OPTIMIZATION OF AUTONOMOUS HYBRID SYSTEMS WITH HYDROGEN STORAGE. LIFE CYCLE ASSESSMENT

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Abstract

The design of autonomous systems for the electrification of rural, or isolated zones of the national or regional electrical line, is a complex task due to the diversity of variables involved in such process. The absence of programs and methods that carry out this task in a clear and precise manner, constitutes a barrier to the dissemination of these systems, although some tools have been developed that present other possible limitations. The exclusion of the environmental dimension in the design and evaluation process of hybrid systems means that the true benefits are not evaluated in terms of quality and quantity. In an attempt to overcome such deficiencies, this work presents a new method of design; approached from the multi-objective optimization of systems. The multi-objective optimization, by means of enumerative search implemented by the HOMER (Hybrid Optimization Model for Electric Renewable) program, is used to generate a set of solutions optimized economically by the value of the net present cost (NPC); then the analysis of emissions in the GEI (greenhouse effect gases, in tCO2-eq.) life cycle of each one of the system's components is carried out in a calculation book and a set of solutions with the values of the two objective functions is generated, namely NPC and ENE_{CVS} (avoided net emissions in the life cycle). The method is applied to a case study in a Cuban rural community.

Keywords: hybrid systems; hydrogen economy; multi-objective optimization; life cycle.

1. Introduction

Poverty reduction and sustainable development remains a top priority at international level. Climate change threatens the entire world, but developing countries are most vulnerable. They are estimated to bear approximately 75% and 80% of the cost of damage caused by climate change. Even warming of 2 ° C above preindustrial temperatures could result in a permanent reduction in gross domestic product (GDP) of between 4% and 5% in Africa and South Asia. In order for temperature to not deviate from the 2 ° C above pre-industrial levels (probably the best outcome that can be achieved), a true revolution is needed in the energy sector, namely the rapid dissemination of energy efficient technologies with low carbon emission levels, accompanied by massive investment in next generation technologies, without which growth cannot be achieved with low carbon emissions.

The International Energy Agency, (IEA) in its 2009 World Energy Outlook (WEO) publication, addresses issues of special relevance to the world energy situation and forecasts for this area until 2030. According to the report, expanding access to modern energy for the world's poor remains a priority. An estimated 1.5 billion people (more than a fifth of the world population) still lack access to electricity. Approximately 85% of these people live in rural areas, mainly in sub-Saharan Africa and South Asia. It is estimated that by 2030 the total number will decrease by only 200 million, although it will increase in Africa.

The energy sector will continue to be an area of profound changes and will face new challenges in the coming years. The need for energy supply in isolated areas with difficult access to utility distribution networks, or areas where these are not economically viable, will remain a challenge for many years to come for various governments in order to ensure rural development.

There have been many alternatives that have been used in different countries to provide electricity for isolated consumers. Traditionally, diesel generators were used, with corresponding environmental cost. Then, with the development of renewable technologies hydroelectric systems, such as photovoltaics and small wind turbines, appeared as an alternative for electrification. Depending on available energy resources, these technologies have been used as independent systems (only one source of energy) or as hybrid systems (which involve more than one source of energy), ensuring the autonomy of the electricity supply.

One of the intrinsic characteristics of these renewable energy resources which substantially differentiates them from fossil fuels is their variability. The intermittency of these resources means that the exploitation by autonomous systems requires the existence of energy storage media. Traditional banks of batteries that have been widely used, have demonstrated technical and environmental constraints. Battery storage requires a high cost; in addition, the batteries are very sensitive to unexpected operating conditions. Most users cannot replace them due to the lack of financial resources, which means a total loss of system performance. Furthermore, the use of heavy metals and more or less aggressive electrolytes in batteries can be disadvantages from the ecological point of view, if there is no careful recycling process.

An alternative to storing energy in batteries is the integration of electricity generation technologies (wind in our case) with hydrogen technologies (electrolyzers, storage tanks and fuel cells). In the research that has been done, the hydrogen energy storage in autonomous wind systems has been approached from several perspectives. The use of various simulation and optimization tools (HOMER, HYBRID2, TRNSYS, HYDROGEMS, INSEL, ARES, RAPSIM, SOMES, SOLSIM, CARE, and HOGA) predominates in most studies [1].

