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Energy supply for sustainable rural livelihoods. A multi-criteria decision-support system

Judith A. Cherni[a,*], Isaac Dyner[b], Felipe Henao[c], Patricia Jaramillo[d], Ricardo Smith[e], Raúl Olalde Font[f]

[a]*Centre for Environmental Policy, Imperial College London, South Kensington Campus, London SW7 2AZ, UK*
[b]*Universidad Nacional de Colombia, AA 1027 Medellin, Colombia*
[c]*Office B 1.32, Doctoral Programme Warwick Business School, The University of Warwick, Coventry CV4 7AL, UK*
[d]*Instituto de Sistemas y Ciencias de la Decisión Escuela de Sistemas Universidad Nacional de Colombia, Medellín, Colombia*
[e]*Escuela de Geociencias y Medio Ambiente, Facultad de Minas, Universidad Nacional de Colombia, Medellín, Colombia*
[f]*Universidad Central "Marta Abreu" de Las Villas, Centro de Estudio de Termoenergética Azucarera, Carretera a Camajuaní Km 5.5. CP: 54830, Santa Clara, Villa Clara, Cuba*

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Abstract

Energy supply to the rural poor in developing countries is a complex activity that transcends the simple selection of a *best* technology. This paper explains the outcomes achieved by using a new multi-criteria decision-support system to assist in calculating the most appropriate set of energy options for providing sufficient power to fulfil local demands that improve livelihoods. The elicitation of the priorities of future users, which are subsequently integrated into the energy selection process, is seen as a mechanism for the promotion of energy policies that ensure that technological developments reduce poverty. The *sustainable rural energy* decision support system (SURE DSS), a methodological package and software designed by the research team RESURL builds upon technical and non-technical features of energy development in remote poor areas, drawing on a sustainable livelihoods approach as part of its rationale. SURE enables simulations and calculation of the disparities that may arise between current and potential livelihoods after specific energy solutions have been installed, as well as measuring potential trade-offs among alternative livelihoods. The paper reports the outcome of an application of SURE to the case of a remote Colombian rural community whose total energy demands are only partly met through a diesel generator.

Keywords: Multicriteria; Renewable rural energy; Sustainable livelihoods

1. Introduction

Despite the fact that extensive vital electrification was achieved in the developing world by expanding national grids to rural areas, millions of people, especially those in poor rural areas, still have no access to modern energy services. Energy provision through decentralised systems represents an important step in reducing this electricity gap in rural areas of the developing world (Chaurey et al., 2004; Takase, 1997). Yet, despite the fast acceptance of decentralised technologies for providing this service, and the interest of governments and others in expanding off-grid solutions for rural areas (see e.g., Byrne et al., 1998; DEP, 2002), progress in planning for future development or appropriate assessment methods remains slower than decision-making and actual expansion and implementation. Prospective users of modern energy systems—particularly of renewable technologies, e.g., micro-hydro and photovoltaic—in rural areas are hardly consulted when it comes to planning the improvement of local infrastructure and making final decisions on what are the most appropriate options. In the case of India, it has been argued that renewable energy technology in particular was promoted as a panacea for the country's energy problems.

*Corresponding author. Tel.: +44 020 7594 7316; fax: +44 020 7594 9334.
E-mail address: j.cherni@imperial.ac.uk (J.A. Cherni).

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However, doing 'too much too soon' resulted in unrealistic expectations leading to equipment and other types of failure (Ghosh et al., 2002).

The aim of this paper is to determine an appropriate set of energy options which provide sufficient power to fulfil local demands whilst improving users' livelihoods and, furthermore, to highlight the policy implications of applying appropriate assessment tools to poverty reduction. The multi-criteria sustainable rural energy decision support system (SUREDSS) is used here to model the likely effects and trade-offs of projected energy solutions on various types of resources that a community might possess. This system enables to look into technological options that are geared to raise the chances of success of future energy developments in poor areas.

