas (BG)	$P_{BG} = R_b(BG_{total} - BG_{C-H})$ • P_{BG}: power generated by the biogas engine generator (kWh) • R_b: overall efficiency of the biogas-fueled engine and generator system. • BG_{total}: biogas available at that instant (m^3). • BG_{C-H}: biogas consumed for cooking and hot water generation at that instant (m^3).
Masip et al. [9]	Solar Thermal Collector (STC)	$P_{STC} = I_b R_{tc} A_a - P_{loss}$ • P_{STC}: power generated by solar thermal collectors (kWh). • R_{tc}: collector optical efficiency. • A_a: absorber area (m^2). • P_{loss}: power loss in the solar collector (kWh).

The total power generation is represented by $P_T(t)$ at any time t, and N_q defines the amount of energy of type q, $\forall_q \in \{PV, WT, BM\}, \forall_{PV,WT,BM} \in \{1, \ldots, 3\}$. The $P_T(t)$ is calculated as follows:

$$\begin{aligned} P_T(t) = & \sum_{PV=1}^{N_{PV}} R_{pv} \times A \times (I_b F_b + I_d F_d + F_r(I_b + I_d)) + \\ & \sum_{WT=1}^{N_{WT}} (P_w \times A_w \times R_w) + R_b(BG_{total} - BG_{C-H}) + \\ & \sum_{BM=1}^{N_{BM}} R_g \times (\phi_w - \phi_B) \end{aligned} \tag{1}$$

3.3. Mathematical Optimization Model

The model that we present can be seen as a Constraint Satisfaction Optimization Model (CSOP). In that representation, we have a tuple $\langle X, \mathcal{D}, C, f \rangle$, where X is a set of variables $\{x_1, \ldots, x_n\}$ and, $\mathcal{D} = \{\mathcal{D}_1, \ldots, \mathcal{D}_n\}$ is a vector of domains. The k-th component $\mathcal{D}_k$ is the domain that contains all the possible values that can be assigned to the variable x_k. C is a finite set of constraints, where each n-ary constraint c_m is defined on a set of variables $\{x_1, \ldots, x_n\}$, restricting the values that the variables can take simultaneously. Finally, f is an objective function to be optimized satisfying all constraints [50].

Taking into account the previous definition and their components, we modeled an optimization model able to provide the amount of energy that can be produced from each type of resource, with the aim to minimize the cost of general production and to consider the availability of energy and the consumption of each energy resource. For instance, using biogas directly for cooking would be efficient and inexpensive compared to the use of biogas as bio-fuel in engines.

The parameters of the problem describe data concerning a real scenario related to the energy sustainability of an isolated rural area. This information is necessary for the resolution of the model. The indexes i and j denote the i-th type of resource (BM, WES, SPV, STC, BG) and the j-th type of consumption of energy (electricity, hot water, cooking), respectively. Let N be the number of houses, and let TE be the total energy demand of all of the houses. Furthermore, in each house, C_j is defined as the amount of energy needed for each type of consumption of energy j. The variable TE is calculated as $N \sum_{j=1}^{3} C_j$. For each type i of resource $\forall_i \in \{1, \ldots, 5\}$, D_i is the existing availability, R_i is the system efficiency (the relationship between the energy produced and the energy required for its operation), and A_i is the device area. For each type of consumption of energy j obtained from resource i, $\forall_j \in \{1, \ldots, 3\}$, and $\forall_i \in \{1, \ldots, 5\}$, M_{ji} is the operation and maintenance (O&M) cost, and V_{ji} is the production cost.

The decision variables are the following:

- COE: cost of energy.
- P_{ji}: amount of energy for consumption of type j produced from resource i, $\forall_j \in \{1, \ldots, 3\}, \forall_i \in \{1, \ldots, 5\}$. The unit of P is kWh/yr.
- T_i: device or equipment for the amount of resource type i, $\forall_i \in \{2, 3, 4\}$.

