USING A LP MODEL FOR THE DESIGN ANALYSIS OF AN INTEGRATED RENEWABLE ENERGY SYSTEM

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ABSTRACT

In this paper, the optimal design of an integrated energy system (biomass, solar, wind and water) is approached by the perspective of linear programming (LP) modeling. A model that minimizes the equipment's costs and its installation/operation expenses is implemented, taking into account the efficiency of each type of energy for certain tasks (cooking/heating, mechanical rotation and AC and DC power). To this end, it is assumed in the context that hypotheses are met by the previously formulated objective function, constraints and parameters, in order to obtain results that best show the generation sources' distribution in the integrated energy system. This work aims to contribute for the insertion of hybrid and micro distributed generation into the countryside scenery.

KEYWORDS. Linear programming. Integrated energy systems. Renewable sources.

Main Area: EN - OR in Energy

1. Introduction

The primary sources for energy production can be divided into two classifications: renewable and non-renewable sources. According to Reis [2003], non-renewable resources are considered to be those likely to be exhausted for being used much faster than they can be formed, thus creating an energy deficit over generations, whilst renewable sources are those which its replacement by nature is quicker than its energy utilization, or at least in a compatible way with human's needs in terms of management. There are several renewable energy sources and they are constantly being improved. The most cited ones nowadays are hydroelectric, wind, biomass and solar photovoltaic.

According to British Petroleum researches, by the end of 2013 almost all the power consumption worldwide was based on fossil fuels, being the most used resource oil, followed by coal and natural gas (Figure 1) - all of them non-renewable sources of energy. It may also be noticed that nuclear power - which is equally non-renewable - is consumed as much as the only highlighted renewable energy on the chart, the hydro.

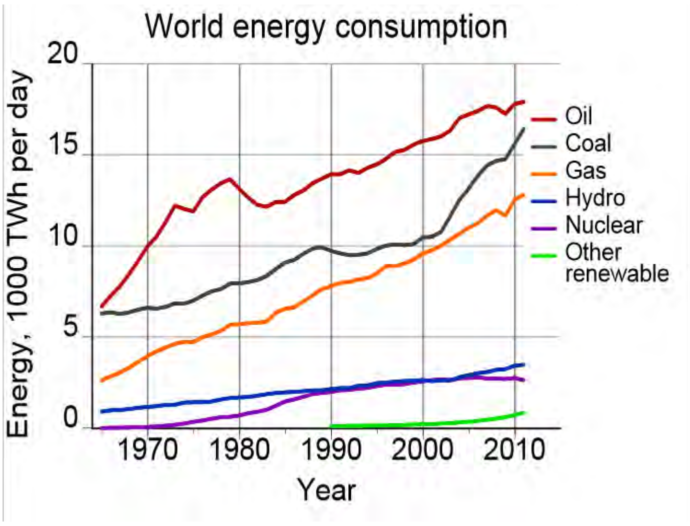

Figure 1: Worldwide energy consumption (BP, 2013).

However, an article on Deutsche Welle's website [Bowen, 2015] presents a village called *Feldheim*, located 60 kilometers from Berlin, Germany, where people not only achieved self-sufficiency in power generation from renewable resources, but also sell 99% of their surplus. As well as in the village of *Feldheim*, such implementations might mean an improvement in the local economy in the medium and long term. Furthermore, boosting the region's life quality, in addition to be an alternative that contributes to the sustainable development of the village.

A way to make a more efficient generation (or even just apply the same idea in other locations around the world) is modeling all the systems to enable optimization of each resource and its usage in the community's performed activities. Thus, this work aims to apply the contents proposed by Ramakumar et al. [1986] and Nogueira et al. [2004] that, although outdated, provide the basis for a good understanding of the problem. Moreover, it proposes to improve their models by not only considering the average annual values, but different demands and power generation capabilities in accordance to the season, and using current data that matches the Brazilian reality when it comes to financial factors and natural resources availability.

Therefore, this paper is organized in five sections, being the first one this introduction. The next section presents the problem description in more details. Based on that, the third section presents the implementation of a model that minimizes the costs involving equipment (taking into consideration economic factors of interest rates and amortization), installation, maintenance and operation of an integrated system, as well as making an analysis of the availability of each resource with greater focus on the efficiency of each type of energy to perform specific tasks: heating, mechanical rotation, and AC and DC power. Following it, the section 4 provides an analysis of the obtained results of the investment's optimal distribution needed in each of the resources to meet the demand. Finally, the last section concludes the paper and suggests future works.

