Choosing energy supply options for rural communities: an MCDA approach

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Abstract

Rural energy planning requires a rigorous analysis for the determination of the best energy alternatives for the supply of electric energy, either through the extension of electricity grids, or using local energy resources such as photovoltaic solar energy, wind energy or hybrid systems, including local micro-grids. Several selection criteria are considered for the evaluation of a set of defined alternatives, according to economical, technical, social and environmental objectives. The choice of an adequate tool to help in decision making for the selection of the best alternative, taking into consideration multiple criteria, is then a needed step, as well as the definition of the preferences of decision makers regarding how to use the obtainable information to make an informed and documented decision.

The presented work reviews multi criteria decision methods used in energy planning. The process of defining models to decide between complex or conflicting alternatives is presented, starting with the process of structuring the problem and choosing a multicriteria methodology adapted to the characteristics of the problem. A second part is dedicated to the effort of obtaining the information needed to define the preferences of decision makers, according to the chosen methodology and dealing with the implications of this choice. Finally, the results of applying MCDA methodologies to case studies regarding electric energy supply to rural communities in developing countries is presented, discussing alternatives and their implications.

The choice of convenient MCDA methods allows the use of both quantitative and qualitative criteria, avoiding the need to discard important issues due to difficulties in quantifying impacts or in measuring them in appropriate scales. Compensation effects can also be avoided by establishing the possibility of vetoing certain ranking/classification hypothesis due to poor performances in certain criteria, even when performing very well in other criteria. In the case studies, solutions with micro-grids and dispersed generation, namely solar based, got the general preference to other alternatives, namely, to grid extensions.

Introduction

The electric grid coverage of rural areas in Ecuador is still small when compared to urban areas: 89% vs 95% (Ministerio de Electricidad y Energía Renovable 2014). This is due to major constraints faced when deciding the cost-effectiveness of grid-extension investments, namely: the low demand, difficult access, environmental issues and naturally the high costs to extend the grid (Rojas-Zerpa and Yusta 2015). Planning the energy supply to rural areas, using renewable sources, imply also complex problems, as a deficient analysis may lead to incorrect sizing of equipment, environmental impacts, social impacts or excessive costs (Domenech Léga 2013). A correct analysis of the available options to supply electricity to remote consumers requires the consideration of these multiple aspects becoming an obvious target to a multicriteria decision process.

Multicriteria decision methods explicitly consider the multiple dimensions of reality. Instead of looking for an "optimal" solution, the aim is to identify the solutions that better suit the preferences stated by the decision maker. A carefully chosen procedure may also include the treatment of the uncertainty of data, allowing the analysis of the decision robustness. In this way, different combinations of local energy resources and grid extension options can be analyzed as discrete alternatives. Different studies (Benítez Leyva 2015; Domenech Léga 2013; Jaramillo 2011; Ochoa Ramón 2009) present small solar and wind generation to supply electricity to rural areas. In the cases of great sparsity, individual systems present the obvious choice but, when house agglomerates exist, microgrids become possible alternatives, as shown in figure 1 (Rojas-Zerpa and Yusta 2015).

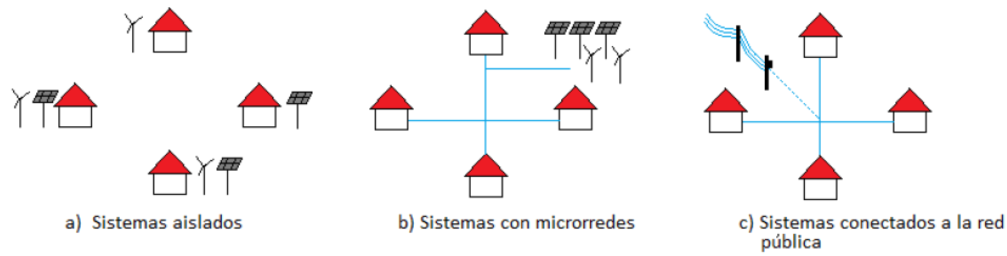

Figure 1 - Alternatives to supply electricity to rural communities (Adapted from Ochoa Ramón 2009).