The *COE* is a tool that allows for the analysis of different generation projects, which can be of different sizes or different technologies, using a common unit of comparison, (see [51]). This comparison unit facilitates the decision making of the investor, allowing a portfolio of projects to be evaluated and compared according to their costs. This value of the *COE*, in any system not requiring fuel, is solely due to the amortization of the capital cost, operation, and maintenance cost, if taxes and insurance charges are neglected.

The *COE* of renewable energy technologies is different by country, project, and technology, based on capital and operating financial indices, renewable energy resources, and the efficiency of the technology. There are many potential trade-offs to be considered when developing a *COE* modeling approach. The approach taken here is relatively simplistic, given that the model is applied to different technologies. This approach has the additional advantage, however, that the analysis is transparent and easy to understand. Additionally, more detailed *COE* analyses show a significantly higher overhead in terms of the granularity of assumptions required [51].

This model minimizes the *COE* of a SIRES, and it is obtained by adding the amount of energy produced, multiplied by the corresponding cost and divided by the total amount of energy produced. In the proposed scenarios, the energy demanded can always be covered, and in some cases the total energy produced is equal to the total energy demand.

The objective function is formulated as follows:

$$minimize \left(\frac{\sum_{j=1}^{3} \sum_{i=1}^{5} (M_{ji} + V_{ji}) \times P_{ji}}{TE} \right) \tag{2}$$

subject to:

$$\sum_{i=1}^{5} P_{ji} \geq C_j \times N, \quad \forall_j \in \{1, \ldots, 3\} \tag{3}$$

$$\sum_{j=1}^{3} \frac{P_{ji}}{R_i} \leq D_i, \quad \forall i \in \{1, 5\} \tag{4}$$

$$\frac{P_{1i}}{R_i} \leq D_i \times T_i, \quad \forall i \in \{2, 3, 4\} \tag{5}$$

$$P_{ji} \geq 0, \quad \forall j \in \{1, \ldots, 3\},\ i \in \{1, \ldots, 5\} \tag{6}$$

$$T_i \in \mathbb{N}, \quad \forall i \in \{1, \ldots, 5\} \tag{7}$$

Constraint (3) ensures that the total energy produced, regardless of the source, is at least the existing energy demand in the studied area. Constraints (4) and (5) consider the energy viability. Renewable energy resources must provide energy efficiency that can meet the expected demand. Constraint (6) indicates that the production of each type of energy must take positive allocations (so that there are no resources with negative resource values), and finally, constraint (7) determines that the quantities of installed processors must be positive integer values, even when the installation of any of them is not performed.

A feasible solution to the problem is to assign values to the decision variables satisfying the set of restrictions shown above. An optimal solution is one that, in addition to being feasible, minimizes the value of the *COE*. The linear programming model was developed in IBM ILOG CPLEX v12.9.0 to optimize the problem.

For a better understanding, we illustrate the application of the optimization model in this research. A flowchart diagram is shown in Figure 2.