SURE is a methodological package designed to fill the present gap in the planning of future energy development that is both technologically appropriate and sustainable in the long-term. Further, approaching the problem of rural energy provision is assisted by the inclusion of economic and/or environmental factors. SURE is a complete software package designed by the renewable energy for sustainable rural livelihoods (RESURL) research project, funded by the UK Department for International Development (DFID). RESURL recognises that to increase the chance of success fully and sustainably introducing appropriate energy provision into remote rural areas, prior to any energy system installation, a comprehensive assessment must be undertaken of local and regional conditions and requirements. In this way, SURE attempts to facilitate decisions that promote *planned* energy infrastructure with the goal of long-term enhancement of rural livelihoods, paying attention also to non-technical aspects of energy provision. RESURL provides a systematic and multi-dimensional approach, taking into consideration the social, financial, environmental and human impacts of a given energy project. An assessment of how SURE operates in the field is presented through first-hand information gathered from a remote isolated rural community in Colombia. Here, the SURE tool is applied in a community reliant on a small diesel plant generator.

2. Facilitating rural energy decision-making

In approaching the planning of energy provision, assessment methods often emphasise only a few aspects of the rural energy problem. Among these, we distinguish the following main areas: technological (maximising supply); economic (reducing costs; Koroneos et al., 2005); social (minimising welfare impacts; Beccali et al., 1998); and environmental (mitigating damage; Mirasgedis and Diakoulaki, 1997; Georgopoulou et al., 2003). Undoubtedly, these approaches are useful systematically to address the pivotal factors that influence successful rural energy provision. The economic approach, for example, has often played a central role (e.g., Smith et al., 2000; Georgopoulou et al., 1997), and consideration of economic indicators would continue to be vital in any new project evaluation. Of such indicators, the most frequently cited measures have been investment and operational costs; the cost of reducing greenhouse emissions (Borroto et al., 1998; Georgopoulou et al., 1997, 2003; Kolhe et al., 2002); available resource costs (Kablan, 1997); battery replacement and fuel costs (Kolhe et al., 2002); and cost per unit of both installation and generation (Angel and Smith, 2000; Polatidis and Haralambopoulos, 2002).

However, problems do exist with single or bi-dimensional approaches: for example, technological and economic considerations dominate during service expansion (Mirasgedis and Diakoulaki, 1997; Georgopoulou et al., 1997), while considerations such as ensuing income generation and the effect on the environment are often sidelined (as observed during the rural electrification of the 1970s and 1980s). A further claim that energy planning methodologies based solely upon academic criteria are poorly received by policy-makers has been made (GLERS, 1990). *Homer*, the computer programme of the USA National Renewable Energy Laboratory (NREL, 2003), proposes an optimisation model for evaluating the distribution of power for remote stand-alone generation applications. It is a useful tool and has been successfully applied in a number of developing countries with good results. However, *Homer* judges outcomes based upon two criteria only, their economic and technical merits, and while these are crucial aspects of any off-grid energy system, the model nevertheless has not been designed to evaluate such significant impacts as the social and environmental. Biswas et al. (2001) proposed that four criteria must be fulfilled to ensure acceptance of renewables in rural areas in particular: technological, financial, social and institutional. Unfortunately, however, no indication is given regarding the necessary trade-offs, should one criterion prevail over another. Equally, the rural energy decision-making process has, in many cases, neglected the factors that influence electrification, and most approaches seem inevitably to result in disregard being shown for the needs of the population. Perhaps unsurprisingly, the general outcome in these cases tends to suggest that such reductionism is counter-productive, be the adverse results technological, social, economic or ecological.

A multi-criteria analysis is useful as the prioritisation of electricity generation options is a multi-faceted problem, requiring consideration of both qualitative and quantitative factors; furthermore, the expansion of off-grid solutions, particularly those utilising renewable energy technology, face numerous obstacles (Polatidis and Haralambopoulos, 2002). In the 1980s, the need to incorporate environmental considerations into energy planning accelerated the use of multi-criteria approaches (Georgopoulou et al., 1997). Action A may be better than Action B according to one criterion but worse according to another; hence *compromise solutions* must be found (Munda et al., 1994).

