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Selection of hybrid systems with hydrogen storage based on multiple criteria: application to autonomous systems and connected to the electrical grid

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SUMMARY

This study presents a selection of optimal energy alternatives for electrical self-sufficiency in a rural university (Universidad del Istmo, UNISTMO), located in the state of Oaxaca, Mexico and for the electricity supply for a rural community (Gran Piedra) in Santiago, Cuba. The analysis follows a multicriteria approach. It uses a method called compromise programming and takes into account the technical, economical, environmental and social criteria. The hybrid optimization model for electric renewables (HOMER) software was used to generate alternative energy sets through enumerative search, with which decisional matrices were built for each case study. The influence of weighting for each criterion was assessed. In the case of self-sufficiency in UNISTMO, when the decision-making center has a preference for the minimization of equivalent emissions in the life cycle (E_{SLC}), a wind system is suitable. On the other hand, when there is a preference for the minimization of levelized cost of energy, a photovoltaic (PV) system is suitable; both systems connected to the national electrical grid. Obviously, a preference for the minimization of capital cost led to keeping the power supply from the grid. In the case of Gran Piedra, a diesel generator-based system is suitable when the criterion 'capital cost' absorbs 70% or more of the preferences of the decision-making centers. When the preference is less than 70% regardless of the weighting given to other criteria, the best alternatives are those involving renewable technologies, reaching renewable fractions of 75% and 94% in two potential configurations of energetic systems. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS
hybrid systems; multicriteria analysis; hydrogen technology; life cycle; HOMER software

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1. INTRODUCTION

Renewable energy systems have faced various problems that affect their sustainability and hence their use and dissemination. One of them deals with the sizing process of the systems. Several models have been developed, but they have a number of practical constraints. Conventionally, computational tools are used primarily with technical or economical variables as decision-making criteria. Indeed, the inclusion of environmental and social criteria that take into account the performance of the system's life cycle does not appear in the optimization schemes reported in the literature. A more accurate comparison between different generation systems must take into account multiple criteria.

As an analytical tool of great potential in system engineering processes, multicriteria analysis can be viewed as a sequence of steps or activities in which it is necessary to choose among different alternatives. Its application is both rational and objective so that it improves our understanding of the decision-making measures that underlie systemic processes. It also helps the decision-making center to manage required comparisons among alternatives [1].

Several authors use multicriteria analysis in studies related to decision-making in engineering as well as in other areas of science. Indeed, some studies use multicriteria analysis in planning the development of the electricity sector in many regions or in evaluating the electrical energy production systems based on conventional technologies [2–5].

Climato *et al.* [2] used a multi-objective linear programming model for this purpose. They presented the objective functions as net current cost, reliability of components and environmental impact to plan new power production systems based on nuclear energy, coal and oil. Their study included neither renewable technologies nor the impact of the decision-making center in the energy planning. Kagiannas *et al.* [3] conducted a strategic review of major energy models in Mozambique and selected those, which could best be used in that country. They also identified the main energy resources available. Dagdeviren and Eraslan [4] used analytical network processes to plan strategies for energy development in Turkey. Want *et al.* [5] developed a multicriteria evaluation for 16 types of systems that combine heat and power using a fuzzy relational method. They contemplated the subjectivity of the decision makers in their study.

Inquiries about systems with renewable technologies evolved from analyses based solely on economic criteria to those that involve environmental criteria [6–18]. Rodolfo and José [6] performed the triple multi-objective optimization of a hybrid system by using an evolutionary algorithm and a genetic algorithm. In this case, the environmental target was the emissions of greenhouse gas during the life cycle of the system components. For this reason, the model included only the emissions from the diesel generator that was part of the hybrid system. Shi *et al.* [7] used multi-objective evolutionary algorithms for the technical and economical design and optimization of isolated hybrid systems. They used the total system cost, its autonomy level and the wasted energy as decision variables. Kaviani *et al.* [8] designed a hybrid wind/photovoltaic/fuel cell system using an optimization algorithm for cloud particles. Their study took account of failures in each of the system components. Katsigiannis *et al.* [9] solved the multi-objective optimization problem for hybrid systems with renewable technologies using genetic algorithms. They used the energy cost of the system as an economic objective and the total emissions in the life cycle of each of the components as the environmental target. The study did not include any applications of multicriteria analysis methods in the decision-making process.

Sedat *et al.* [10] applied a multi-objective optimization genetic algorithm to select the optimal location for wind turbines in a wind farm, maximizing production capacity thereof. Yongping *et al.* [11] achieved the multi-objective optimization of the load dispatch in energy systems that consist of conventional and renewable technologies, with carbon capture and storage systems (CCS). The objectives to minimize were: coal consumption, NO_x emissions, CO_2 emissions and the costs of renewable energy and CCS systems. The suggested methodology was tested in a case study where the influence of the variations in the weighting of each objective was evaluated.