2. Problem Description

The main difficulty for implementing this technology is to perform the integration among all the energy sources and direct them to specific tasks [Nogueira e Zürn, 2005; Nogueira et al., 2004]. In this section, it will be shown a simplified version of the model for a system that integrates several sources of renewable energy applied in rural areas. Furthermore, it discusses some hypotheses and approximations, as well as the optimization of the energy harvesting yearly costs.

In the literature [Ramakumar et al., 1986], an approach to the optimization problem of an integrated renewable energy system is presented, which can be split into two stages. In the first, the renewable energy sources are considered, such as: biomass, solar radiation and wind, which can be converted into biogas, DC electricity, mechanical rotation and thermal energy by the plant. In the second stage, the converted energy together with the heated water and its potential energy are reprocessed and conditioned to perform different tasks, that is, for using in small industries, residences and agriculture. Figure 2 shows a simplified version of an integrated renewable energy system in the country [Ramakumar e Hughes, 1981].

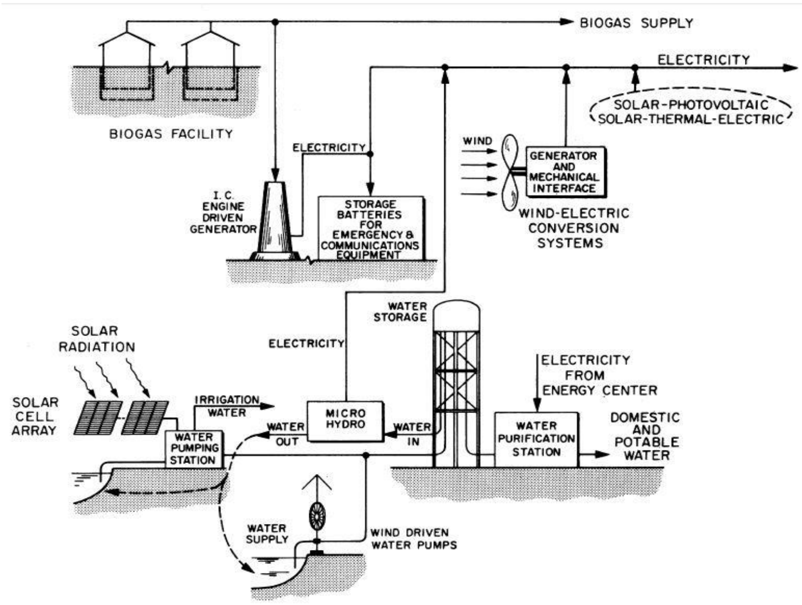

Figure 2: Schematic of an integrated renewable energy system for rural areas illustrating a possible combination of devices and their suitable interconnections for an integrated renewable energy system (IRES) in the rural area.

In this case study, two villages of about 1000 people are assumed, one in the North of the country (05° 39' 57" S 36° 36' 03" O) and another in the South (28° 37' 51" S 51° 34' 15" O) in order to observe the influences on the design as a result of the solar radiation and the temperature associated to different regions of Brazil, which has an extremely wide territory, making it impossible to state a generalization. Furthermore, both communities are located in a distance of approximately 200 kilometers from the capital of their states and are driven by agricultural activities and small industrial production. They also rely on water tanks that could be placed in a height from 5 to 10 meters, which are used for irrigation, biogas production, domestic and potable use. Another assumption is that the parameters do not vary according to the months in the seasons, i.e. a seasonal average value is used, which makes the model more accurate when compared to previous work.

The possible application for each source in a specific task is shown in Figure 3.

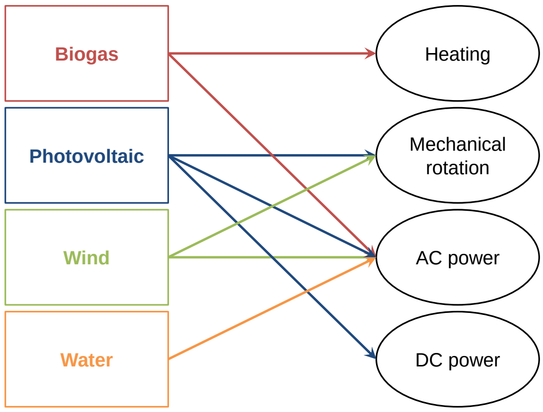

Figure 3: Applicability relationship between sources and tasks.