Multi-criteria analysis has been employed to support decisions taken in relation to rural energy supply in the developing world in order to replace existing capacity (e.g., wood burning for fuel), or to expand it (see e.g., Huang et al., 1995; Kablan, 1997; Beccali et al., 1998; Watson and Ter-Gazarian, 1996; Hobbs and Meier, 2000) whilst also mitigating environmental impacts (Georgopoulou et al., 2003; Borroto et al., 1998). Finally, using this approach, Polatidis and Haralambopoulos (2002) conceptualised a normative decision-making framework for renewable energy planning at the local level where, it is argued, multi-criteria decision aid methodologies offer a reliable structure for integrated renewable energy assessment and should consequently become best practice.

However, although multi-criteria methodology can address rural energy problems, it has so far been incapable of taking into consideration every relevant livelihood dimension. As an example, the rural electrification of certain remote areas in Colombia clearly illustrates the disciplinary division that guides energy planning. In that country, the UPME (Unidad de Planeamiento Mino-Energético) has conducted studies that include planning as an important element of rural electrification. A review of these studies indicates that assessment tasks have continued to focus on separate issues such as energy supply and demand in isolated areas (ICEL, 1994; UPME, 1999, 2000); energy supply cost calculations (UPME, 1999, 2000); updates of current energy developments in a number of villages and towns using Geographical Information Systems (UPME, 1999); and the development of ideas concerning implementation of rural energy planning policies (ICEL, 1994; García, 1997; UPME, 1999, 2000). Few studies in Colombia and Cuba have attempted comprehensively to address the problem of rural electrification (see Smith and Mesa, 1996; Smith and Pulgarín, 2002; Olalde et al., 2004). These address technological, financial, social and institutional dimensions. No indication is given, however, on the likely trade-offs that may take place should one criterion prevail over another.

In summary, multi-criteria approaches to energy planning have yet to overcome a number of limitations. For example, policy decision-making still tends to privilege technical criteria and quantitative information, i.e., power output and costs. Thus, the technical features of technology expansion tend to prevail in the models and decision-makers' minds rather than equally valid priorities, such as social wellbeing. Also, multi-criteria methods have as yet failed to measure the sustainability of an energy option, i.e., the likely improvement of a community's assets over the longer term, as a result of effective application of the technology. SURE, the RESURL DSS tool, starts to address these deficiencies. A main advantage associated with SURE is that, in employing a multi-criteria approach, it allows full consideration of the large quantities of data, relationships and objectives that are generally present in real world policy problems. A factor in the unsuccessful provision of effective energy technology projects is the failure explicitly to identify target user's wishes, needs and strengths (Santos and Linares, 2003). Increasingly, rural energy experts have come to appreciate that in order to succeed, energy projects must involve the local community from the very beginning, prioritising their input and harnessing their interest, support and investment (e.g., Kartha and Leach, 2001). This is a considerable advance compared to the purely technocratic approaches of previous decades. Unfortunately however, current methods often require the population to participate only after the experts have made the technical decisions.

It is desirable, if not vital, for both planning and assessment to encourage the participation of those on whom the given energy interventions will impact most, rural individuals and households (see Bannister, 2002; Barnes, 2000; Barnett, 2000). Participatory methods aim to learn from rural individuals what the status quo is in their communities and how their existence might best be improved through external assistance. The sustainable livelihoods (SL) framework is a particularly people-centric approach, which acknowledges that a community owns assets or capitals, and that the overall aim of any activity must be to ensure sustainability (see, e.g., Ashley and Carney, 1999; Chambers and Conway, 1992; DFID, 2000, 2002; Ellis, 2000). It is a useful approach on which to build methodologies to calculate the energy needs and overall priorities of a population. The SURE package offers the possibility of assessing the capabilities of a community with the help of the SL approach.

3. SURE: a multi-criteria approach and participatory tool

The new DSS SURE aims to assist future energy development for enhancing rural livelihoods. SURE is a 'package' designed to aid decision-makers to define and select appropriate energy supply options. SURE reflects the complexities of attaining sustainability in poor rural areas and simulates how possible solutions may impact a community. The model combines quantitative and qualitative criteria. Unlike other existing software that assists rural energy decision-making, the SURE approach enables the priorities of a group of prospective users to be considered in the analysis. A part of the model builds on the perspective (as defined in the SL approach) that communities possess five capitals or resources, i.e., the physical (e.g., houses, roads), financial (e.g., wages, savings), natural (e.g., water, land resources), social (e.g., network and local organisations), and the human (e.g., education). The capitals act as indicators for assessing existing conditions in a rural community and for simulating their future condition through the operation of energy systems.