Catalina *et al.* [12] implemented a multiple criteria decision methodology along with an energy system analysis from multiple sources. They argued that 'a further research idea would be to apply this approach with a larger number of criteria (i.e. degree of implementation, mean life cycle of the hybrid system, social impact)' and showed the proper functioning of the ELECTRE III algorithm in such situations. Meanwhile, San Cristobal [13] used the compromise ordering method (Vikor) combined with analytical hierarchy processes to select a renewable energy project in Spain.

Geovanni *et al.* [14] performed the optimization of a hybrid system with hydrogen storage for a coastal community in Cuba. They included the calculation of greenhouse gas emissions in the life cycle of the energy systems. However, they ignored any multicriteria decision analyses that would appraise the influence of the decision-making center in selecting the compromise solution. Cai *et al.* [15] developed a model to study the impacts that the climate changes may cause in the planning of energy systems with different technologies such as hydroelectric, wind and photovoltaic. Suha *et al.* [16] used a genetic algorithm to achieve a multi-objective optimization of a direct methanol fuel cell. The objective functions to maximize were the output power and the energy and exergy efficiencies.

Laurence and Adisa [17] assessed the sustainability in the life cycle of different options for the production of electricity in the UK. They evaluated the use of coal, gas, nuclear energy, offshore wind and photovoltaic energy. They also compared them with regard to their environmental, economic and social effects, using different indicators of sustainability. In connection with the social aspects, the indicators were job creation and the impacts on human health. Samuel *et al.* [18] used criteria such as the net present cost and the potential for global warming to select the optimal sizes of each component in a combined system of electric and thermal energy with solar technologies. The corresponding Pareto set was generated, but the decision-making center did not use any multicriteria analysis technique to select the optimum alternative.

Researchers have not assessed completely the selection of hybrid systems with renewable technologies based on multiple criteria, even though these tools have been widely used in diverse branches of engineering. A proper selection of energy alternatives for a particular application would benefit from adopting a multicriteria approach. It should not contemplate only the technical and economic dimensions but the environmental and social issues as well. That is why, in this study, the optimal energy alternatives for both localities were selected according to multicriteria and the preferences of each decision-making center.

Two systems of self-sufficient energy at UNISTMO and *Gran Piedra* were compared using multicriteria analysis tools. The evaluation criteria are: capital costs, levelized cost of energy and equivalent emissions in the life cycle of the systems. In the case of *Gran Piedra*, the criterion 'community acceptance' replaced the criterion 'levelized energy cost'. It measured the degree of

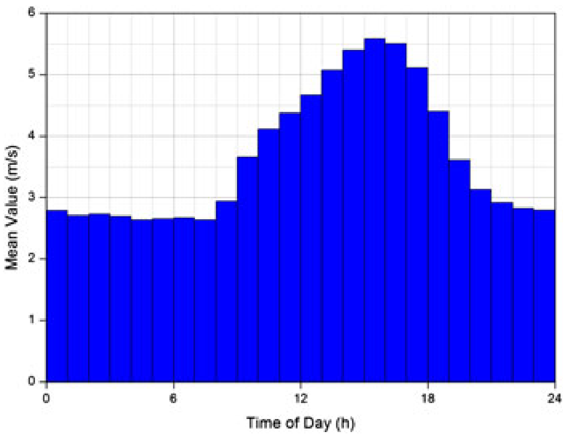

Figure 1. Daily average profile of wind speed at UNISTMO.

acceptance by the residents with regard to the different technologies involved. Compromise programming was used as a tool for multicriteria analysis.

The Isthmus of Tehuantepec in the state of Oaxaca is an important region for the development of renewable energy technologies in Mexico. There are currently wide and growing varieties of investments in wind farms. Conversely, *Gran Piedra* is located in an ecologically vulnerable area in the Great National Park *Sierra Maestra*, located at 1225 m above sea level in the municipality of *Santiago*, *Cuba*. It has a population of 200 inhabitants who live in about 40 dwellings. There is a meteorological station, a hotel and some tourist attractions. The average daily energy demand throughout the community is 145 kWh, with a peak power consumption of 35 kW. At the moment, the community receives electricity by means of diesel generators that consume a significant amount of fuel. Wind resources have been evaluated as an alternative for electricity production.

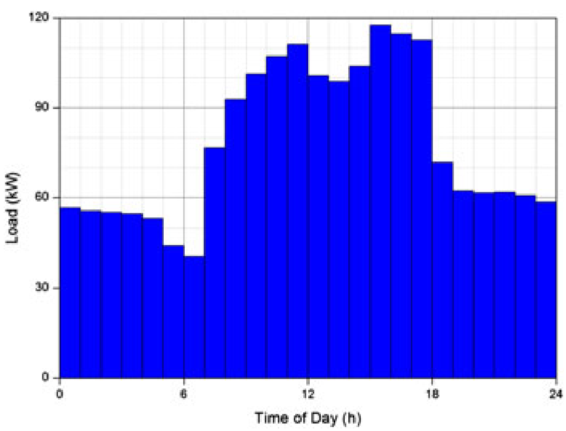

Figure 2. Daily average profile of the energy consumption at UNISTMO.