Sensitivity analyses carried out by several authors [2], [3] have shown that by lowering the costs of hydrogen storage systems to expected values in the medium and long term they will be competitive with battery storage systems, even without taking into account externalities.

Several works have been published that investigate the technical and economic feasibility of hydrogen storage in autonomous systems [4-8]. M.J. Khan and M.T. Iqbal [9] perform the modeling, simulation, and analysis of an isolated wind system with hydrogen storage. MATLAB-Simulink is used for system dynamics modeling. The simulation results showed the proper functioning of each system component and their mutual interactions.

M.O. Abdullah et al. [10], conducted a comparative study between different power schemes for electrification of a rural information and telecommunications center located in a remote area of Sarawak, East Malaysia. This case study demonstrates that combined photovoltaic and hydrogen systems are more reliable, although currently more expensive than stand-alone PV systems.

K. Sopian et al. [3], describes the behavior of an integrated wind/photovoltaic/hydrogen/battery system. Mathematical models are developed for each component of the system and compared with experimental results. It was concluded that there are no insurmountable technical difficulties associated with hydrogen production by hybrid systems. Field observations showed that hybrid systems are feasible and reliable enough, and require less maintenance. In addition, electrochemical effects caused by the intermittent nature of wind and solar resources can be decreased through the use of batteries as short-term storage systems.

Rodolfo D.L and José L. B.A [11] made a multi-objective triple design of an isolated hybrid system, simultaneously minimizing the total cost over the lifetime of the system, pollutant emissions, and the load not served. They used a multi-objective evolutionary algorithm and a genetic algorithm to find the best combination of hybrid system components and control strategies. Of the research papers that have been published on the subject, this is one of the most innovative, given the advantages of multi-objective optimization compared to the mono-objective.

A. Kashefi Kaviani *et al.* [12] designed a hybrid wind / photovoltaic / fuel cell system, under the criterion of minimizing the annualized cost over 20 years of operation. The optimization problem is subject to a reliable supply of demand, including in the analysis the flaws of wind turbines, photovoltaic arrangements and the DC/AC converter. PSO (Particle Swarm Optimization), an optimization algorithm based on particle clouds, is used. The results demonstrate the influence of component failures on reliability and system cost.

The optimization of particle clouds is also used by S.M. Hakimi and S.M. Moghaddas-Tafreshi [13] in the design of an autonomous system for a residential area of south-eastern Iran. The system consists of fuel cells, wind turbines, electrolyzers, a reformer, an anaerobic reactor, and some tanks of hydrogen. Biomass is used as an available energy source. In the system, the hydrogen produced in the reformer is delivered directly to a fuel cell. When the energy produced by a wind turbine plus the fuel cell (fed by the reformer) is higher than the demand, the excess is delivered to the electrolyzer. Otherwise, it uses an additional fuel cell that is fueled by the stored hydrogen. The optimized objective function is the net present cost of the system.

Despite research on the subject, limitations such as the following remain to be overcome:

- Only Weibull's probability density function (PDF) is used to adjust the distribution of frequencies of observed wind speeds, which does not always represent the best fit. This introduces errors in estimating diverse parameters such as wind power available, the energy produced by wind turbines, and others. This fact is accentuated when the observed wind histogram is bimodal.
- An adequate analysis of adjustment by the wind turbine to wind resource available, so that you can choose between different models to achieve the best energy performance expected in the specific site, is lacking. This would allow a better approach to overall system optimization.
- Calculations of GHG emissions, at best, are estimated for the period of operation of the system and not for the life cycle of each of its components, which would give a more accurate environmental dimension.

With this in mind, this research presents the multi-objective optimization of autonomous systems with hydrogen storage, using the enumerative optimization carried out by HOMER in order to then carry out the optimization of net emissions avoided in the life cycle, from the calculation of equivalent GEI emissions for each of the components of the system.

2. Material and methods

The research was conducted by means of a case study involving the electrification of a rural community of 40 Cuban homes, with approximately 200 inhabitants: the rural coastal community of Caletones Beach located in the Gibara Municipality of Holguin Province (Fig.1.).

Fig. 1. Location of the Playa Caletones rural community on the island of Cuba.