In this way, index numbers (from 1 to 4) are given to the energy sources (i), tasks (j) and seasons (k). These arrays are shown in Table 1.

Table 1: Index numbers associated to each available source, demanded task and existing season.

	Source (i)
1	Biogas
2	Photovoltaic
3	Wind
4	Water

	Task (j)
1	Cooking/Heating
2	Mechanical rotation
3	AC power (residential)
4	DC power (battery bank)

	Season (k)
1	Spring
2	Summer
3	Autumn
4	Winter

In Table 2 the efficiency in addressing each source for a certain task (η_{ij}) is displayed. These coefficients are regarded to the power conversion plants, not depending on the season the village is in.

Table 2: Efficiency ratio η_{ij} for source-task different combinations.

	Task			
Source	1	2	3	4
1	0.6	-	0.25	-
2	-	0.6	0.9	0.85
3	-	0.5	0.8	-
4	-	-	0.65	-

According to Nogueira et al. [2004], the biodigesters are mainly dependent on the temperature and the amount of excrements that can be collected from the cattle. These parameters are later weighted properly in the constraints. For now, the efficiency ratio for heating and cooking (η_{11}) is 0.6 whereas for DC power (η_{13}) is only 0.25. The η_{22}, η_{23} and η_{24} come from the efficiency of the photovoltaic inverter (0.9), battery charging (0.85) and the performance for mechanical rotation taking into account the discharge depth of the battery (the two last factor times 0.8) [Nogueira et al., 2004]. The model for the wind power is given by Dalence [1990] and an example of its curve is shown in Figure 4. For this case study it will be considered that the wind speed will always be in the linear area and, therefore, its efficiency ratio for mechanical rotation (η_{32}) and DC power conversion (η_{33}) are 0.5 and 0.8, respectively [Nogueira et al., 2004]. The η_{43} was found considering the turbine and generator average efficiency for the hydroelectric system as 0.75 and 0.95, respectively.

Also, the loss in the waterfall's pipeline can be simplified as being 5% of the total generated energy [Eletrobrás, 1985].

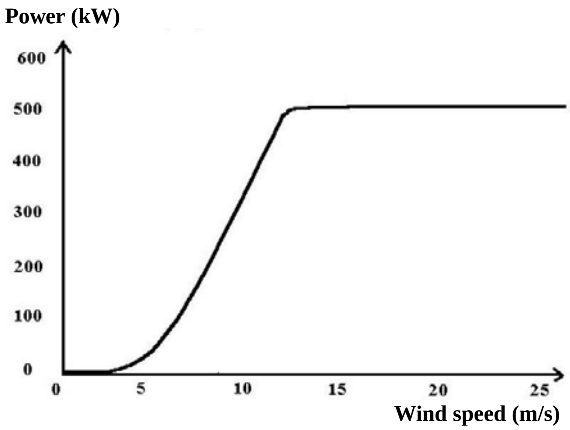

Figure 4: Example of a power curve behavior of a wind turbine with the diameter of 40.3m (Dalence, 1990).

The objective, therefore, is finding the required amount of each energy source and the ideal equipment's size to supply the demand for each season in such a manner that minimizes the total cost per year. In this case, capital, maintenance and operation costs are considered.

3. Modeling the Optimization

The problem was modeled based on some hypotheses, allowing to describe the variables, objective function, constraints and parameters. In this section they are presented and discussed.

3.1. Variables

The variables x_i stand for the amount of resources per season or the equipment sizing, that is:

- x_1: Total volume of biogas $[m^3]$;
- x_2: Photovoltaic array area $[m^2]$;
- x_3: Wind turbines area $[m^2]$;
- x_4: Total volume of water $[m^3]$.

However, such amounts may be distributed to be used in more than one task and in different quantities depending on the season's demand. Therefore, the variables x_{ijk} are considered to be a portion of the total x_i required to perform its share of the j^{th} task in the k^{th} season, where M and O are the total number of task and season, as indicated by Equation 1:

$$x_i = \sum_j^M \sum_k^O x_{ijk}, \quad i = 1, 2, \ldots, M, \tag{1}$$

where x_{ijk} is the amount of each source (i) destined for the task (j) performed in the season (k).