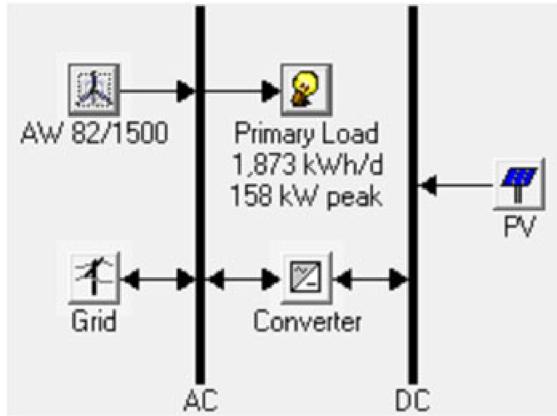

Figure 3. Composition of self-sufficient system at UNISTMO.

2. METHODOLOGY

Measurements of wind speeds at a height of 10 m over a period of three years were used for the study of the self-sufficient system at UNISTMO. They were recorded at the Meteorological Station located at the Wind Energy Laboratory of UNISTMO's Institute for Energy Research.

Figure 1 shows the daily average profile. The mean speed is always higher than 4 m/s between 11.00 and 19.00. A FLUKE 435 energy-quality analyzer was used in the study of the annual electricity consumption at their three campuses. Figure 2 shows the average daily profile of the measured load, the daily consumption being equal to 1873 kWh with a peak power consumption of 158 kW.

The site under study is rich in solar (5.6 kWh/m^2/d) and wind resources. Thus, the estimation of the self-supply system assessed the grid connection of wind and photovoltaic technologies. Figure 3 shows the simulated system diagram.

The presence of manufacturers from the wind energy sector in the Isthmus of Tehuantepec is a factor that influenced the selection of the wind turbine to be installed in the site. According to the peculiarities of the wind resource in the area, the wind turbine model AccionaAW 82/1500 Class IIIb was selected. Its specifications are given in Table I.

In the case of *Gran Piedra*, the most important factors were the average annual wind speed and the average daily consumption. The average annual wind speed obtained from the average monthly wind speed data was 4 m/s,

Table I. Characteristic of the *Acciona AW 82/1500* wind turbine.

Rated power	1500 kW
Hub height	80 m
Rotor diameter	82 m
Start-up wind speed	3.0 m/s
Rated wind speed	11.6 m/s
Cut-out wind speed	20.0 m/s
Manufacturer	Acciona

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while the average daily consumption calculated from the hourly consumption was 145 kWh/d [19]. The Energie PGE 20/25 wind turbine was selected in this case. Its specifications are given in Table II.

This study does not include the energy storage in batteries. It evaluates the option of hydrogen technologies (electrolyzer/hydrogen tank/fuel cells) even if the costs are higher. This is due to the following reasons:

1. The use of batteries is ecologically disadvantageous. The risks are higher, and the recycling process needs to be done very carefully. Since *Gran Piedra* is difficult to be accessed and is located in an ecologically vulnerable region, the use of batteries is hazardous.
2. The life cycle of conventional batteries is much shorter than the life cycle of the hydrogen technologies. This represents an extra risk if the financial resources to cover the cost of replacement are not sufficient.
3. The market for hybrid system components in Cuba is very limited. This could affect the sustainability of the energy system in *Gran Piedra*.
4. The capacity for energy storage is greater in hydrogen technologies. Moreover, the maximum discharge depth does not limit it as in the case of conventional batteries.
5. Maintenance costs of electrolyzers are about the same as that for conventional batteries. Some studies have shown that total maintenance costs for the use of conventional batteries are higher than the costs for hydrogen technologies in systems with power peaks similar to the ones observed at *Gran Piedra* [20,21].
6. Normally, the fuel cell, the electrolyzer and hydrogen storage tanks are maintenance free in their normal operating conditions (temperature, humidity, pressure limits). Normally, these equipment have specified operating conditions and limits. One can buy and install fuel cells, hydrogen tanks and electrolyzers suitable for different climatic conditions. The normal maintenance required is cleaning the system to remove dusts, fill water in the case of electrolyzer, etc. There are only routine maintenances in the case of these equipment.
7. The HOMER model used in this study does not include any penalties for environmental damages caused by the batteries. However, a few studies deal with this aspect.

Table II. Characteristic of the *Energie PGE 20/25* wind turbine.