Briefly, the model initially assesses the strengths and weaknesses of a community by indicating its overall status of capitals or assets. It then proceeds to draw up energy plans which would affect assets differently. The model aims to find energy solutions that would impact assets singled out by future users of the technology as in need of improvement. Particularly useful aspects are that SURE allows graphical representations of changes and trade-offs as they might occur during implementation of different energy alternatives; it also includes technical as well as non-technical aspects of energy and livelihoods; and finally, SURE implicitly refers to the time dimensions of 'before' and 'after' an energy intervention is put in place. The SURE DSS software uses the compromise programming multi-criteria method with metric two for decision-making and weights. The method assumes that decision-makers' preferences can be expressed as the measure of a metric distance between two alternatives in the space of objectives (Yu, 1973; Zeleny, 1973).

The SURE system determines what would be the most appropriate energy system for particular individuals, community or regions. The output is the result of measuring the impact of different energy solutions on the five assets or resources of a community (or individuals) as defined by the model. A proposed solution should minimise the difference between the maximum possible access to, or possession of, physical, financial, natural, social and human assets of a population (that is, the ideal situation, with a theoretical value of 1), and the new situation whereby access to or control of the same assets has been changed as the result of the installation of an energy technology that would provide the required services.

The SURE software procures measures that are indicative of a community livelihood 'baseline' by considering existing resources, as well as recognising the priorities of a community—i.e., which capital items are desired to grow, and what would be the future uses of the electricity—and forecasting a number of livelihoods impacts resulting from the application of various energy alternatives. This is a useful step and a particular attribute of this methodology because it is precisely changes to the initial condition of a community, region or individual baseline that will occur with the application of modern technology.

In Eq. (1) below, X_j represents a separate set of factors for each asset function. Each factor has a range of values between 0 and 1, where 0 reflects no positive effect or outcome of the energy alternative i on asset j, and 1 means its highest effect. In other words, the ideal and maximum measure of positive impact that a community may attain is 1; a further result represents a community baseline; and a final calculation is obtained from the impact of energy alternatives on the same community's assets.

Eq. (1) presents the structured function for the five community's resources in relation to energy technology options ($C_j, j = 1, \ldots, 5$)

$$C_j(A_i) = \frac{1}{1 + e^{-\alpha_j X_j(A_i)}}, \quad (j = 1, \ldots, 5; \; i = 1, \ldots, n), \qquad (1)$$

where $C_j(A_i)$ represents the evaluation of the ith energy alternative (A_i, $i = 1, \ldots, n$) against the resource C_j, $j = 1, 2, \ldots, 5$, (1 indicates physical, 2 financial, 3 natural, 4 social and 5 human assets); $X_j(A_i)$ represents the effects of the ith energy alternative on the corresponding community's resource j; and α_j is a scale parameter, associated to the number of factors that compose each resource j.

The system allows the decision-maker to assess the effect that new operating energy systems might have on every asset owned by the community. It does so by calculating and comparing the different initial condition of the assets in a community with values resulting from the implementation of the new energy alternative in relation to an ideal condition of full development of all the resources (the pentagon below, Fig. 1, will help to represent these changes). A main contribution of the system therefore is that it enables quantification, through a numerical index, of the gaps between the theoretical and ideal livelihood; the possible effects on livelihoods of particular energy technologies; the existing condition of the assets and their possible improvement with the application of energy; and finally, the system calculates the trade-offs among alternative livelihoods with different energy solutions.