The economic optimization of the system was made with the free software HOMER, which optimizes the system by the value of the net present cost (NPC) by means of enumerative search. For the study, data on wind speed recorded over two years on the study site was used, as well as consumption profiles estimated for the type of rural community in question, based on studies conducted in similar communities (Fig. 2).

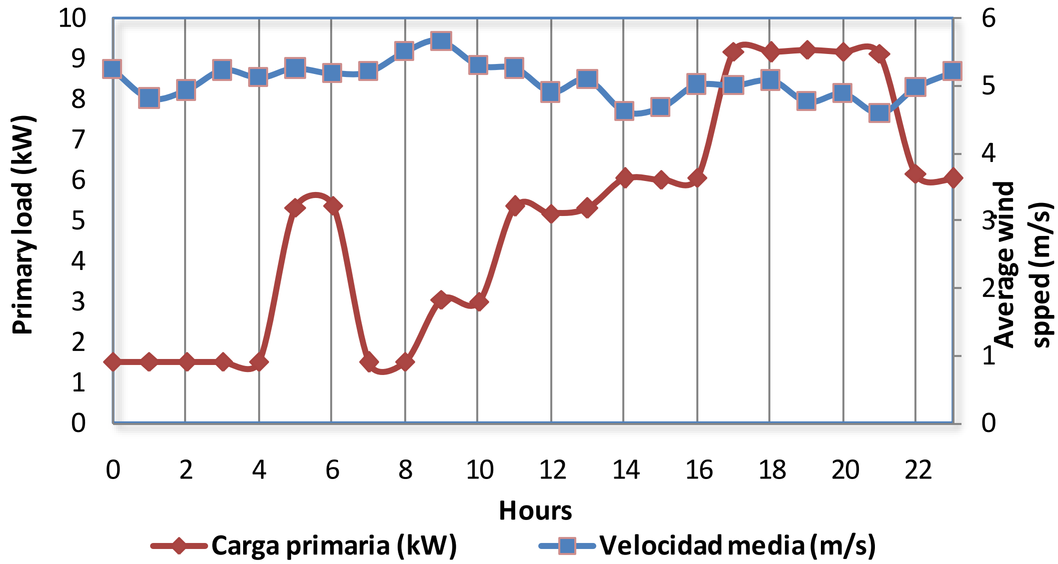

Fig. 2. Average daily consumption and wind speed profiles for Playa Caletones rural community (40 homes)

Prior to the economic optimization of the system, optimization on the wind turbine was carried out according to the best coupling between the power curve and the theoretical distribution of frequencies of wind speeds at the study site. The calculation of the optimum operating speed that the wind turbine must have (start-up wind speed V_s, rated wind speed V_r and cut-out wind speed V_o) to better match the site, was based on the Weibull parameters estimated by Windographer through the method of maximum likelihood (k = 1.09 and c = 5.24 m/s). Given the value of k, we use the following equation to determine the optimal value of V_r, as shown in Figure 3, which is derived from the results published by Geovanni H.G *et al.* [14]:

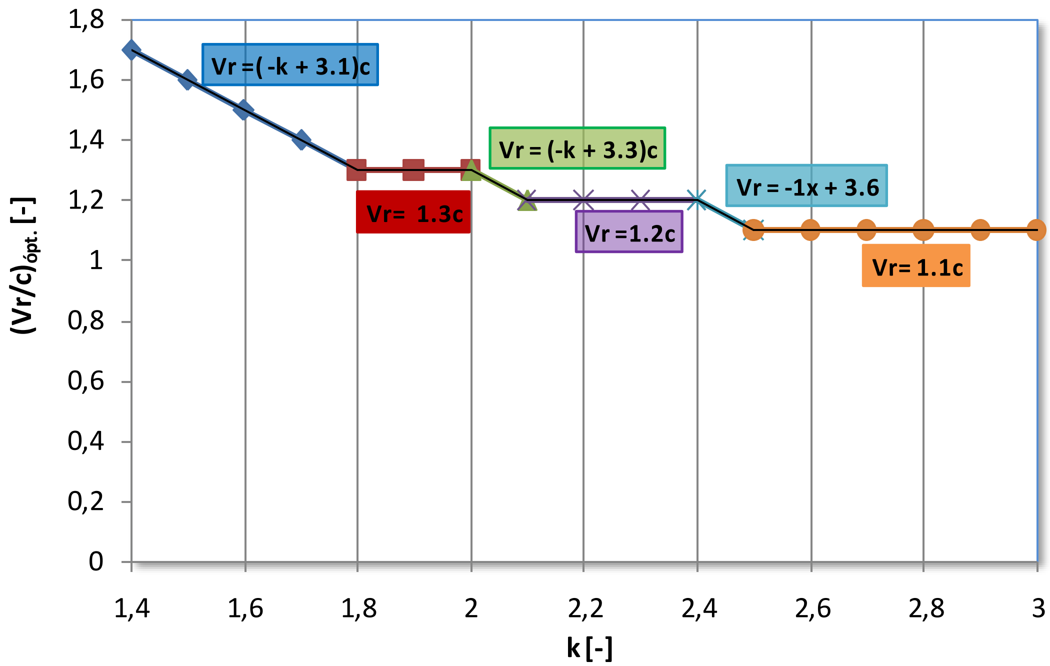

Fig.3. Optimal rated wind speed (normalized with respect to the scale factor of Weibull c) for different ranges of variation of the shape factor k.

$$V_r = (-k + 3.1)c \qquad k \leq 1.8 \tag{1}$$

Equations (2) and (3) were used to determine the values of V_s and V_o [5]:

$$V_s = 0.275 * V_n \tag{2}$$
$$V_o = 1.850 * V_n \tag{3}$$

The configuration of the system under study is shown in Figure 4.

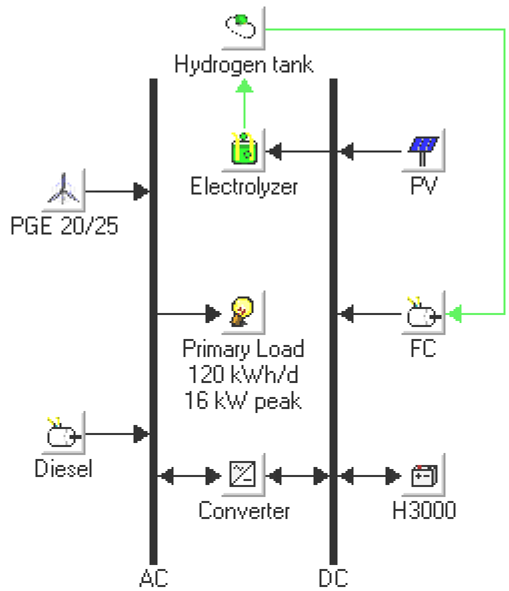

Fig. 4. Outline of the autonomous system that involves all the components.

The system includes a wind turbine, a fuel cell, hydrogen tank, an electrolyzer, batteries and a converter. The system, including photovoltaic modules and a diesel generator, was also analyzed. Capital costs used in the simulation of the system are shown in Table 1.

Table 1. Capital costs for components.

Components	Capital cost
Wind turbine	1500 $/kW
Fuel cell	3000 $/kW
Electrolyzers	2000 $/kW
Hydrogen tank	1300 $/kg
Batteries	1.3 $/Ah
Converter	1000 $/kW
Diesel generator	800 $/kW
Photovoltaic modules	6900$/kW

The calculation of emissions in the life cycle was performed in equivalent tons of carbon dioxide, using the emission rates reported in system components [18]. Table 2 reports the values used, based on the energy produced during the lifetime of each of the components.

Table 2. CO_2 equivalent emissions in the life cycle system components.

Components	GEI (kg CO_2-eq./kWh)
Wind tubines	0.011
Photovoltaic modules (mono-Si)	0.045
Diesel generator	0.88
Fuel cells (H_2 por electrolisis)	0.02
Electrolyzer and hydrogen tank	0.011
Pb Batteries	0.028
Converter	0

For each of the combinations of components generated by *HOMER*, equivalent emissions were calculated in the life cycle, and then the net avoided emissions, NAE_{SLC} (equation 4, where the subscript means *SLC* system life cycle), were calculated. The latter was the objective environmental type function, and its value was determined by reference to the provision of 100% of the demand for electricity by diesel generators. Equivalent emissions for the latter also appear in Table 2.

$$NAE_{SLC} = E_{C-Diesel} - GEI_{SLC} \tag{4}$$

In Equation 4, $E_{C\text{-Diesel}}$ represents the total energy demanded by the load during the project's life cycle and which is supplied entirely by diesel generators. GEI_{SLC} represents the emissions of the autonomous hybrid system in its life cycle. We preferred to use the net avoided emissions rather than emissions in the life cycle in order to better illustrate the environmental impact of each of the possible combinations of components, However, for the purposes of selection of non-dominated solutions it is does not matter which of these two environmental functions is used.