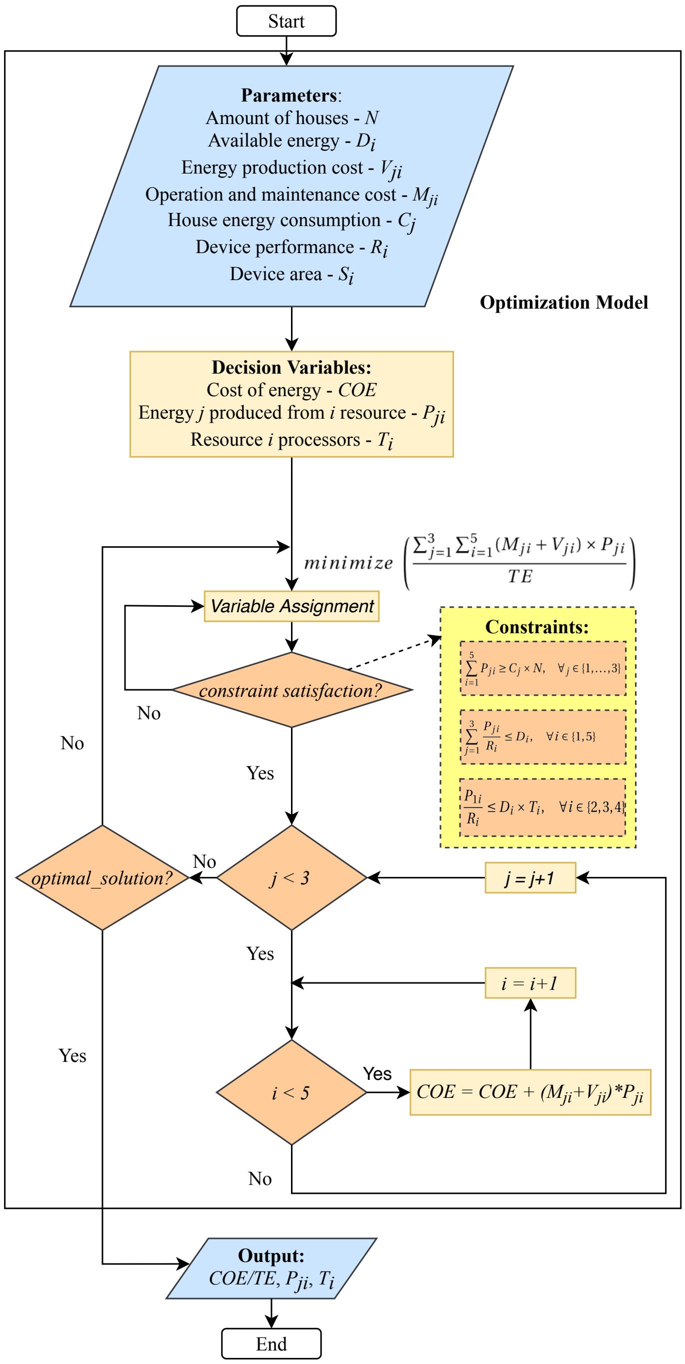

Figure 2. Graphical representation of the optimization model.

The main steps of this procedure are as follows:

1. The set of model parameters/data obtained from the known data of the real problem is initialized. The indices (i and j) refer to the type of resource and type of energy, respectively.
2. The decision variables in the model are defined.
3. The variable assignment process is performed.
4. The constraints of the set of decision variables must be satisfied. If the constraints are not satisfied, Step 3, is repeated until a set of values that satisfy the constraint set is found.
5. If the constraints are satisfied, then the current value of the *COE* is calculated, and this variable is updated considering that it is the variable to be optimized.
6. In each iteration, a global optimum of the model is checked. If this is not the case, the procedure returns to Step (3).
7. If the optimal solution is determined, then the result is shown.

4. Results and Discussion

This section presents the results of the proposed optimization model applied in a case study with different scenarios, as well as the management and administration of resources and requirements that are necessary to satisfy the energy demand. In addition, we conducted an analysis of the configuration of the SIRES and here propose a discussion of those results and analyze the sustainability factor (CO_2 Emissions).

4.1. Case Study for Off-Grid Region in Valparaíso

Currently in Chile, there are around 24, 556 non-electrified households [52], where approximately 75,000 people live (considering data from the National Census 2017). This amount represents 0.4% of the total population nationwide and 3.5% of the population living in villages. Specifically in the Valparaíso region, it was reported that rural towns were located outside the electricity grid, and approximately 735 rural households in this region are without electricity. The work proposed in [9], shows an evaluation summary oriented towards the resources, load, and demand in different villages of the region of Valparaíso. It is observable that the highest average energy contribution is the village of "La Mora" (https://goo.gl/maps/AJpQvPHsgmZKoHX26), located 15 km from "Cabildo" and with 34 off-grid houses, where the main energy source to produce electricity consists of a diesel generator.