The present paper starts by analyzing the problem and explaining the possible alternatives to supply electricity to rural areas in Ecuador. Secondly, presents available multicriteria decision methods, focusing one that fulfills the requirements of the problem under analysis, a classification procedure based on ELECTRE TRI (W. Yu 1992). Thirdly, an evaluation model for a case study using ELECTRE TRI is proposed, describing procedures needed to assess the required parameters that describe the preferences of a decision maker. Finally, conclusions are drawn about the case described and the applicability of the chosen method.

Literature review

Rural or isolated regions lacking electricity supply are often characterized by significant challenges as the distance from national or regional electricity grids, difficult terrain such as rivers or jungles, harsh weather conditions etc (Amutha and Rajini 2016). This imply a different type of analysis when compared to urban areas (Rojas-Zerpa and Yusta 2015).

As Papadopoulos and Karagiannidis (2008) states, the extension of the grid is often not the most cost-effective solution as the population density in rural areas can become too low. In such cases, the investment needed to extend the grid overrides the costs associated to the investment in renewable sources and other required equipment. Local solutions also avoid energy losses in transmission lines.

Rojas-Zerpa and Yusta (2015) performed an analysis of 3 supply options for rural communities, namely, the extension of the grid, an individual generator set for each house or a single microgrid for the whole community. As Domenech Léga (2013) also confirmed, until a certain distance, the grid extension results in the lowest cost option, but, for longer distances, depending on the load demand, the orography or the climatic conditions, local generation and specially renewable based generation, become the best options. If the community is sparse, individual systems are more adequate, but, for agglomerates, small microgrids may become cost-effective(Rojas-Zerpa and Yusta 2015).

According to Ferrer-Martí *et al* (2010), due to the dispersion of isolated houses in rural communities of developing countries, the most common solution has been the installation of individual systems, with generation and storage at each point of consumption: houses, health centers, schools or community centers. However, the most common is to use a single technology, profiting from eventual complementarities. Also, due to the variability of both the resource and the demand, systems are normally oversized, resulting more expensive, and usually not much prepared for incremental upgrades.

Microgrids may offer a few advantages in some cases (Kirubi et al. 2009):

- One point of consumption is not constrained by the potential resources at its location, benefiting from the possible connection to other locations with more potential.
- Economies of scale may result, allowing the use of bigger equipment with lower unitary costs.
- Flexibility of individual consumption is increased, benefiting from complementarity among consumers.

The electricity consumption in rural areas of developing countries is very different from the electricity consumption in urban areas. The main use of electricity is lighting and for equipment required for agriculture. Usually the consumption is very low, implying a difficult return of any investment in the infrastructure. However, it is considered an essential element for the social and cultural development of the populations, e.g., by favoring education.

Peralta Jaramillo (Jaramillo 2011) performed the characterization of the electricity consumption at a rural area in Ecuador, collecting information about the main electric apparatus used daily, in order to be able to estimate the total daily demand for different kinds of installations, namely houses and community services like churches and schools, community centers and recreation areas. Table 1 represents the information collected regarding individual houses in the settlement.

Table 1 - Estimated demand per house (adapted from Jaramillo, 2011)

Equipment	**Power** [W]	**Number of appliances**	**Working time** [h]	**Daily consumption** [wh/day]
Lamp	20	5	4	400
Radio	40	1	3	120
TV	65	1	1	65
Others	50	1	2	100

For most electric utilities in Ecuador, the demand is estimated according to pre-defined rules, defined for both the urban areas and rural areas. As an example, the regional utility

"Centro Sur" (EERCS) uses the values defined in Table 2 and Table 3 to estimate the maximum demand estimated of new distribution lines for a 10 year horizon (DMUp 10) and for a 15 year horizon (DMUp 15).

Table 2 - Determination of the demand for urban areas (Centrosur, n.d.)