The underlying goal of minimising the gap between the maximum possible value (= 1) for each asset (a theoretical state) of greatest development and the real value that it could achieve through the application of an energy technology is illustrated:

$$\text{Minimise} \left[\sum_{i=1}^{5} w_i^p f^p (1 - Capital_i) \right]^{1/p},$$

such that:

Community requirements are satisfied by each energy alternative j

$$Capital_i. = g_i(\text{energy alternative } j); \quad i = 1, \ldots, 5; \; j = 1, \ldots, n, \qquad (2)$$

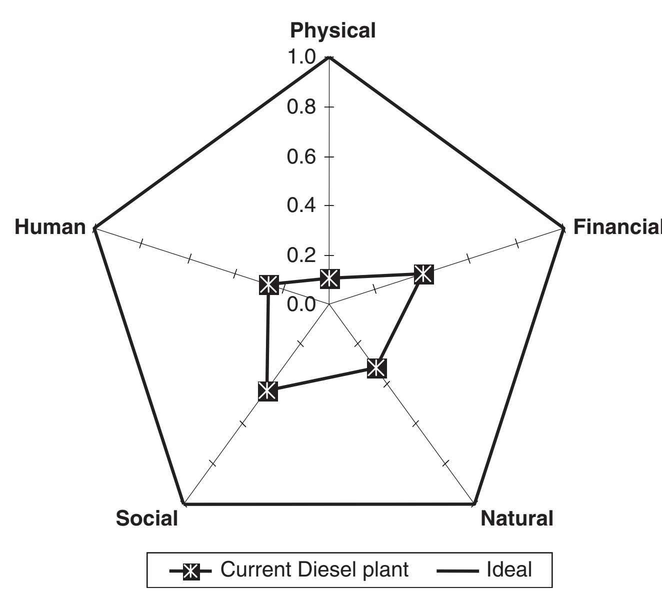

Fig. 1. The resource baseline* when operating a 5 kW h diesel plant, SJCN II, Colombia 2003: *Small pentagon; Baseline index: 0.0–1.0.

where $f(1-Capital_i)$ represents the difference between the maximum possible value for each physical, financial, natural, social and human capital and each increment of natural, financial, physical, human and social capital for each installation of an energy alternative; w_is are the assets' weights that express the preferences of decision-makers (planners, community and/or government); and g_i is the function that describes the influence of the different energy alternatives j on each $Capital_i$. The formula captures a dynamic relationship among the assets people possess when energy is provided to a rural population.

4. Methods

In November 2003, RESURL applied the SURE structured survey to 101 households and to local leaders in the rural community of San José de Cravo Norte II (SJCN II). The case study was run in this remote rural community with 400 inhabitants, situated to the east of Colombia in the oriental plains of Arauca (DANE, 2000), around 30 km from San Jose de Cravo Norte, a larger rural community of some 7000 people already connected to the national grid. Access to the small community is difficult. The SURE package included the household survey and a semi-structured questionnaire for stakeholders and local leaders. Information gathered in this manner was later statistically processed and provided to the software in order to build the community baseline including identification of the population demands for energy and other services. Drawing on the multi-criteria approach of SURE, the DSS ranked the possible energy system options that would enable the village to achieve the required changes and to fulfil its demands.

At the time of the research, a 5 kW h diesel generator plant operated that only supplied electricity to about 12% of the population. Due to high operational costs and the community's limited finances, the diesel plant only operated for 7 h in every 24. The objective of the survey was thus to identify the main characteristics of the population, their current energy requirements and how they would use additional electrical power. The research team's aim was to define, evaluate and select a number of energy technology alternatives that were best suited to the community's conditions.

The survey involved key stakeholders in the process who helped to determine the larger demographic, physical and political regional context in which new technological solutions would have to be framed.

5. Baseline information on future user community San Jose Cravo Norte II (SJCN II), Colombia

The primary and secondary information collected from the study indicated that the population of SJCN II required an energy technology solution that would supply electricity 24 h a day to power the refrigeration of vaccines in the current health clinic, and for a community centre. Importantly, the new energy system should enable the community to increase the current limited hours of daily access to electricity for pumping water, while enabling a significant increase in the number of residents who could access the electricity supply. The survey identified that in SJCN II a minimum of 70% of the population required access to freshly pumped water.

Due to the hot weather that prevails in this Colombian region, proper refrigeration of food and medicines, and ventilation in people's homes and other buildings such as schools or clinics, was a considerable issue. Power was also required for lighting houses, and running TVs and radio. Given that the needs were very similar in every household surveyed, it made sense to provide a common energy solution to the community. Livestock is the main economic activity in the region. Any energy design should in some way aspire to contribute to the enhancement of the conditions of production in those sectors, or in new economic activities. Electricity supply could be used to improve physical capital in SJCN II, e.g., new machinery that refrigerates and pasteurises milk locally or that mechanises elements of livestock rearing, further improving welfare of the community.