The equivalent energy is a set of factors denoted by the various resources as follows:

$$E_i = R_i x_i = \sum_k R_{ik} x_{ik}, \quad i = 1, 2, \ldots, M, \tag{2}$$

where R_{ik} are conversion factors that vary according to the k^{th} season, as listed below:

- R_{1k}: Biogas equivalent energy [kWh/m^3]
- R_{2k}: Photovoltaic DC power [kWh/m^2]
- R_{3k}: Wind turbines mechanical rotation [kWh/m^2]
- R_{4k}: Water tank potential energy [kWh/m^3]

3.2. Objective Function

As presented in Ramakumar e Hughes [1981], the yearly cost of a renewable energy system is given by:

$$C = \left[\frac{r(1+r)^n}{(1+r)^n - 1} + m \right] \frac{P}{87.6k}, \tag{3}$$

- C: Power generation cost [\$/kWh], which involves the production, operation, maintenance and depreciation costs of each device;
- k: Average annual generation factor [kWh/8760], which amounts to all the hours contained in one regular year;
- m: Operation and maintenance costs [\$/year], specific for each device;
- n: Depreciation [1/year], estimating the equipment's' lifespan in 20 years;
- P: Capital cost [\$/kW], the initial investment prorated among the equipment according to its lifespan and productivity;
- r: Interest rate, which depends on the possible subsides and funding that may be obtained.

As may be verified in Ramakumar et al. [1986], the Equation 3 can be rewritten as a combination of costs (C_{ij}), Equation 4, depending on each source-task relationship ($T_{cr,ij}$), Equation 5. However, once the seasons are considered, the cost depends on the largest value that (E_{ijk}) assumes among the seasons and it is given by:

$$C_{ij} = \frac{T_{cr,ij} P_{ij} E_{ijk\_\max}}{8760 k_{ij}}, \quad i = 1, 2, \dots, M, \quad j = 1, 2, \dots, N, \tag{4}$$

where

$$T_{cr,ij} = \left(\frac{r(1+r)^{n_{ij}}}{(1+r)^{n_{ij}} - 1} + m_{ij} \right), \quad i = 1, 2, \dots, M, \quad j = 1, 2, \dots, N. \tag{5}$$

Finally, the objective function is given by the C factor minimization presented in Equation 6.

$$C = \sum_{i=1}^{M} R_i \left[\sum_{j=1}^{N} \sum_{k=1}^{O} a_{ij} x_{ijk\_\max} \right], \quad a_{ij} = \frac{T_{cr,ij} P_{ij}}{8760 k_{ij}} \quad [\$/kWh]. \tag{6}$$

3.3. Constraints

This model has four main constraints. In this subsection they are presented and discussed individually.

Constraint 1: The sum of energy provided by the M sources regarding the j^{th} task performed in the k^{th} season must be equal to the required total energy (U_{jk}) for the j^{th} task in the k^{th} season. Thus:

$$U_{jk} = \sum_{i=1}^{M} R_{ik} \eta_{ij} x_{ijk}, \quad j = 1, 2, \dots N, \tag{7}$$

where η_{ij} are the power factors provided in Table 2.

Constraint 2: The energy resources are limited in two ways: conversion incompatibility and limited availability for maximum power. In other words: it defines the upper bound. The first problem prevents the power supply for certain tasks thoroughly depending on its source. In the second case, the sum of the amount of energy distributed by a particular source must be less than or equal to their ability to supply it, as observed in the inequality below:

$$E_{i\_\text{max}} \geq \sum_{j=1}^{N} \sum_{k=1}^{O} R_i x_{i\_\text{max}}. \tag{8}$$

Since $E_{i\_\text{max}} = R_i x_{i\_\text{max}}$, the Equation 8 is rewritten as:

$$x_{i\_\text{max}} \geq \sum_{j=1}^{N} \sum_{k=1}^{O} x_{ijk}, \quad i = 1, \ldots, M', (M' \leq M). \tag{9}$$

It is important to notice that if there is no upper bound for a source (e.g. solar radiation) the model can just assume a relatively large value compared to the other upper bounds.