Households in urban areas			
Average footprint area (m2)	Type of household	DMUp10 (KVA)	DMUp15 (KVA)
A > 400	A	7,47	7,99
300 < A < 400	B	3,93	4,29
200 < A < 300	C	2,23	2,48
100 < A < 200	D	1,36	1,55
A < 100	E	0,94	1,09

Table 3 - Determination of demand for rural areas (Centrosur, n.d.)

Rural households			
Sector	Type of household	DMUp10 (KVA)	DMUp15 (KVA)
City outskirts	F	1,02	1,16
Village center	G	0,84	0,98
Rural	H	0,65	0,76

Multicriteria decision methods for choosing among energy supply alternatives

Choosing among energy supply options imply the consideration of multiple issues, namely economic, social, environmental and technical. The models and methods of Multi-Criteria Decision Analysis, or Multi-Criteria Decision Aiding (MCDA) (Belton and Stewart 2002; Ishizaka and Nemery 2013; Roy 1996) are particularly adequate and are widely applied. Numerous MCDA models and methods can be used to appraise policies, projects, or any other type of alternatives in a decision process, explicitly using multiple evaluation dimensions (the criteria, or objectives). These approaches recognize that decisions involve compromises between conflicting objectives, but that is more transparent than, e.g., trying to measure all kinds of social, technical and environmental benefits or negative impacts in monetary units, which often implies questionable computations or the simple disregard of important impacts only because a credible monetary measure is not viable. MCDA usually allows a simpler analysis by assessing the performance of each alternative on each criterion separately, and then aggregating these assessments to derive a recommendation.

The use of MCDA methods firstly requires the definition of alternatives and evaluation criteria and the assessment of each alternative on each evaluation criterion. Criteria such as costs, emissions, populations or areas are usually measured on quantitative scales, whereas criteria such as degree of opposition of the population or aesthetic impact on the landscape will usually be assessed using qualitative levels (e.g., negligible, weak, strong, etc.).

There are several distinct schools of thought regarding multicriteria decision making. One which is sometimes referred as the “French School” or the “European School” (Roy and Vanderpooten 1997) resulted from the development of the ELECTRE methods (Roy 1996, 1985) and gave origin to several other works like PROMETHEE (Brans and Vincke 1985). The methods of the European school are based on the concept of outranking. In a typical outranking method an alternative *a* outranks another alternative *b* if the majority of the criteria agrees that *a* is at least as good as *b* (taking into account the criteria weights), and there is no criterion in which *a* is so much worse than *b* that it would “veto” the outranking. The ELECTRE methods have been applied to many areas and is one of the most common for MCDA applied to energy problems (Benítez Leyva 2015).

Different variants of the ELECTRE methods have been developed according to different objectives of the MCDA application, or the “problématique” (Roy 1996):

- Selection (or choice) consists in identifying the best alternative (or the best k alternatives), e.g., developing an energy plan for a country, selecting the best photovoltaic technology, or choosing the location for a wind farm;
- Ranking (or prioritization) consists in ordering the alternatives from best to worst, e.g., prioritizing the order by which several projects will be implemented, or ranking the environmental performance of energy producers;
- Sorting (or classification) consists in assigning alternatives to categories, which are typically defined a priori and ordered.
- Description consists in describing the decision situation in a formal language, in terms of actions, criteria and evaluations.

The use of a MCDA requires a decision maker to clearly state his structure of preferences, through a set of parameters that depend on the method chosen, but that will define how the necessary compromises between conflicting objectives will be handled. It must be understood that, unless the different objectives concur to define which option is the best, a case that, occurring, makes the method somehow useless, no optimal solution exists. The best solution represents a specific decision maker, thus becoming intimately attached to him/her, and even to the specific time in which he/she was called to define his/her preferences.

The ELECTRE TRI method (W. Yu 1992; Roy and Bouyssou 1993) aims the classification of alternatives into pre-defined categories C_j bounded by reference alternatives b_h (profiles), as represented in Figure 2.