Rated power	25 kW
Hub height	24 m
Rotor diameter	20 m
Start-up wind speed	3.5 m/s
Rated wind speed	9.0 m/s
Cut-out wind speed	25.0 m/s
Manufacturer	Energie PGE

This study also examined diesel generators since they currently supply electricity to the community. These are parts of the hybrid system that are under study. However, there is an additional 35 kW generator that would never work at less than 20% of its nominal capacity. Rather than totally replacing this technology, a hybrid system might help to reduce the period of time it is used. The hybrid system helps reducing the amount of diesel that is consumed. This fuel is currently transported from the city quite irregularly. This has caused breakdowns in the electricity supply for some time. Figure 4 shows the schematic diagram of the simulated hybrid system.

Both studies use the enumerative search method implemented by the HOMER v2.68 program to achieve the economic optimization of the systems. Table III lists the assumed capital costs for each system components [14,22,23].

HOMER is a recognized program for the optimization of hybrid energy systems supported on renewable sources.

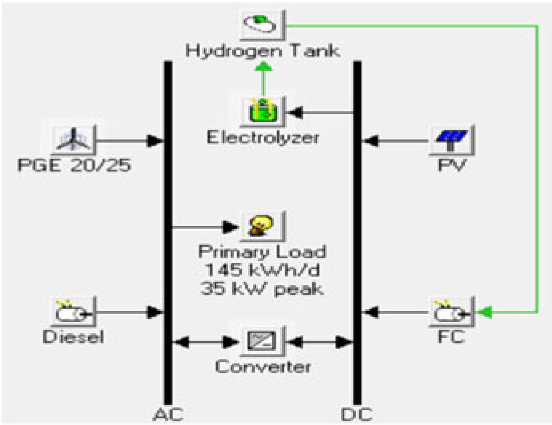

Figure 4. Composition of the hybrid system at *Gran Piedra*.

Table III. Capital costs for components.

Components	Capital costs	Sources
Wind turbine	1700 US$/kW[a] 1500 US$/kW[b]	[23]
Fuel cell	3000 US$/kW	[14,20,24]
Electrolyzer	2000 US$/kW	[14,20,24]
H_2 tank	1300 US$/kg	[14,20,24]
Converter	1000 US$/kW	[14,20,24]
Diesel generator	800 US$/kW	[14,20,24]
Photovoltaic generator	6900 US$/kW[c] 3900 US$/kW[d]	Different providers

[a]Capital cost for Acciona AW 82/1500 wind turbine.
[b]Capital cost for Energie PGE 20/25 wind turbine. In this case, it was assumed that the Cuban government would absorb 50% of the cost estimated in 3000 US$/kW and Non-Governmental Organizations the rest.
[c]It corresponds to the price of the PV generators in Cuba. It is almost twice the price in Mexico, possible due to the lack of providers in Cuba.
[d]It corresponds to the price of the PV generators in Mexico.

It is widely used in research [24–31]. It models the functioning of a particular system configuration at any time of the year to establish its technical viability and cost over its lifetime (simulation). Indeed, it simulates many different configurations and searches the one that satisfies the technical restrictions at the lowest cost (economical optimization). Also, it makes various optimizations assuming possible changes in some of the input variables (sensitivity). For more detailed information about HOMER, visit the website http://www.homerenergy.com or the help menu of the program.

The operation and maintenance costs of the wind turbines equaled 2% of their capital cost. The energy cost for the public from the electrical grid in the case of UNISTMO is about 0.08 US$/kWh. This coincides with the average price for most of the sectors in Mexico (with the exception of agriculture). CFE reports that this price is below the production cost of the conventional energy [32].

Equivalent emissions for the life cycle of each energy alternative were calculated from the indices of CO_2 equivalent emissions for all the technologies involved (expressed in $gCO_2eq./kWh$). The exact calculation of these indices is difficult. Indeed, they depend on the industrial, economic and energy sectors in the country where the technology is generated. Some studies show that in the case of renewable technologies, the equivalent emission indices depend on phases previous to their operation. They are sensitive to the source of energy used in these phases [9,17,33–40].

It is important to mention that, in general, renewable technologies are improving rapidly. That is why there are numerous publications of new studies that include these improvements. As a reference, this study uses the equivalent emission indices that Katsigiannis *et al.* (Table IV) [9] used.

The following generation matrix for the electrical grid [42] with its corresponding emission indices (Table V) was used in the UNISTMO case study. There is little available data about the matrix in the electrical grid in Mexico. There are only some data from the Energy Secretariat (SENER), the public institution responsible for the energy policies in the country. This study uses the data from one of its reports [41].