4.2. Management and Evaluation of Resources and Load/Demand

To evaluate the applicability of renewable energy sources, we carried out exhaustive data collection to capture information related to the levels of solar radiation, biomass, and wind speed. Figure 3 shows the monthly averages of solar irradiation for a complete single-year period, with a yearly average solar irradiation value of 1949 kWh/m^2/yr, according to [53].

In this research, data obtained from the wind speed proposed in [53] are considered, and these are used to calculate the wind energy. These data represent the availabilities for active values related to wind speed. In Figure 4, the monthly average wind speed is shown for an annual period, with annual average speeds up to 2.7 m/s, and the temperature and atmospheric pressure influences the speed of the wind [54,55].

In Chile, the differences between the atmospheric pressure and temperatures of the summer with respect to the winter months are significant, and the wind has different orientation in the same location. In addition, the irregular geography of the country also modifies the velocity profile of the wind. Specifically, in the region of the study, its place in the central zone of the country (see the previous link) and the surrounding mountains creates a compass rose that is different in the summer months with respect to the winter. It is important to emphasize that cool, moist, maritime polar air, forms over the colder subpolar ocean waters just south and east of the large, winter oceanic low-pressure regions.

Over the continents, cold, dry, continental polar air and extremely cold, dry, continental arctic air that forms in the high-pressure regions are especially pronounced in winter, while hot, dry, continental tropical air forms over hot, desertlike continental domains in summer in association with low-pressure areas, which are sometimes called heat lows. Due to the seasonal changes in surface heating, the pressure centers exhibit seasonal changes in their characteristics.

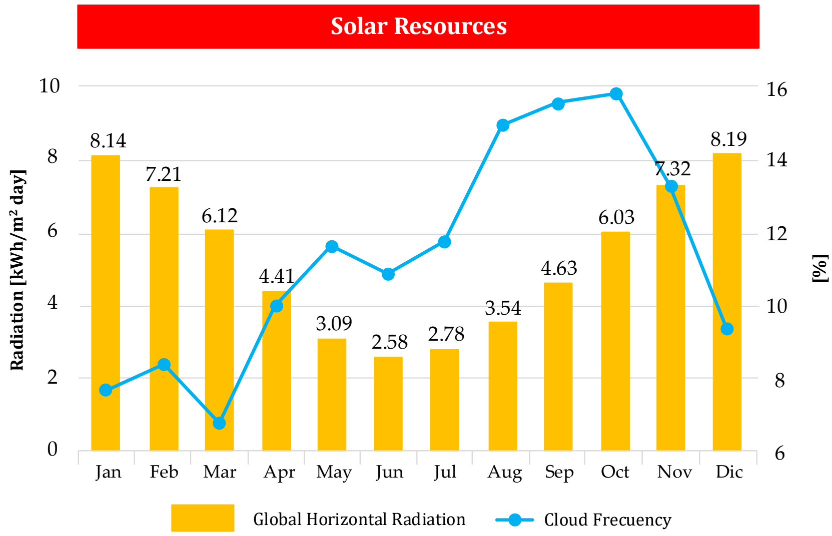

Figure 3. Global horizontal radiation for the county studied.