The area was well provided with water and solar power that could be harnessed. However, despite the considerable quantity of available water, the source was located far from the village. There was also a fair amount of organic waste originating from livestock and restricted agricultural practices. The landscape was not particularly noteworthy and biodiversity of plants and animals was found to be average. The combination of easy access to natural resources in the region, including wood, and the entrenched custom of cooking outdoors with firewood explains its heavy use by the village as the latter's main source of fuel.

Finally, the criteria proposed by the regulator UPME emphasised that any energy solution provided to rural communities with up to 500 inhabitants such as SJCN II, must supply electricity of almost the same quality as that generated by the national grid and provided to the country's main cities (UPME, 2000). Therefore, at least 18 h of stable electricity delivery to nearly 100% of the population would be expected from any new energy system. As a result, since the community already possessed a diesel generator that supplied 12% of the population with electricity, a less costly option would be to leave it in place and achieve the required power through the acquisition of a renewable energy technology rather than increasing the community's dependence on fossil fuels, and their transportation through badly kept roads. A selected option would thus seek to add to the present capacity of the diesel generator.

An assessment of the extent of the five types of resources found in SJCN II, i.e., the physical, financial, natural, social and human, before the implementation of an additional source of electricity highlighted the weaknesses and strengths of this rural community. Further, it was possible to visualise the condition of the community by

Table 1
State of local assets when using a diesel generator, SJCN II, Colombia 2003

Energy technology	Resources owned by SJCN II				
	Physical	Financial	Natural	Social	Human
Diesel generator plant 5 kW h	0.1	0.4	0.3	0.4	0.3

means of the livelihoods pentagons that the model SURE produced (see Fig. 1). The distance from the centre of the figure to the borders of the smaller pentagon represents the extent of the resources that SJCN II owned at the time of the survey. The closer any edge of the small pentagon is to the centre, the weaker the access to, or ownership of that particular asset.

It was found that the extent of resources owned by SJCN II while using its small diesel generator was below half of the possible maximum assets (highest baseline index = 1; i.e., the external pentagon in Fig. 1; see Eq. (1)) that could be registered for any community. However, the community had access to more social and financial capital assets (0.4, respectively) and owned natural (0.3) and human (0.3) were higher than the physical resources (0.1) (see Table 1). The Baseline index indicated that there was room for every asset to be improved with additional energy supply, should the priorities of the community indicated that they wanted to do so. A realistic electricity alternative for SJCN II needed to generate at least an additional 40 kW h if it was to fulfil users' demands.

6. Projected energy solutions and trade-offs

Modelling the data from the household survey and regional sources with possible energy options enabled researchers to ascertain not only possible technologies solutions, but importantly, projected scenarios of the impact of each energy technology on the current state of assets in SJCN II and the possible trade-offs that might arise. The energy impact index (EII) shows the potential effect for each alternative technology solution on existing assets where '1.0' reflects the larger positive effect and '0.0' is the least impact (see Eq. (2) above).

Overall, the most noticeable change in SJCN II as a result of providing any additional energy technology would be to physical capital (an improvement of 0.5 points; see Table 2). Such impact would enable at least 75% of the interviewees' energy demand to be met, which would have achieved the main objective of this particular development project in terms of livelihoods improvement. New energy provision would help improve the villagers' financial assets (moving it up to 0.5 from 0.4) for example by creating direct and indirect employment that would be generated in the community. Hence, technology performance, efficiency and potential applications to everyday life are also important factors in improving financial assets.

Table 2
Impact* of potential energy technology options upon the community baseline, San José de Cravo Norte II, Colombia, 2003

Energy technology	Resource impact (EII)				
	Physical	Financial	Natural	Social	Human
Micro-hydro	0.7	0.7	0.5	0.5	0.5
Solar photovoltaic	0.3	0.0	0.7	0.2	0.3
Biogas	0.4	0.7	0.3	0.4	0.6
Grid	0.6	0.5	0.2	0.5	0.8
Hybrid diesel–biogas	0.4	0.7	0.2	0.5	0.5
Hybrid diesel–solar	0.3	0.0	0.3	0.4	0.6
Hybrid diesel–hydro	0.7	0.8	0.2	0.6	0.7
Energy index impact by resource	0.5	0.5	0.3	0.5	0.6

*Energy impact index (EII).