The optimization problem has been focused so that decisions are taken a posteriori that is to say after the optimization has reached a set of equally feasible solutions, called Pareto optimal set. As reported in the literature, a posteriori techniques show the best results and are the focus of current research on multi-objective optimization.

Finally a decisional matrix was constructed, composed from the group of non-dominated solutions and the respective values of the objective functions. From this matrix, the decision maker will make the final decision on which combination of components to select. This would be a multicriteria decision problem, whose solution can be sought from the weight that the decision-maker places on the optimized functions.

3. Results and discussion.

Figure 5 shows the empirical and theoretical distributions of frequencies of wind speeds in Playa Caletones. It is a site with an average speed at 10 m above ground level of 4.16 m / s. Weibull parameters' values for the best fit are shown in the chart.

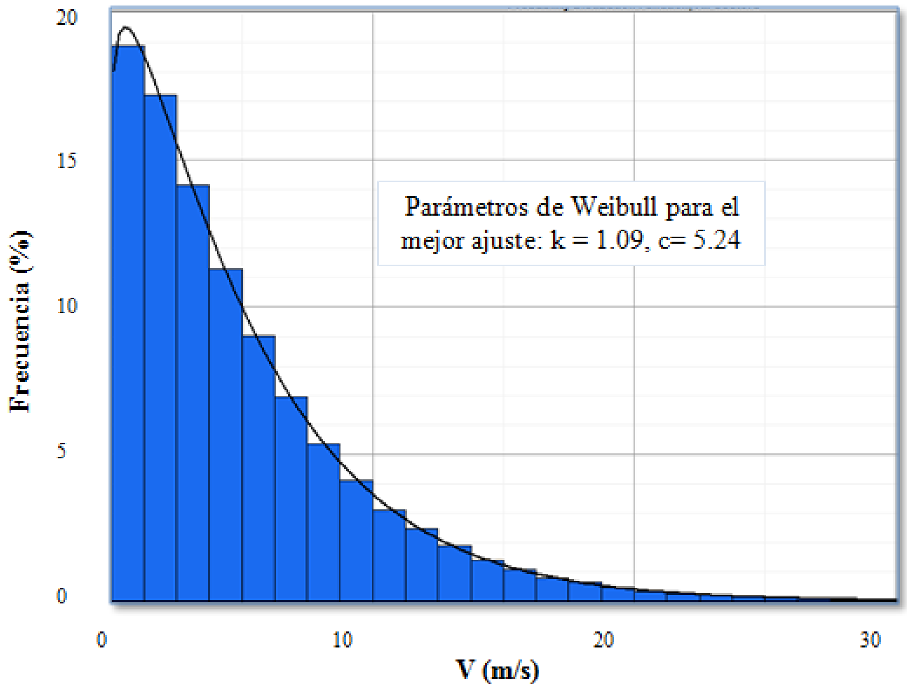

Fig. 5. Observed and theoretical distributions of wind speed frequencies at Caletones Beach (results generated by Windographer).

The optimum wind turbine operating speeds calculated by equations (1) - (3) are shown in the second column of Table 3. Five models of commercial wind turbines were selected, with nominal powers of 25 kW, 30 kW, 35 kW, 80 kW and 100 kW. Their operating speeds are shown in Table 3 and the power curves in Figure 6.

Table 3. Optimum Wind turbine operating speeds of 5 commercial wind turbines

Wind turbine design velocities (m/s)	Optimum wind turbine Eqs. (1)-(3)	Selected wind turbines				
		Energie PGE 20/25	Fuhrländer AG 13/30	Energie PGE 11/35	WES 18/80	Northern Power 19/100
Vs	3	3.5	3	4	4	4
V_r	**10.5**	**9**	**12**	**14**	**14**	**14**
V_o	20	25	25	25	20	25

Of the five wind turbine models, the one which best fits the characteristics of the wind in Caletones Beach PGE is 20/25. When operating at full speed it is closest to the calculated optimum (10.5 m / s). For this reason, after making the HOMER calculations, this model was chosen over any other of the selected models for the installation of various turbines. The results reported below all refer to this model of wind turbine.