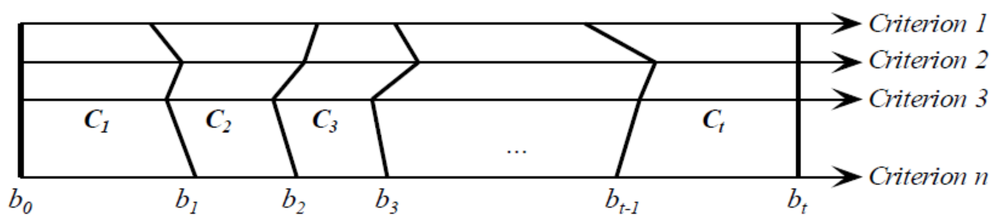

Figure 2 - Definition of categories through reference alternatives b_h

Considering *A* the set of alternatives and *B* the set of reference profiles, the assignment of alternatives to categories is based on the outranking relation in $A \times B$. An action $a_i \in A$ outranks a profile $b_h \in B$ (denoted $a_i\ S\ b_h$) if a_i is at least as good as b_h, given the evaluations of a_i and b_h in the n criteria and their relative importance. The evaluations in each criterion are compared according to a fuzzy relationship that considers the possibility of indifference, weak preference or strong preference. The outranking relation results from the coalition of criteria in favor, according to their weights. A veto threshold can also be defined for each criterion, meaning that a poor performance in such criterion may veto any outranking relation, independently of the performances on the remaining ones.

The following section will focus the evaluation of renewable sources and energy planning according to economic, technical, social and environmental criteria.

Classification of electricity supply options for rural areas in Ecuador, using ELECTRE TRI

The planning process starts with a socio-economic analysis of the location under study, finding out the characteristics and the needs to satisfy, and establishing the relevant issues to consider when comparing alternatives, the values. Secondly, a definition of the viable alternatives to consider is required, as a function of the local energy resources. With the definition of both criteria and alternatives, an evaluation matrix can be assessed.

Table 4 presents a summary of criteria and the types of systems used in different studies performing analysis of rural electrification options, namely, individual systems (IS), microgrids (uG) or grid expansion (GE).

Table 4 - Criteria and types of alternatives used in different studies

Reference	Criteria				Types		
	Technical	Economic	Social	Environmental	IS	uG	GE
(Domenech Léga 2013)	Energy consumption; Resource persistence; Flexibility; Local support; Local manufacture; Security	Infrastructure costs	Management simplicity Equity; Household benefits; Community services; Productive uses; Impact on local resources		X	X	
(Rojas-Zerpa and Yusta 2015)	Efficiency coefficient; Energy not supplied; Availability to supply primary energy; Reliability	Net present costs; Variable O&M costs	Job creation; Social acceptance; Human development index	Emissions of CO2, NOx, SO2 Land use	X	X	X
(Benítez Leyva 2015)		Investment costs; O&M costs	Social acceptance;	Emissions of CO2, NOx, SO2	X	X	
(Jaramillo 2011)	Continuity of supply; Estimated demand; Analysis of energy resources	Net present value	Community service; Land use		X	X	

(Ochoa Ramón 2009)	Supply; Flexibility; Support and maintenance; Local manufacture; System risks	Initial investment/benefit O&M costs; Payment effort	Simplicity of management; equity; Access to basic services; household benefits; Impact over solar resources	Noise; Pollutants emissions; Waste production; Visual impact	X	X	

Although criteria may change, depending on the location, the summary presented in Table 4 shows that a number of criteria are common. From these, a selection was made regarding the ones to use on the case study here described, represented in Table 5 with their respective measuring units and sub-criteria.