Constraint 3: Naturally, all the x_{ijk} values must be non-negative. That is:

$$x_{ijk} \geq 0, \quad \begin{array}{l} i = 1, 2, \ldots, M \\ j = 1, 2, \ldots, N \\ k = 1, 2, \ldots, O \end{array} \tag{10}$$

Constraint 4: In addition to satisfy the Equation 7, this one imposes the rate of power that should also be considered. It limits the maximum rate of energy use (power) expected of the i^{th} source (P_i), that can be written in terms of k_i and x_i, as follows:

$$\frac{1}{k_i} \sum_{j=1}^{N} \sum_{k=1}^{O} x_{ijk} - \frac{1}{d_i} \sum_{j=1}^{N} \sum_{k=1}^{O} \frac{x_{ijk}}{k_{ij}} \geq 0, \quad i = 1, 2, \ldots, M \tag{11}$$

where d_i is the diversity factor denoted as

$$d_i = \frac{\text{Unit maximum demand}}{\text{Total maximum demand}} \tag{12}$$

and k_i is the effective load factor.

With the previously stated objective function (minimize C) and subjected constraints being linear, this model can be solved by the linear programming methods and becomes an optimization problem.

3.4. Parameters

The conversion coefficients R_{ik} in this model are updated average values of Brazil's northern and southern regions for each season, which are implemented as parameters in order to provide evidences for the feasibility in using renewable energy systems nowadays.

The temperature is the most important variable when it comes to verify the amount of produced biogas. Such quantity is linearly increased from the range of 15°C to 44°C [Lucas e Santos, 2000], making it possible to calculate the conversion factor based on the villages' temperature data [INMET, 2014] as it is shown in Table 3.

Table 3: Average temperature for each season in the villages [°C].

	Season			
Region	Spring	Summer	Autumn	Winter
North	26	27	26	25
South	21	25	22	17

For the photovoltaic energy, the intensity of solar radiation during the season is what sets the conversion factor for this source. Table 4 gives the parameters for the average daily irradiation in each season(γ_α) [CRESESB, 2015]. Equation 13 is applied in order to get the coefficients for R_2, where η_p represents the panels' conversion efficiency and it has the value of 15% [Ruther, 2000].

$$R_2 = \eta_p \sum_{\alpha=1}^{365} \gamma_\alpha \tag{13}$$

Table 4: Average solar irradiation per day for each season in the villages [kWh/m^2].

	Season			
Region	Spring	Summer	Autumn	Winter
North	5.94	5.74	5.20	4.79
South	4.91	5.14	4.43	3.62

The mean wind speed for each village-season is presented in Table 5 [CRESESB, 2015] and Equation 14 converts its value into the factor R_3 used in the model [Justus, 1987].

$$R_3 = \eta_w \sum_{\alpha=1}^{8760} v_\alpha^3 \tag{14}$$

Table 5: Average wind speed for each season in the villages [m/s].

	Season			
Region	Spring	Summer	Autumn	Winter
North	5.31	4.86	5.62	6.01
South	5.59	5.19	5.86	6.21

According to Eletrobrás [1985] and considering a waterfall of 5 meters and gravity of $9.8m/s^2$, Equation 15 calculates the parameter R_4 for both villages in every season given in [kWh/m^3].

$$R_4 = \frac{gh}{3600} = 0.014 \tag{15}$$

Thus, the numeric values of R_{ik} are as presented in Table 6.

Table 6: Conversion factors coefficients parameters (R_{ik}) given in numeric values for each existing source-season in the northern (left) and southern (right) villages. Biogas and water [kWh/m^3], PV-array and wind turbines [kWh/m^2].

	k			
i	1	2	3	4
1	6.030	6.210	6.030	5.850
2	325.398	314.083	284.518	262.435
3	262.312	201.114	310.988	380.327
4	0.014	0.014	0.014	0.014

	k			
i	1	2	3	4
1	5.050	5.930	5.270	4.170
2	268.640	281.598	242.725	198.195
3	306.034	244.927	352.555	419.574
4	0.014	0.014	0.014	0.014

Upper bounds are defined here for the usage limits of biogas, solar panels, wind turbines area and water. Assuming the villages have a population of 1000 people in 250 households and 700 cattle each, the amount of available biogas (having its value later corrected by the conversion factors for each season) per day would be about $430m^3$ [Lucas e Santos, 2000], whilst the available water for electricity generation in a pumped-hydro mode is $150m^3$, since the villages can store $300m^3$ in an overhead tank and half of it is dedicated to this end. Also, the given limit for the wind turbines must be restricted to an isolated area because they make too much noise and might annoy the villagers. However, the upper bound for the photovoltaic panels can be estimated as being the roof area of 250 houses. Therefore, $x_{1\_max} = 430 \times 365 = 156950m^3$, $x_{2\_max} = 50 \times 250 = 12500m^2$ $x_{3\_max} = 2000m^2$ and $x_{4\_max} = 150 \times 365 = 54750m^3$.