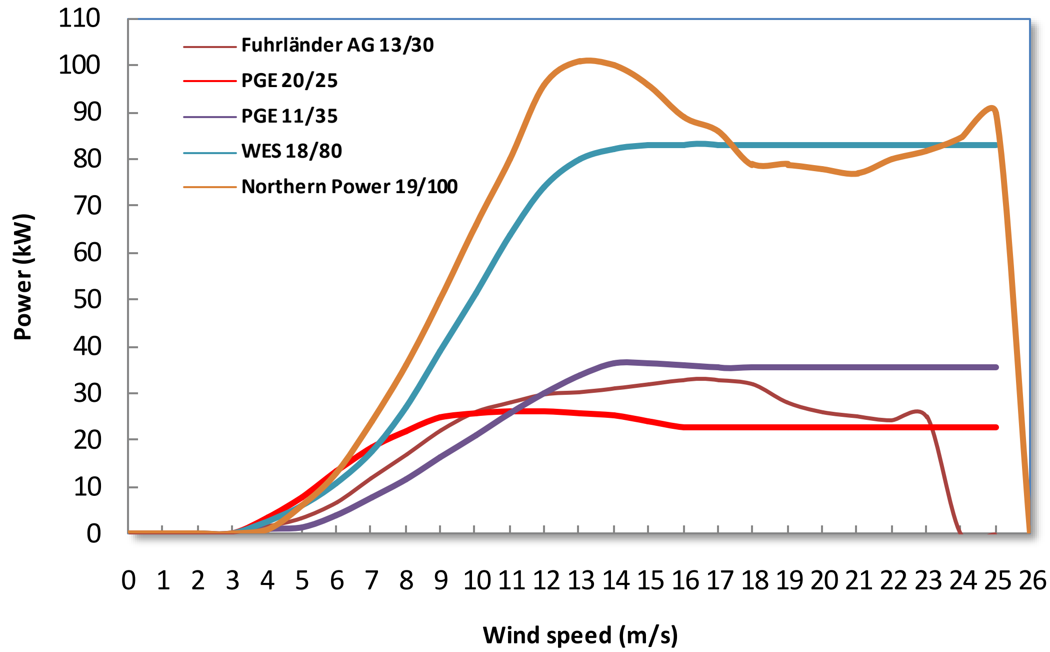

Fig.6. Power curves of the five wind turbines selected for study.

Figure 6 shows the set of feasible solutions generated by HOMER, with corresponding values of net emissions avoided in the life cycle of each of the system components. It generated a total of 2962 feasible solutions optimized for the value of the NPC, corresponding to different combinations of components:

- Wind-batteries, wind-hydrogen, wind-hydrogen-batteries.
- Photovoltaic-batteries, photovoltaic-hydrogen, photovoltaic-hydrogen-batteries.
- Wind-PV-batteries, wind-photovoltaic-hydrogen, wind-photovoltaic-hydrogen-batteries.
- Wind-photovoltaic-diesel-batteries, wind-photovoltaic-diesel-hydrogen, wind-photovoltaic-diesel-hydrogen-batteries.
- Photovoltaics-diesel-batteries, photovoltaic-diesel-hydrogen, photovoltaic-diesel-hydrogen-batteries.
- Wind-diesel-batteries, wind-diesel-hydrogen, wind-diesel-hydrogen-batteries.

As can be seen in Fig.6, there are solutions on the negative side of the axis of net emissions avoided in the life cycle. This means that although these solutions are economically feasible under HOMER, they are not from the environmental point of view as they do not avoid emissions in their life cycle, but will generate more emissions than those produced by the diesel system capable of supplying the same energy demand with the same reliability. For this reason, this subset of solutions is eliminated from our optimized searched solution space.