Table 5 - Criteria and sub-criteria to consider

Criteria	Sub-criteria	Unit
Technical	g1 - Availability of supply	%
	g2 - Demand coverage	%
Economic	g3 - Investment costs	$
	g4 - O&M variable costs	$
Social	g5 – Social acceptance	%
Environmental	g6 - CO2 emissions	kgCO2/y
	g7 - Land use	0-3
	g8 - Visual impact	0-3

To note that, in Table 5, the availability of supply, which uses the ratio of the lowest availability to the average availability, the demand coverage, which expresses the ratio of the daily production (energy access) to the total estimated consumption, and the social acceptance, are to be maximized. The remaining criteria are to be minimized. The social acceptance and CO_2 emissions were determined based on information available in the literature (Rojas-Zerpa and Yusta 2015).

To define alternatives, all criteria must be taken into account. In this case, locations must be analyzed and screened, identifying alternatives which present promising possibilities. The knowledge of the evaluation matrix is a very important next step in the procedure.

The case study is a small settlement located in the south-east of Ecuador, in the province of Zamora Chinchipe, near the border with Perú, at 36km from the city of Palanda. The place has difficult access, being located in a mountainous area with too much vegetation. The settlement is dedicated to agriculture, with some coffee plantations and also some small cocoa plantations, as well as cattle breeding. In the area, there are 17 houses not served by electricity.

The electricity consumption is mainly for lighting, as during most of the day the population works in agriculture, only requiring a few appliances for food preparation and a refrigerator.

Figure 3 - The settlement under study

Table 6 summarizes an estimate of basic requirements.

Table 6 - Estimate of energy and demand requirements

Description	Number	Unit power (watts)	Total power (watts)	Working time (h/day)	Total energy (Wh/day)
Light bulbs	5	9	45	4	180
TV set	1	100	100	2	200
Refrigerator	1	168	168	6	1008
Food prep. appliances	1	260	260	0,5	130
		Total	573		1518

The following are the alternatives proposed for supplying electricity to the 17 homes:

A1. Individual systems with PV panel and battery
A2. PV panels + 3 microgrids + batteries at each house (variant 1)
A3. PV panels + 3 microgrids + batteries at each house (variant 2)
A4. PV panels + 4 microgrids + batteries at each house
A5. PV panels + batteries + Grid extension
A6. PV panels + batteries + microgrids + Grid extension
A7. Only grid extension

Alternative A1 proposes a system with battery capacity for 3 days of autonomy. Alternative A2 proposes the same kind of systems but considering 3 microgrids covering the areas where houses are less scattered. Alternative A3 is similar to A2, but considering a larger area covered by one of the microgrids (Figure 4), although supported in two points of generation to minimize the voltage drop. Alternative A4 considers M1 divided in two, each with its own PV panel. Alternative A5 extends the grid to the 10 consumers closer to the existing feeder, leaving the remaining consumers supplied by individual systems and alternative A6 is similar but considers a small microgrid connecting two of the houses.

Finally, alternative A7 considers the extension of the grid to connect all houses. Table 7 summarizes the evaluation of all alternatives for the different criteria. To note that, the value assigned to option A7 on criteria g2 tried only to express the almost infinite availability of energy when using grid expansion to supply the whole set of houses. For alternatives A5 and A6 the option was to use the worst case, regarding the availability of energy to the house not connected to the grid. To note that wind-generation options were not considered due to the low potential in most of Ecuador (Ministerio de electricidad y energias renovables 2013).