In each case study, the corresponding decision matrix was generated. They contain the group of non-dominated alternatives that satisfy the restrictions applied to the optimization problem. Each alternative comprises a certain combination of components with the respective values of the objective functions. Once the Pareto set is obtained, it is important to establish which alternative or solution is the best. The Zeleny axiom is helpful to do this. When an alternative is out of reach, the optimal choice or better solution is the closest to the ideal one.

Table IV. Equivalent emissions for different technologies and components.

Components	Equivalent emissions ($gCO_2eq./kWh$)
Wind turbine	11.0
Photovoltaic modules (mono-Si)	45.0
Diesel generators	880.0
Fuel cell (H_2 by electrolysis)	20.0
Electrolyzer and H_2 tank	11.0

Table V. Composition of the electricity grid in Mexico and its corresponding emission indices.

Energy sources	Participation (%)	Equivalents emissions ($gCO_2eq./kWh$)
Coal	9.2	881.0
Diesel	25.6	880.0
Natural gas	38.3	540.0
Nuclear	2.7	42.0
Hydroelectric	23.2	40.0
Wind energy	1	11.0
Total emissions		520.0

For each matrix generated, the optimal solution or the one closest to the ideal point is selected through compromise programming, introducing the main decision maker's preferences. The criteria used in this analysis are: 'capital costs', 'levelized cost of energy' and 'equivalent emissions in the life cycle'. Nevertheless, for the case study *Gran Piedra*, the criterion 'levelized cost of energy' is replaced by the 'community acceptance', which measures the degree of acceptance by the residents with regard to the different technologies involved. This is a factor that may affect the sustainability of a self-sufficient energy system. In this study, it has values between 0 and 5, the highest value corresponding to the one that expresses the greatest acceptance by the community.

The criterion 'community acceptance' was included to show the incidence of users in the selection of the optimal isolated system to be installed. However, the study does not explore the reasons why they had this preference or how they could take part in the study and be better informed.

The first step in the compromise programming is to establish the ideal and non-ideal vectors for each case study. The ideal vector is represented as:

$$F^* = \left(F_1^*, F_2^*, F_3^*\right) \quad (1)$$

where, F_1^*, F_2^* and F_3^* being the minimum values (maximum for the non-ideal vector) for the criteria 'capital cost', 'levelized cost of energy' and 'equivalent emissions in the life cycle', for the case study UNISTMO. For the case study of Gran Piedra, F_1^*, F_2^* and F_3^* are the minimum values (maximum for the non-ideal vector) of the 'capital cost', 'equivalent emissions in the life cycle' criteria and the maximum value (minimum for the non-ideal vector) for the community acceptance.

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The following step is to define the degree of proximity ($d_{i,j}$) amongst the F_i criteria and their F_i^* ideal values for each 'j' alternative from the decision matrices.

$$d_{j,i}\left|F_i^* - F_{j,i}\right| \quad (2)$$

where,
$i = 1, 2, 3$ (there are three criteria included in the study).
$j = 1, 2,\ldots, n$. 'n' being the number of alternatives in each decision matrix.

Thus, for each case study, a degree of proximity matrix is created as follows:

$$\begin{pmatrix} d_{1,1} = \left|F_1^* - F_{1,1}\right| & d_{1,2} = \left|F_2^* - F_{1,2}\right| & d_{1,3} = \left|F_3^* - F_{1,3}\right| \\ d_{2,1} = \left|F_1^* - F_{2,1}\right| & d_{2,2} = \left|F_2^* - F_{2,2}\right| & d_{2,3} = \left|F_3^* - F_{2,3}\right| \\ d_{3,1} = \left|F_1^* - F_{3,1}\right| & d_{3,2} = \left|F_2^* - F_{3,2}\right| & d_{3,3} = \left|F_3^* - F_{3,3}\right| \\ \vdots & \vdots & \vdots \\ d_{n,1} = \left|F_1^* - F_{n,1}\right| & d_{n,2} = \left|F_2^* - F_{n,2}\right| & d_{n,3} = \left|F_3^* - F_{n,3}\right| \end{pmatrix}$$

Then, each element in the previous matrix is normalized. This is due, amongst other factors, to the lack of dimensional homogeneity among the criteria. For instance, the capital cost is given in US$, the levelized cost of energy in US$/kWh and the equivalent emissions in the life cycle in tCO_2eq.

The following normalizing process is based on Eqn 3 [1]. The normalized degree of proximity for each criterion ($d_{j,i}^N$) is 0 when it reaches its ideal value and it is 1 when it reaches its non-ideal value.

$$d_{j,i}^N = \frac{\left|F_i^* - F_{j,i}\right|}{\left|F_i^* - F_{*i}\right|} \quad (3)$$

where F_{*i} is the non-ideal value or the worst value for the criterion i.