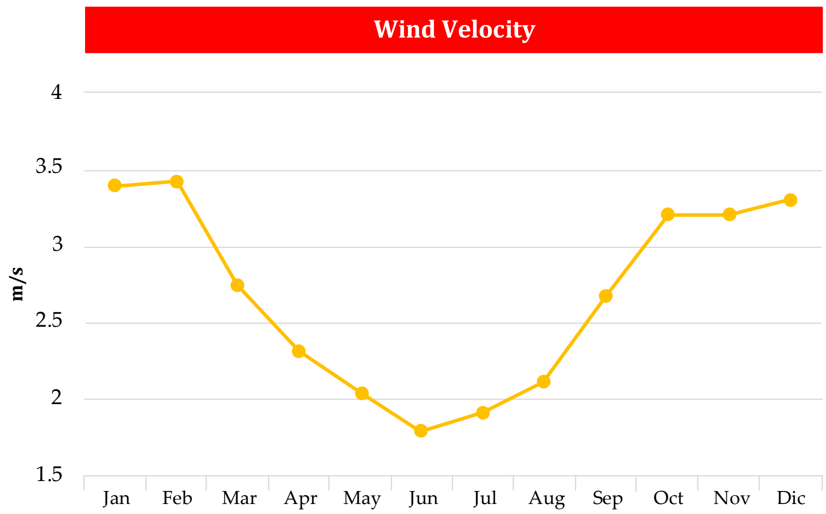

Figure 4. Wind velocity for the county studied.

Waste associated with forestry and animal manure is the main source of renewable energy for people dedicated to the production of biogas and biomass. An electricity generator has a time limit of useful life around 20, 000 h, producing a load of 30. Information on the capacities and resources available was taken from [9]. The data indicate that biogas resources are highest, followed by solar energy and biomass, including crop residues, forest canopies, and wind potential. Table 2 shows the annual availability of resources available in each of the scenarios proposed by the authors of [12]. These scenarios are considered in this research with the objective of optimizing those resources available for use and reducing the *COE*, an index that economically restricts the implementation of these systems.

Table 2. Values of renewable energy resources and the cost of energy obtained from the proposed optimization model.

Scenario	Available Resources				
	BM kWh/yr	WES kWh/m^2/yr	SPV kWh/m^2/yr	STC kWh/yr	BG kWh/yr
S1	912.500	158.050	941.700	941.700	1558.600
S2	0.000	158.050	941.700	941.700	0.000
S3	912.500	259.200	1949.100	1949.100	1558.600
Production Cost USD $/kWh	0.080	0.170	0.085	0.100	0.080
Cost of O&M USD $/kWh	0.005	0.025	0.020	0.025	0.005

In the village selected to test our model, it is evident that energy consumption depends considerably on the different types of energy used in each household, such as thermal consumption (for cold) and food cooking implements. We take into account that the energy contribution that is provided through the RES must have the highest degree of reliability and effectiveness possible to avoid energy leaks and not incur economic expenses greater than necessary. The proposed real case refers to a family of four people who all live in a common house using the "basic" and "equipped" types of components. In [9], the calculation of energy consumption was proposed for a house with the above criteria and disconnected from the electrical network. The authors of [56] showed the difficulties of measuring the energy consumption of any household and in a given period of time, since it depends on a set of factors/variables such as the type of food, its inhabitants, and the economic income of each resident. To obtain the consumption of SHW and the energy required to obtain an acceptable temperature in the water, it is first necessary to obtain some parameters before proceeding to the calculation. The technical standards of the Chilean government related to low temperature solar collectors were obtained from the report [57]. Annually in Chile, there is an annual demand for electricity, as follows: 1329 kWh/yr for kitchen use, 767 kWh/yr for water, and 2168 kWh/yr for domestic hot water.

4.3. SIRES Configuration

In this study, we will assess the implementation of the proposed SIRES in a specific off-grid village, "La Mora". In Chile, the seasons of the year strongly demarcate the amount of solar energy that can be obtained, making it necessary to consider different scenarios. The process of collecting and producing energy from biogas and biomass is somewhat more complex for the villages, which is why we assume a scenario where we do not have biogas or biomass.

Therefore, three different scenarios were used for our study. Scenario 1 (S1), represents a stage of the year where it is possible to obtain less solar energy, with biomass, biogas, and WES. Scenario 2 (S2) represents a stage of the year where it is possible to obtain less solar energy and an equal amount of WES energy, but there is no biomass or biogas. Scenario 3 (S3) represents a stage of the year where it is possible to obtain a greater amount of solar energy (increases in 3%), with biomass, biogas, and WES. Table 2 shows, for each scenario, the energy resources available related to biogas, biomass, and solar energy (photovoltaic and thermal).