The Table 7 presents the village requirements in energy (U_{jk}) for each season, while load factors (k_{ij}), effective load factor of the energy converting plant (k_i) and the diversity factor (d_i) are shown in Table 8 and Table 9.

The sizing of the biodigester must be done in order to match the demand for cooking (mainly) and heating (totally unnecessary in the north), but it can also be used for cooling when converted in AC power [Beduschi et al., 1982; Ramakumar et al., 1986, 1995]. The required energy for mechanical rotation and DC power is defined based on Ramakumar et al. [1986], slightly modified to attend differences in demand during seeding and harvesting periods. For the demand analysis of the AC power, the average energy variation for both region north and south was calculated through monthly evaluation of the residential consumption of each season in 2014 [EPE, 2015].

Table 7: Required energy (U_{jk}) given in [MWh/season] for each existing task-season in the northern (left) and southern (right) villages.

	k			
j	1	2	3	4
1	35	35	35	35
2	60	50	60	50
3	142.6	130	127.8	135.7
4	1.5	1.5	1.5	1.5

	k			
j	1	2	3	4
1	37	35	37	40
2	60	50	60	50
3	136.2	158.2	137.2	135.5
4	1.5	1.5	1.5	1.5

Table 8: Load factor parameters (k_{ij}).

	j			
i	1	2	3	4
1	0.29	-	0.21	-
2	-	0.21	0.21	0.21
3	-	0.21	0.21	-
4	-	-	0.21	-

Table 9: Effective load factor (k_i) and diversity factor (d_i).

Source (i)	1	2	3	4
k_i	0.3	0.22	0.21	0.21
d_i	1.4	1.2	1.2	1.0

Finally, the economic parameters are defined as: $r = 0.15$ (current interest rate in Brazil), $n_{ij} = 20$ (equipment's life span), $m_{ij} = 0.05$ (maintenance cost). Besides, capital costs parameters given in [$/kW] are presented in Table 10.

The cost to build a biodigester - including all the material and labor costs - is, according to Beduschi et al. [1982], Ramakumar et al. [1986] and Ramakumar et al. [1995], estimated in $300/kW and the electric generator to convert biogas into AC power has $400/kW added on its price [Ramakumar et al., 1992]. A set of photovoltaic system for isolated areas is typically composed of: panels, inverter and battery. For the Brazilian market, a reasonable price for such a system may vary from $3000/kW to $4000/kW [Ruther, 2000]. As any other system, the capital cost for the wind turbines depends on where it is bought and the proper converter for each application. According to Ramakumar et al. [1995] and William e Scott [2000], the prices are in a range from $1800/kW to

$2500/kW. Lastly, some works [Ramakumar et al., 1986, 1995; Tolmasquim e Filho, 2003] suggest average costs between $900/kW and $1500/kW for hydro generation.

Table 10: Updated capital costs for each source-task in Brazil given in [$/kW].

	j			
i	1	2	3	4
1	300	-	700	-
2	-	3500	3500	3500
3	-	2000	2500	-
4	-	-	1500	-

4. Results and Discussions

The optimization model (based on the last section's equations) was formulated and solved by linear programming - LP using the software IBM ILOG CPLEX Optimization Studio 12.6 [ILOG, 2013] to run it. For the correct operation for different scenarios it is necessary to update the hypotheses concerning economic factors (m, n, P and r), performance (R_{ik}), efficiency (η_{ij}) and availability of each energy source (x_{ijk}) that describe the region's reality. An important particularity to point out is that some parameters do not exist because some source-task combination are not possible, which would lead into implementation problems once the solver tried to divide the variables by some k_i, k_{ij} or d_i without assigned values. The adopted solution was simply not to create the variables that would result in a division by zero.

For a HP® AMD™ A10 CPU, 8 GB memory RAM, the necessary processing time to achieve the optimal solution has always been less than 3.5 seconds. By using the current parameters presented in the previous sections, the unique optimal solution was obtained and its results minimizing the system's cost are shown in Table 11 and Table 12, results that highlight the differences across the country and how inserting different data in the parameters can change the model's output. Although the conversion devices have been improved during the last decades, in this integrated renewable energy system, the biogas, even with its low efficiency, is dedicated for both cooking and AC power due its reduced cost, whereas the photovoltaic array area is only being applied on AC power and battery charging as a consequence of the stated upper bounds in other sources. The linear programming model was solved and gave the total cost of $286,952.84 and $328,116.78 per year as result for the northern and southern village, respectively, which leads to an average energy cost of $0.33/kWh and $0.37/kWh.