Once the degrees of proximity are normalized, the preferences of the decision-making center are given to each criterion (W_i to establish which alternative is the closest to the ideal for each case study. The following distance function [1] is used to establish it.

$$L_\pi = \sqrt[\pi]{\sum_{i=1}^{n} W_i^\pi \left(\frac{\left|F_i^* - F_{j,i}\right|}{\left|F_i^* - F_{*i}\right|}\right)^\pi} \quad (4)$$

where, the π parameter represents the metric that defines the distance function (for $\pi = 1$ it is the Manhattan distance, for $\pi = 2$ it is the traditional or Euclidian distance and for $\pi = \infty$ the Tchebycheff distance). The solution associated to point L_∞ is a well-balanced solution. Thus, it is appealing from a choice perspective [1]. This is why this metric is used in the decision making. For this last metric, the distance of each alternative 'j' to the ideal point is established with this expression [1]:

$$L_{\infty,j} = max\left|W_1 d_{j,1}^N, W_2 d_{j,2}^N, W_3 d_{j,3}^N\right| \quad (5)$$

where, W_1, W_2 and W_3 are the preferences of the decision-making center for each of the three criteria analyzed in the case studies.

One objective in this study is to evaluate the incidence of the decision-making center in the selection of the optimum alternative. Three scenarios for a preferential weight to the analyzed criteria were considered (Table VI).

4. ANALYSIS AND DISCUSSION

4.1. UNISTMO case study

The decision matrix in the case of self-sufficiency at UNISTMO consists of four alternatives or possible combinations of energy technologies (Table VII). These form the non-dominated solutions to the problem of simultaneous optimization of the capital cost and equivalent emissions in the life cycle criteria.

The first alternative is the one currently used at UNISTMO: energy supplied by the national grid. This alternative would not involve any initial investment (zero capital cost), and the corresponding COE would be the second lowest. Nevertheless, the equivalent emissions in the life cycle are more significant. The second and third alternatives consist of photovoltaic systems connected to the electricity grid: one with a RF of 56% and the other with a RF of 62%. The difference in capital costs is $ 220,000.00, and the difference in equivalent emissions is 138 tCO_2eq. The fourth alternative is a wind turbine connected to the grid, which would achieve 93% of renewable fraction and avoid the emission of 3781 tCO_2eq., due to the use of energy from the grid. Figure 5 shows the four alternatives with the corresponding values of capital cost and equivalent emissions.

The alternative with the least of equivalent emissions would be to combine the electrical grid with a wind turbine, which has the highest capital cost but the lowest

Table VI. Preferential weights considered in the study.

Preferential weights (%)								
W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3
20	60	20	40	20	40	40	40	20

W_1: Preference for criterion 'equivalent emissions in the system life cycle'.
W_2: Preference for criterion 'capital cost'.
W_3: Preference for criteria 'levelized cost of energy' in UNISTMO case study and 'community acceptance' in Gran Piedra case study.

Table VII. Decisional matrix for energy self-sufficiency for UNISTMO.

	Alternatives							
Order number	Grid (kW)	PV (kW)	WT (kW)	Converter (kW)	Capital cost (US$)	COE (US$/kWh)	E_{SLC} (tCO_2eq.)	RF (%)
1	1,500,000	0	0	0	0	0.08	7165	0
2	1,500,000	250	0	160	1,060,000	0.13	4405	56
3	1,500,000	300	0	200	1,280,000	0.14	4267	62
4	1,500,000	0	1500	0	2,550,000	0.03	3384	93

PV: Photovoltaic
WT: Wind turbine
RF: Renewable fraction

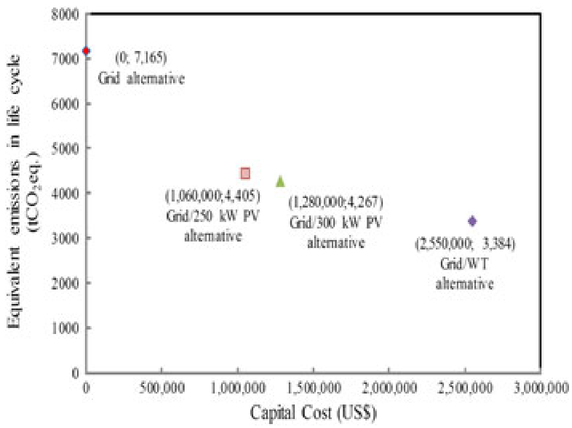

Figure 5. Alternatives or non-dominated solutions for the case of energy self-sufficiency at UNISTMO.

COE (0.03US$/kWh). The other two alternatives include PV systems connected to the grid with differently sized converters (Table VII) and have intermediate values relative to those of the other two alternatives.

Table VIII shows the results of the multicriteria analysis for the optimum solution. It assesses the impact of the weighting on the decision-making center for the three assigned criteria: equivalent emissions in the life cycle (W_1), capital cost (W_2) and levelized energy costs (W_3).