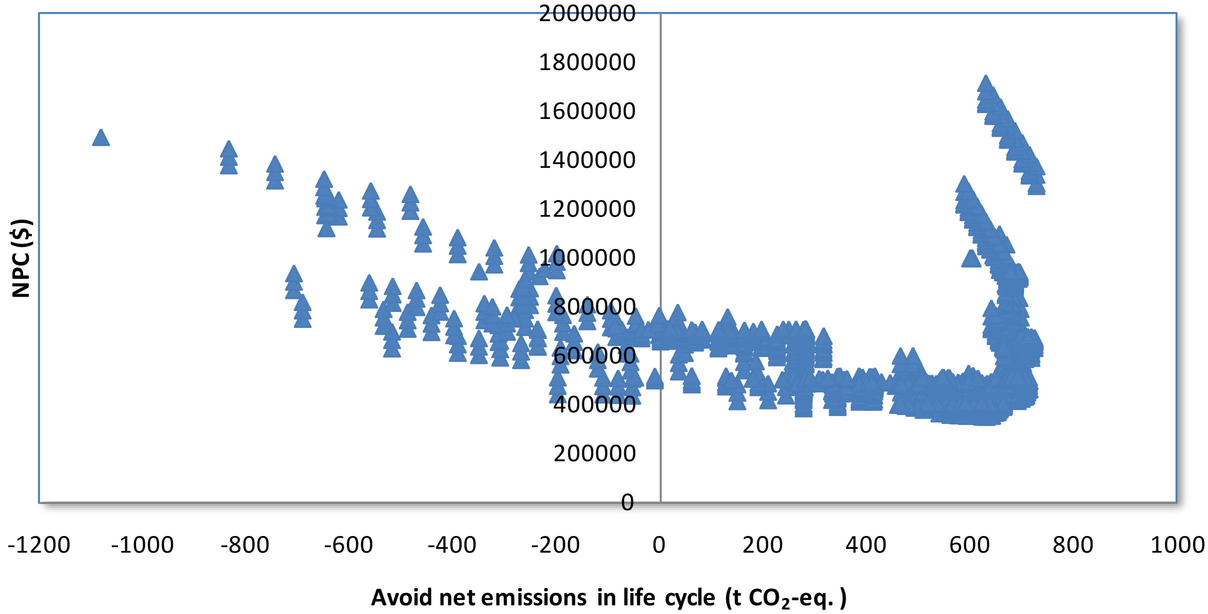

Fig.6. Group of feasible solutions for different combinations of components for an autonomous system. Population size: 2962 combinations

As can be seen in Fig.6, there are solutions on the negative side of the axis of net emissions avoided in the life cycle. This means that although these solutions are economically feasible under HOMER, they are not from the environmental point of view as they do not avoid emissions in their life cycle, but will generate more emissions than those produced by the diesel system capable of supplying the same energy demand with the same reliability. For this reason, this subset of solutions is eliminated from our optimized searched solution space.

The two evaluated objective functions are functions in conflict, meaning that the solution of less NPC will be that which also produces less avoided emissions (or emits more emissions in the life cycle). This can be seen in Figure 7, where there is the non-dominated solutions group, from which the decision maker can choose which is most appropriate.

Table 4 is the decisional matrix, with which the user can select the appropriate solution based on qualitative assessments. The least-cost solution would be a system consisting of: 10 kW photovoltaics, 2 PGE 25 kW wind turbines, 10 kW fuel cell, 10 kW diesel generator, 30 kW converter, 15 kW electrolyzer and a 10 kg hydrogen tank. While the solution for higher emissions avoided would consist of: a PGE 25 kW wind turbine, 120 Hoppecke 24 OPzS 3000 Ah batteries (two rows connected in parallel, each with two 60 V batteries connected in series) and 20 kW converter. This solution, besides being the most expensive, has the disadvantage of needing batteries in parallel connection.