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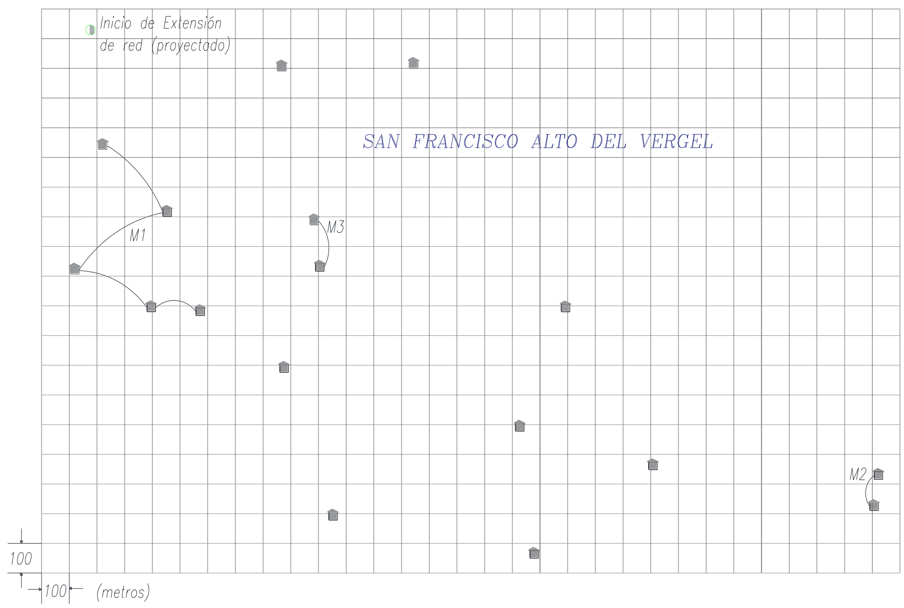

Figure 4 - Example of one of the alternatives (A3), depicting 3 microgrids and 8 isolated systems

Table 7 - Evaluation matrix

CRITERIA / ALTERNATIVES	g1	g2	g3	g4	g5	g6	g7	g8
A1	83%	132%	$ 101 354	$ 1 775	71%	2,364	1	1
A2	83%	117%	$ 91 732	$ 1 462	71%	2,238	1	1
A3	83%	111%	$ 89 863	$ 1 227	71%	2,191	2	1
A4	83%	111%	$ 92 887	$ 1 357	71%	1,895	1	1
A5	96%	132%	$ 113 913	$ 908	63%	1,976	2	1
A6	96%	120%	$ 101 989	$ 804	63%	1,934	2	2
A7	99%	1000%	$ 137 259	$ 302	57%	1,705	3	3
	Maximize	Maximize	Minimize	Minimize	Maximize	Minimize	Minimize	Minimize

As a first step, when applying ELECTRE TRI, it is necessary to establish the categories in which alternatives are to be assigned, as well as, the reference profiles that define their boundaries. For the case study, 3 categories C1, C2 and C3 were established, defined as low priority, medium priority and high priority of implementation. These 3 categories impose the definition of 2 reference profiles, b1 and b2, defined by reference evaluations in each criterion.