Table VIII. Distance matrix for different decision-maker's preferences for some criteria over others (UNISTMO case study).

	L_∞								
	W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3
Alternatives	0.2	0.6	0.2	0.4	0.2	0.4	0.4	0.4	0.2
1		0.20			0.40			0.40	
2		0.25			0.36			0.18	
3		0.30			0.40			0.20	
4		0.60			0.20			0.40	

For example, when the decision-making center assigns greater importance to the capital cost (60%), the optimum alternative is the national grid (Option No.1 in Table VII), and the one farthest from being the most optimum is the wind turbine connected to the grid (Option No. 4 in Table VII). However, this setup changes if the decision-making center gives less importance to the capital cost and more importance to the E_{SLC} and COE. Thus, when a preference of 20% is given to the capital cost and 40% to the E_{SLC} and COE, the optimum solution is the wind turbine connected to the grid, with a RF of 93%, followed by the 250 kW PV system connected to the grid.

If the importance assigned to capital cost raises to 40%, the E_{SLC} remains at 40% and the value for COE drops to 20%, then the best alternative is No. 2, which is the 250 kW PV system connected to the grid, with 56% of RF. In this case, the national grid and a wind turbine connected to the grid would be the alternatives that are farthest from the ideal (Table IX).

4.2. *Gran piedra* case study.

For the case study *Gran Piedra*, the decisional matrix consists of four alternatives. Table X shows the combinations of components for each of the four alternatives that make up the Pareto front (Figure 5), with the corresponding values of capital cost, E_{SLC} and COE. It also includes a column with the values of RF for each alternative.

As Table X and Figure 6 (Pareto front) show, the alternative that includes a diesel generator has the lowest capital cost. However, this is the alternative with the most important equivalent emissions in the life cycle and the highest levelized energy cost. This is due to the high cost of diesel. This is an important disadvantage, especially because *Gran Piedra* is located in an ecologically vulnerable region.

Numbers 3 and 4 (Table X) are the alternatives with the lowest levelized energy costs and equivalent emissions in the life cycle. Both alternatives consist of diesel generators and wind turbines (and one photovoltaic generator for alternative number 4) integrated to hydrogen technologies. The capital cost for alternative number 4 is the highest but there are less equivalent emissions in the life cycle and the levelized energy cost is the lowest. It consists of a 15 kW photovoltaic generator, two 25 kW wind turbines, a

Table IX. Ranking of solutions for UNISTMO case study (in each case the solution to the left represents the best or nearest to the ideal point).

Preferences for W_i criterion	W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3
	0.2	0.6	0.2	0.4	0.2	0.4	0.4	0.4	0.2
Ranking of alternatives	1 ← 2 ← 3 ← 4			4 ← 2 ← 1-3			2 ← 3 ← 1-4		

W_1: Preference for criterion 'equivalent emissions in the life cycle'.
W_2: Preference for criterion 'capital cost'.
W_3: Preference for criterion 'levelized cost of energy'.

Table X. Decisional matrix for the case of energy supply to *Gran Piedra* rural community.

Alternatives											
Order number	PV (kW)	WT (kW)	FC (kW)	DSL (kW)	Converter (kW)	Ely (kW)	H_2 Tank (kg)	Capital cost (US$)	E_{SLC} (tCO_2eq.)	COE (US$/kWh)	RF (%)
1	0	0	0	35	0	0	0	10,500	1278	1.86	0
2	0	50	0	40	0	0	0	87,000	785	1.29	75
3	0	50	10	30	30	30	20	230,000	260	0.64	92
4	15	50	10	30	30	15	10	290,500	233	0.62	94

PV: Photovoltaic
WT: Wind turbine
FC: Fuel cell
DSL: Diesel generator
Ely: Electrolyzer
RF: Renewable fraction

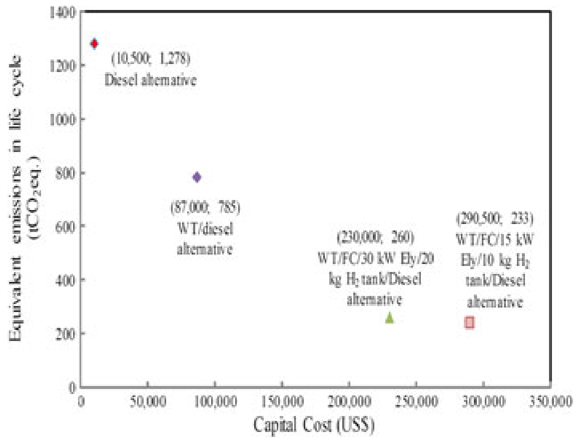

Figure 6. Alternatives or non-dominated solutions for the case of the energy supply to *Gran Piedra*.

10 kW fuel cell, a 30 kW diesel generator, a 15 kW electrolyzer, a 10 kg hydrogen tank and a 30 kW inverter.