Table 11: Optimal values for the variables (x_{ijk}) using current parameters from a Brazilian northern village (05° 39' 57" S 36° 36' 03" O). The first column shows the assigned source (i) to a specific task (j), whilst the four next columns expose their amount dedicated to each season (k).

Variable (x_{ij})	Sizing (k=1)	Sizing (k=2)	Sizing (k=3)	Sizing (k=4)	Task
x_{11}	9,673.85 m^3	9,393.45 m^3	9,673.85 m^3	9,971.51 m^3	Biogas for cooking/heating
x_{13}	29,563.65 m^3	29,844.05 m^3	29,563.65 m^3	29,265.99 m^3	Biogas for AC power
x_{22}	-	-	-	-	PV for mechanical rotation
x_{23}	303.77 m^2	293.82 m^2	213.71 m^2	87.53 m^2	PV for AC power
x_{24}	5.42 m^2	5.62 m^2	6.20 m^2	6.72 m^2	PV for DC power
x_{32}	457.47 m^2	497.23 m^2	385.87 m^2	262.93 m^2	Wind for mechanical rotation
x_{33}	42.53 m^2	2.77 m^2	114.13 m^2	237.07 m^2	Wind for AC power
x_{43}	13,687.50 m^3	13,687.50 m^3	13,687.50 m^3	13,687.50 m^3	Water for AC power

5. Conclusions

In this work, an IRES designing method has been presented. It combines several sources of renewable energy (biogas, solar radiation, wind and water) simultaneously in a LP model that results in the optimal sizing of the equipment for minimizing the total cost yearly, considering

Table 12: Optimal values for the variables (x_{ijk}) using current parameters from a Brazilian southern village (28° 37' 51" S 51° 34' 15" O). The first column shows the assigned source (i) to a specific task (j), whilst the four next columns expose their amount dedicated to each season (k).

Variable (x_{ij})	Sizing (k=1)	Sizing (k=2)	Sizing (k=3)	Sizing (k=4)	Task
x_{11}	12,211.22 m^3	9,836.99 m^3	11,701.45 m^3	15,987.21 m^3	Biogas for cooking/heating
x_{13}	27,026.28 m^3	29,400.51 m^3	27,536.05 m^3	23,250.29 m^3	Biogas for AC power
x_{22}	-	-	-	-	PV for mechanical rotation
x_{23}	312.58 m^2	380.75 m^2	255.46 m^2	130.78 m^2	PV for AC power
x_{24}	6.57 m^2	6.27 m^2	7.27 m^2	8.90 m^2	PV for DC power
x_{32}	392.11 m^2	408.29 m^2	340.37 m^2	238.34 m^2	Wind for mechanical rotation
x_{33}	107.89 m^2	91.71 m^2	159.63 m^2	261.66 m^2	Wind for AC power
x_{43}	13,687.50 m^3	13,687.50 m^3	13,687.50 m^3	13,687.50 m^3	Water for AC power

demands and resources availability for each season in two villages, both located in the countryside of Brazil. This approach takes into account a set of constraints (resources availability and energy/power requirements) for each source-task relationship.

The great results obtained in this work are mainly related to the huge energy potential that can be found in Brazil, where the solar radiation is higher than most countries, as well as the average wind speed, water availability and temperature (which directly influences the biomass efficiency) during the year, increasing the chances of feasibility when implementing renewable energy projects. As the method widely depends on estimating parameters properly and accurately, it is important to notice that some of the cost reduction in comparison to past studies was due the improvement in efficiency of modern equipment, while some economic factors such as interest rate undermined the viability of the system.

In previous work, some load requirements and resource availabilities were not considered according to the season. Hence, the final design was based on satisfying the average demand along the year, which would cause a shortage in the energy production due an undersized system. This paper contributes in making it clear and showing how a the climate conditions interfere when it comes to choose an acceptable allocation for each available source in the rural areas.

As future work, the authors intend to incorporate some more operation costs into the model, assuming the existence of labor costs for the process to work as supposed. In addition, implementing some funding conditions applied on domestic products (tax reduction) and subsidies (incentives to use green energy in large scale) that would reduce the capital cost. Finally, a more careful analysis considering reliability requirements would complement the model.

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