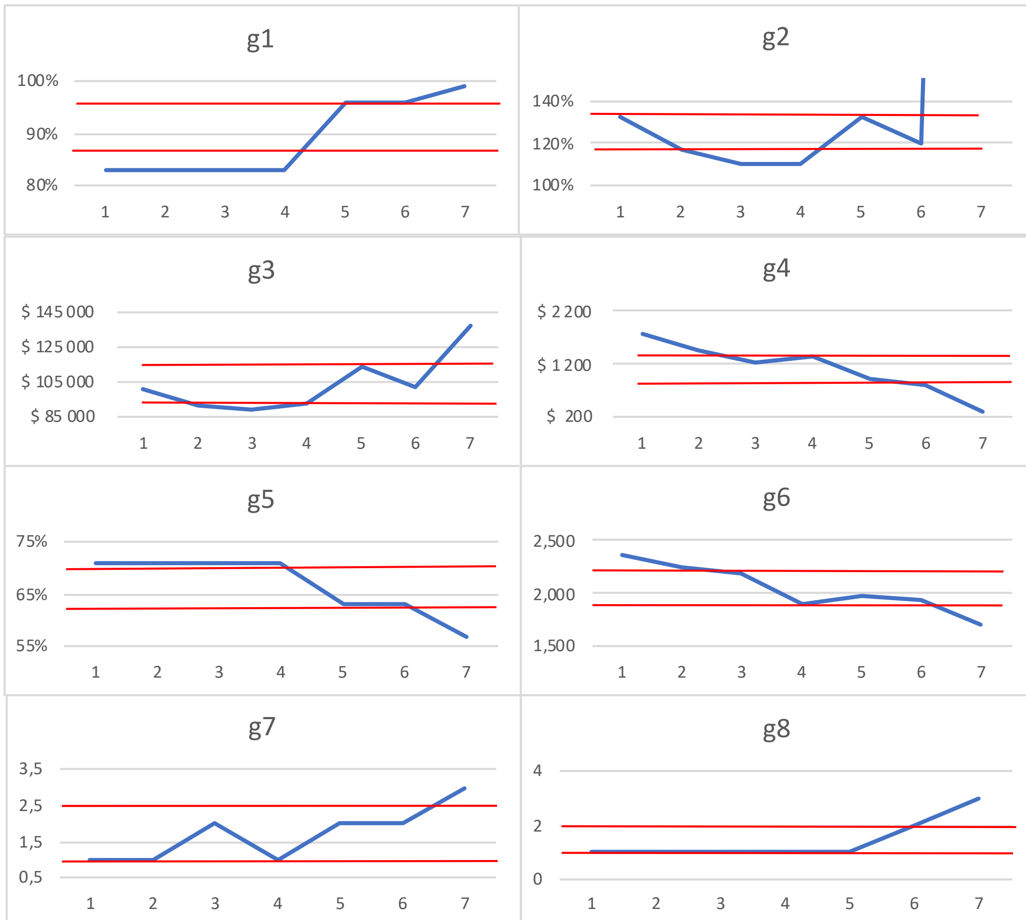

Figure 5 - Boundary definition by graphic analysis

Without a unique methodology to define these reference evaluations, the followed approach made use of a graphical representation of the evaluations on each criterion of the alternatives under consideration, as represented in Figure 5. The values obtained for the profiles are resumed in Table 8.

Table 8 - Evaluations of the reference profiles

Graphic analysis								
b1	87	119	115000	1300	60	2200	2,5	2
b2	96	130	92000	800	70	1900	1	1
	Maximize	Maximize	Mininize	Mininize	Maximize	Mininize	Mininize	Mininize

Regarding the definition of the required thresholds of indifference, strong preference and veto, a simplified procedure was established by considering indifference to be under 5% for criteria 1 to 5, under 1% for criterion 6, and zero indifference for criteria 7 and 8. The same kind of reasoning was applied to strong preference, by considering it above 12% for criteria 1 and 2, above 10% for criteria 3 and 4, above 15% for criterion 5, above 5% for criterion 6, and above 40% for criteria 7 and 8. The veto threshold was defined in absolute terms for each criterion. The final figures are represented in Table 9.

Table 9 - Indifference, Strong preference and veto thresholds

	g1	g2	g3	g4	g5	g6	g7	g8
q(b1)	4,35	5,95	5750	65	3,0	22	0	0
p(b1)	10,44	14,28	11500	130	9,0	110	1	1
v	15	15	15500	700	18	200	2	2
q(b2)	4,80	6,50	4600	40	3,5	19	0	0
p(b2)	11,52	15,60	9200	80	10,5	95	1	1
v	15	15	15500	700	18	200	2	2

The application of ELECTRE TRI was made through the use of the software IRIS (Interactive Robustness analysis and parameters' Inference for multicriteria Sorting problems). IRIS (Dias and Mousseau 2002) implements the “pessimistic” classification of ELECTRE TRI with a few additional features, namely to allow for the treatment of uncertainty. Instead of imposing the definition of precise parameters, namely the weights and cut value, IRIS allow the use of ranges and performs a robustness analysis identifying the range of viable classifications for each alternative. Through interaction, the decision maker may then arrive to a robust classification without having to specify precise values for the different parameters. IRIS also accepts example classifications, by assignment of minimum and maximum categories for a given alternative, then inferring the set of parameters consistent with the imposed limits or supplying ways to deal with eventual inconsistencies.