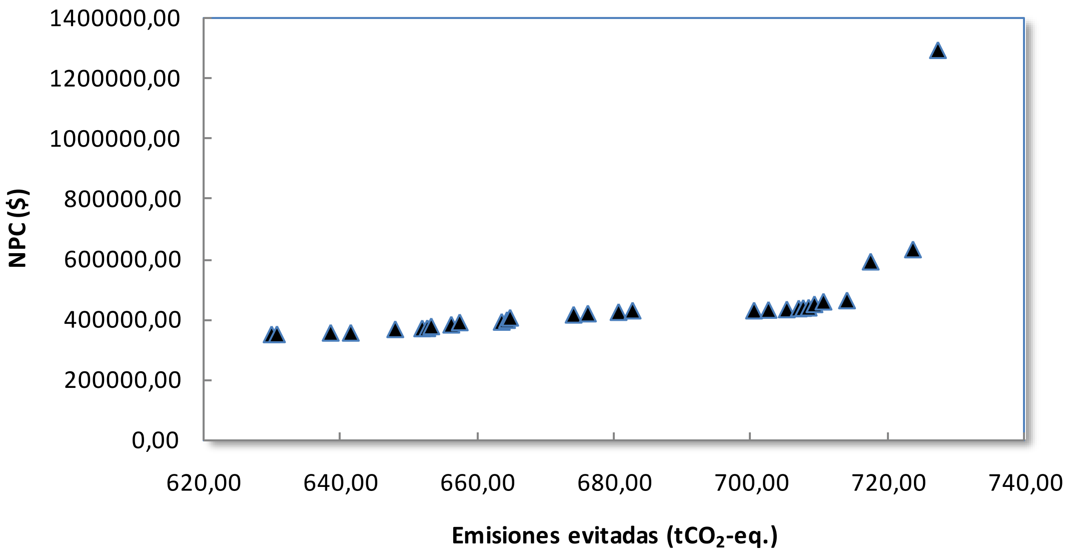

Fig.7. Non-dominated solutions group, resulting from the multi-objective optimization process(0% of energy not supplied)

Tabla 4. Non-dominated solutions group with its components and values of objective functions (columns 10 and 11)

Order Nomber	PV (kW)	Wind turbine PGE25kW (Cantidad)	FC (kW)	DSL (kW)	Batteries Hoppecke 24 OPzS 3000 Ah (quantities in series)	Con-verter (kW)	Electrolyzer (kW)	H_2 Tank (kg)	NPC ($)	Emissions avoided (t CO_2-eq.)
1	10	2	10	10	0	30	15	10	350102.0	629.83
2	15	1	10	10	0	30	15	20	350424.0	630.61
3	12	2	10	10	0	30	15	10	355353.0	638.47
4	20	1	10	10	0	30	15	10	355399.0	641.41
5	15	2	10	10	0	30	15	10	367197.0	647.92
6	20	1	10	10	0	30	15	20	369952.0	651.86
7	12	2	10	10	0	30	15	20	370448.0	652.60
8	8	2	10	10	0	30	30	10	376759.0	653.18
9	10	2	10	10	0	30	30	10	382303.0	656.11
10	12	2	10	10	0	30	30	10	389911.0	657.34
11	8	2	10	10	0	30	30	20	391626.0	663.49
12	10	2	10	10	0	30	30	20	397642.0	664.27
13	12	2	10	10	0	30	30	20	405341.0	664.72
14	20	2	10	0	6	20	15	20	415329.0	674.01
15	30	1	10	0	6	15	20	10	419359.0	676.09
16	15	2	10	0	6	30	25	20	424149.0	680.58
17	6	1	0	20	24	30	0	0	429148.0	682.63
18	5	1	0	20	24	30	0	0	429187.0	700.40

19	12	2	10	0	6	20	25	40	431341.0	702.51
20	10	2	10	0	6	30	25	40	433009.0	705.19
21	6	1	0	30	24	30	0	0	436121.0	706.93
22	8	2	10	0	6	30	30	40	437591.0	707.59
23	25	2	10	0	6	30	15	10	438834.0	708.38
24	12	1	0	30	24	30	0	0	449995.0	709.23
25	15	1	0	20	24	30	0	0	458734.0	710.55
26	15	1	0	30	24	30	0	0	462831.0	713.99
27	0	2	40	0	12	30	25	60	591578.0	717.46
28	0	2	60	0	24	30	10	40	632051.0	723.64
29	0	1	0	0	120	20	0	0	1293513.0	727.30

4. Conclusions

- The selection of the optimum wind turbine for the specific case study was made, determining the values of operating speeds more suited to the general wind profile observed at the site of installation.
- We performed multi-objective optimization of an autonomous system for a rural Cuban community, analyzing the system's emissions in its life cycle. It was shown that not all economically feasible solutions are feasible from the environmental point of view because some of them emit more emissions than a system consisting only of diesel generators.
- The importance of including the environmental dimension in the process of sizing of autonomous systems was demonstrated by means of analysis of pollutant emissions during the system's life cycle and not only during the life cycle of each of its components.

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