Most authors concur with the belief that hydrogen technologies are not the optimal alternatives for energy storage in self-sufficient systems. Storage in conventional batteries seems to be more widely recommended. The results of this study could have been similar. Nevertheless, due to the aforementioned factors, conventional batteries are not included in the hybrid system under study.

As in the previous case, three possible values of weighting the decision maker assigning to some criteria over others were evaluated. Those are, equivalent emissions in life cycle (W_1), capital cost (W_2) and community acceptance (W_3).

Table XI shows the matrix of distances for different preferences from the decision-making center with regard to other criteria. Table XII shows the arrangement of solutions that was obtained from this matrix.

Table XI. Matrix of distances for different preferences of the decision-maker center for some criteria over others (Case Study of *Gran Piedra* rural community).

	L_∞								
	W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3
Alternatives	0.2	0.6	0.2	0.4	0.2	0.4	0.4	0.4	0.2
1		0.20			0.40			0.40	
2		0.16			0.21			0.21	
3		0.47			0.40			0.31	
4		0.60			0.20			0.40	

Table XII. Ranking of solutions for *Gran Piedra* case study (in each case, the solution to the left represents the best or nearest to the ideal point).

Preferences for W_i criterion	W_1	W_2	W_3	W_1	W_2	W_3	W_1	W_2	W_3
	0.2	0.6	0.2	0.4	0.2	0.4	0.4	0.4	0.2
Ranking of alternatives	2 ← 1 ← 3 ← 4			4 ← 2 ← 1-3			2 ← 3 ← 1-4		

W_1: Preference for criterion 'equivalent emissions in the system life cycle'.
W_2: Preference for criterion 'capital cost'.
W_3: Preference for criterion 'social acceptance'.

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When the decision-making center assigns a greater importance to the capital cost (60%) and 20% to each of the other two criteria, the best solution is the combination of two wind turbines PGE 20/25 (50 kW) with a 40 kW diesel generator. With this alternative, 75% of RF could be achieved. By changing the preferences of the decision-making center and assigning less importance to the capital cost (20%) and equal importance to the E_{SLC} and community acceptance criteria (40%), number 4 would be the optimum alternative. This consists of 15 kW from PV generators, 50 kW from wind turbines and 30 kW from diesel generators with hydrogen energy storage (10 kW from fuel cell, 15 kW from electrolyzers and a 10 kg hydrogen tank). This alternative would achieve 94% of RF and would be followed by option number 2, which would achieve 75% of RF (see Table XII).

If the importance of the community acceptance is 20% and if the same degrees of preference are assigned to the E_{SLC} and capital cost criteria (40%), the ideal alternative is again number two. However, in this instance, it is followed by number three, which would be a system of 50 kW from wind turbines and 30 kW from diesel generators with hydrogen storage (10 kW from fuel fuels, 30 kW from electrolyzers and a 20 kg hydrogen tank). Table XII shows the ranking of solutions for the three values of the different criteria.

To see in which cases the system based solely on diesel generators occupies the place closest to the ideal alternative, we increased the preference of the decision-maker center by the capital cost criterion. We could see that the diesel system is the best one only for values greater than 70% of preference for the aforementioned criterion and whenever the E_{SLC} criterion does not go beyond a meaningful level of 19%.

5. CONCLUSIONS

The results of this work show the importance of multicriteria analyses in energy planning. Two case studies were analyzed. The case study UNISTMO is based on a framework of energy self-sufficiency supported on the regulation system for the electricity sector in Mexico. The other case study is based on an isolated supply of electricity to a rural community in *Santiago*, *Cuba*. In both cases, the study shows that the introduction of criteria different from the economic ones, such as equivalent emissions in the life cycle, levelized cost of the energy and community acceptance, can modify energy supply frameworks.

In the case of UNISTMO, when a greater weighting is given to equivalent emissions in the life cycle and to the levelized energy costs, wind turbine or PV systems connected to the grid are optimal. Conversely, if the systems were compared solely in relation to the capital cost the result would obviously lead to keep the electricity supply to UNISTMO exclusively from the national electricity grid.

Similarly, in the case of *Gran Piedra*, the system based on diesel generators is optimum only when the capital cost criterion reaches 70% or more of the weighting the decision-making center assigns in relation to the E_{SLC} and community acceptance criteria. When the capital cost weight falls below 70%, renewable technologies begin to participate in the optimum solution of energy systems, reaching renewable fractions of 75% and 94% in two of the combinations of components.

In the case of *Gran Piedra*, since it is located in an ecologically vulnerable region and because a great importance is given to the environmental issues, the energy alternatives did not include the use of batteries for the energy storage or diesel generators as sole energy technology. Instead, the integration of wind and photovoltaic technologies with hydrogen technologies happened to be more appealing.

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