The objective of this research is to propose the optimal implementation of a SIRES using an optimization model developed in CPLEX. The proposed model assesses the different sizes of each type of source of renewable energy in accordance with manufacturers' specifications, determining, in addition to the energy that must be produced to cover the existing needs in the town, the number of sources of renewable energy necessary for the production of this energy (see Figure 5).

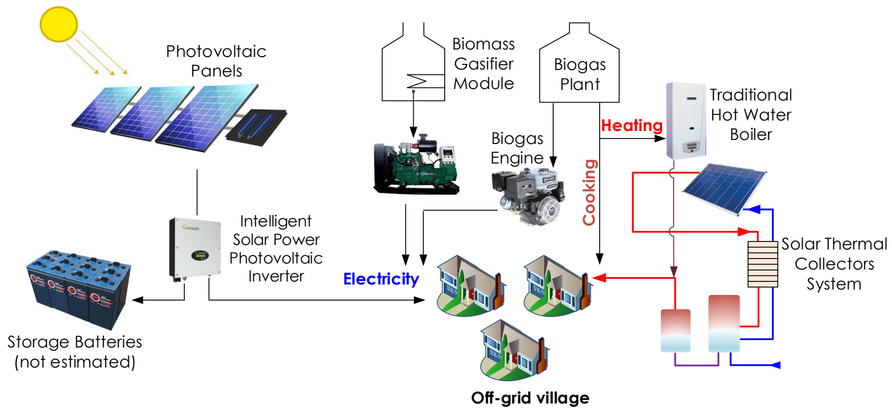

Figure 5. SIRES configuration obtained from the optimization model.

4.4. Discussion

Table 3 shows that, in Scenario 1, BM, BG, SPV, and STC are used to meet the power requirement. For power generation, BM supplies a large part of the existing need. For hot water production, BG contributes 25.7%. For cooking, energy is supplied for only the BG.

In Scenario 2, as there is no biomass or biogas, the needs for hot water and electricity are satisfied only by means of solar energy (STC and SPV). Since there is no BG, the cooking requirements have to be supplied with a traditional system based on a liquid petroleum gas. Scenario 3 exhibits behavior analogous to Scenario 1, because the amounts of existing electrical energy do not influence the result, since the existing levels of BG and BM are consumed.

In general, the scenario with the highest *COE* is Scenario 2, which demonstrates the need for the existence of BM and BG to achieve the efficient execution of a SIRES and thus a considerable decrease in the *COE*.

It is also shown that, for this particular case study, the difference in available energy in the different stages of the year does not influence the *COE* if we have equal conditions regarding the existence of BM and BG are, as is the case in Scenarios 1 and 2.

Finally, it should be noted that, in the three proposed scenarios, the model cancels the use of wind energy that has the highest *COE*.

Table 3. Percentage contributions of renewable energy resources and cost of energy (*COE*) for all scenarios.

Scenario	Energy Production	Resources					*COE* $/kWh
		BM	**WES**	**BG**	**SPV**	**STC**	
S1	Electricity	58.40	-	-	41.60	-	**0.10**
	Cooking	-	-	100.00	-	-	
	Hot water	-	-	25.70	-	74.30	
S2	Electricity	-	-	-	100.00	-	**0.12**
	Cooking	-	-	-	-	-	
	Hot water	-	-	-	-	100.00	
S3	Electricity	58.40	-	-	41.60	-	**0.10**
	Cooking	-	-	100.00	-	-	
	Hot water	-	-	25.70	-	74.30	

In 2015, in Paris, 195 countries pledged to minimize their greenhouse gas emissions (GHGs) to limit the temperature rise over the planet to below 2 °C and even below 1.5 °C by the turn of this century. On 5 October 2016, the minimum demands for entry into the Paris Agreement were met, firmly responding to those agreed upon at the United Nations

Framework Convention on Climate Change [58]. This agreement demonstrates the political commitment of all countries in the world to act urgently to curb climate change.