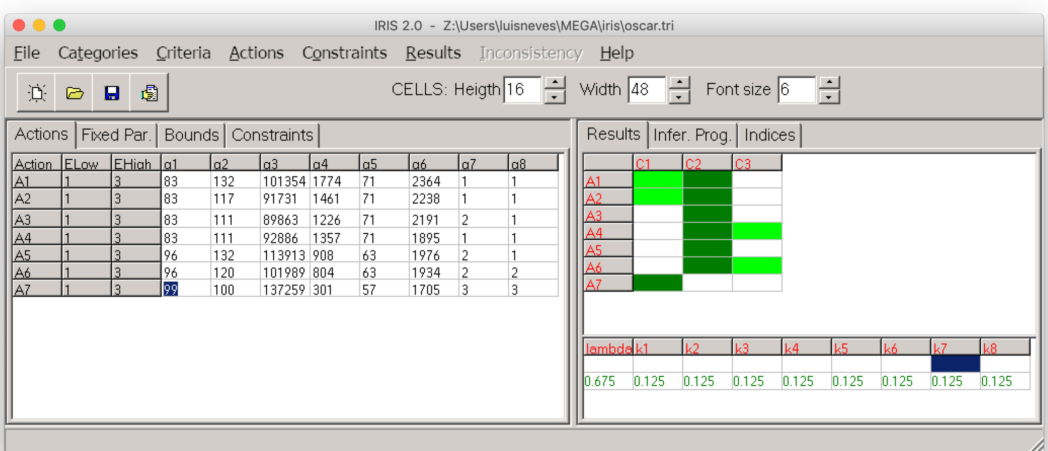

Figure 6 - First trial of IRIS on the case study

Figure 6 shows the first application of IRIS to the case study. The dark green boxes on the right side show the most robust assignments of the alternatives to the categories. It is visible that alternative A7 is robustly assigned to the lowest category (low priority), independently of any weights. A similar conclusion can be made regarding alternatives A3 and A5 which are robustly to category C2 (medium priority). Alternatives A4 and A6 are the ones which offer more possibilities of being assigned to the highest priority category, depending on a necessary analysis on the specific parameters. After a few tests, it is possible to see that alternative A4, composed by a mix of individual systems and 4 microgrids seems to be the most robust alternative to be classified as high priority, according to the evaluation model proposed. In fact, to achieve the same classification for A6 it would be necessary to put too much weight on g4 in detriment of all other criteria.

Conclusions

Electrification of rural areas of developing country presents several challenges associated to the costs of extending the grid, taking into account the frequent isolation of small settlements, the geography of the area and the usual low consumption of the populations affected. Typically, any investment by electric utilities to extend the grid faces a difficult return due to the low demand and such investments need to be highly sponsored by governments or development agencies. Local generation options, especially if based on renewable energies, present a very interesting solution as they avoid infrastructure costs, do not require regular supplies of fuel, and even provide a way to globally reduce the total consumption of primary energy.

For a proper analysis of such projects, MCDA methods present a convenient as they allow the use of both quantitative and qualitative criteria, avoiding the need to discard important issues due to difficulties in quantifying impacts or in measuring them in appropriate scales.

The work here presents resulted from an analysis performed by an Ecuatorian student to a real case, but on an academic framework, as the basis for his MSc dissertation work. Although academic in nature, this case study provided a meaningful insight to the particularities of this problem and to the options presented by the new technologies, namely the possible advantages of microgrids to partially supply the affected houses, benefiting from a scale effect to become more cost-effective, and possibly less constraining.

An effective use of this work implies both the general improvement of all computations and a sensitivity analysis of the values and parameters, although the possibility of interactively face uncertainty with IRIS already simplifies this work. Another relevant work is to extend the analysis of the relevant criteria to assess if there are other important issues which must also be considered, e.g., the degree of upgradability of the system, taking into account that after having acquired the access to electricity, the consumption may start to grow beyond the small limit assumed in the estimates.
Nevertheless, the most important work needs to be done with real decision makers, the only ones that can effectively define the preferences needed to establish the best option.

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