Chile presented the national contribution determined in the 2050 Energy Agenda [59], which includes commitments on mitigation, adaptation, construction and capacity building, the development and transfer of technologies, and financing. In this sense, the country committed to reduce the kilograms of CO_2 equivalent ($kgCO_2e$) per GDP unit (gross domestic product) by 30% by 2030 with respect to the value achieved in 2007. The increase in investments will allow for the implementation of appropriate measures to achieve this agreement. Among these technologies are the use of renewable energy, energy efficiency, and new transport technologies.

An RES causes on average less environmental pollution by reducing CO_2 emissions per kWh, contrary to what happens with an electrical system. The emission factor in Chile generated by the electricity system was 0.4056 $kgCO_2e$/kWh [60]. This is a consequence of the existing dependence on fossil fuels in Chile. Of the total electricity generation in 2019, about 38% came from coal, and 14% comes from natural gas. In the case of liquid petroleum gas (LPG) for cooking and sanitary hot water, the CO_2 emission factor in Chile was 0.227 $kgCO_2e$/kWh, as determined by [61].

Regarding the CO_2 emission factor, through the implementation of the SIRES proposed by the optimization model, it is possible to reduce greenhouse emissions, specifically CO_2 emissions for electricity and thermal energy production of 559 and 667 $kgCO_2e$/yr, respectively. This reaffirms to us that the development and implementation of a SIRES in Chile, if it is possible to displace or exchange the consumption of electricity from electricity grids with off-grid generators and reduce gas consumption, can contribute to the minimization of CO_2 emissions and to a better environmental quality for all inhabitants.

5. Conclusions

In this work, we present a SIRES that can achieve the energy needs of a Chilean off-grid village. The cost of energy for each energy resource was calculated, taking into account the available resources and the requirements of the selected village. Evaluating the different systems such that Solar Photovoltaic, Wind Energy, Biomass Gasifier, Biogas and Solar Thermal Collector considered in SIREs, a mathematical model based on Integer Linear Programming was presented and implemented in CPLEX that allowed for the optimization of energy use in the selected village, selected for its energy availability. There were various limitations regarding data capture due to the fact that the response times of the Ministry of Energy were not as expected, given the costs involved in carrying out the field work to obtain the data, so it was necessary to work with values expected internationally. The results obtained indicate that optimization is characterized by a biomass gasifier engine system (58.4%), a biogas plant (25.7%) for hot water and 100% for cooking), and solar photovoltaic (41.6%) or solar thermal (74.3%) energy, complying with the energy requirements of electricity, hot water, and cooking. This solution minimizes the cost of energy, with no differences between Scenarios 1 and 3. The study validates the use of optimization models in configuring a SIRE and in calculating reductions in greenhouse gas emissions. Furthermore, a significant reduction in greenhouse emissions (CO_2) was estimated using the methodology of the Ministry of Energy of Chile. The values obtained demonstrate that it is possible to reduce electricity and thermal demand by 559 and 667 $kgCO_2e$/yr, respectively.

On the basis of the findings presented in this paper, the next stage of our research will be focused on an extension of our mathematical optimization model values related to the levelized cost of energy, so as to make comparisons with extensions of the electrical network and projects similar to the one proposed in our research. Moreover, in the context of our research, it is interesting at the governmental level to determine where energy systems should be located, which can be formulated as a Warehouse Location Problem.

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Y.M.M. and C.C.; investigation, M.G.S., Y.M.M., A.F.G. and C.C.; data curation, Y.M.M., M.G.S. and A.F.G.; writing—original draft preparation, Y.M.M., J.P.Y. and M.G.S.; writing—review and editing, M.G.S., J.P.Y. and S.M.N.G.; supervision, Y.M.M. and C.C.; project administration, Y.M.M. and C.C. All authors have read and agreed to the published version of the manuscript.

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