However, trade-offs occur where one group of technology rather than another is selected (see Table 3). Such trade-offs are seen in the extent to which access to resources may change as a result of a specific technological intervention. For example, user's financial resources would generally improve (0.5) with the implementation of different energy alternatives, with the exception of two options; if selected, the solar photovoltaic (0) and diesel–solar (0) options would not enhance user's assets due to their plant and installation costs and poor performance in relation to reported demand.

Again, using data generated by the SURE model, natural capital might experience an improvement in comparison to the current situation if a micro-hydro plant (0.5) or a photovoltaic plant (0.7) were selected for these do not emit toxic gases into the atmosphere or create noise, and depend only on renewable natural resources. While the financial impact of the micro-hydro plant could be very high on users (0.7) but is nil at a photovoltaic plant (0), they only remain highly recommended options where protecting the local environment is the main priority for SJCN II. The positive impact of other energy options on the natural asset would be smaller, i.e., between 0.3 and 0.2. A highly positive impact on SJCN II's natural environment may be attainable if the solar option were selected (0.9); yet, the community would be left the poorer (0) because of the expense of the installation livelihoods improvement, small social (0.2) capital, i.e., with less need for social interactions and few human assets (0.3). In the case of grid connection, but also with any energy solution that would include the existing or new diesel generators, the impact on the environment would be noticeably negative, e.g., due to installation of transmission towers and air pollution.

The impact of each technology on the social asset varies but it is apparent that any solution will not much alter the current extent of social resources (0.4; see Table 1). As is shown below, only small changes are expected to occur to the extent of social capital in SJCN II when additional energy services are provided. In fact, further changes to the social resources might be achieved if the village's infrastructure is expanded and social projects initiated (e.g., health and education promotion programmes). Any small improvements in social resources due to energy provision would be reflected in a potential increase of associations or networks in the area. However, negative effects would be attributed to a potential reduction in the amount of time local people (principally women and children) would need to share with other members of the community to perform common tasks, such as wood gathering and water collection, which would now be done with the aid of power. Any free time gained in this way might well lead to a reduction in the time families spend together and consequently the introduction of a 'liberating' technology would also bring about a weakening of this type of communal social ties. Thus, if improvement to social resources was identified as a main priority for SJCN II, it is likely that the addition of a micro-hydro or a biogas plant to the current diesel generator would be preferred (i.e., social resources = 0.6 and 0.5, respectively). The biogas-diesel option is a possible solution for SJCN II because it is likely that it would also enhance financial resources (0.7) (e.g., by adding value to the processing of existing organic waste). The score for the biogas option is, however, slightly

Table 3
Potential trade-offs* by resource and different energy technologies, San José de Cravo Norte, Colombia, 2003

Technology selected	Resource trade-offs									
	Physical		Financial		Natural		Social		Human	
	A	B	A	B	A	B	A	B	A	B
Current diesel plant	0.1	0.9	0.4	0.6	0.3	0.7	0.4	0.6	0.3	0.7
Micro-hydro	0.7	0.3	0.7	0.3	0.5	0.5	0.5	0.5	0.5	0.5
Solar photovoltaic	0.3	0.7	0.0	1.0	0.7	0.3	0.2	0.8	0.3	0.7
Biogas	0.4	0.6	0.7	0.3	0.3	0.7	0.4	0.6	0.6	0.4
Grid	0.6	0.4	0.5	0.5	0.2	0.8	0.5	0.5	0.8	0.2
Hybrid diesel–biogas	0.4	0.6	0.7	0.3	0.2	0.8	0.5	0.5	0.5	0.5
Hybrid diesel–solar	0.3	0.7	0.0	1.0	0.3	0.7	0.4	0.6	0.6	0.4
Hybrid diesel–hydro	0.7	0.3	0.8	0.2	0.2	0.8	0.6	0.4	0.7	0.3

*Resource index indicating A, what can, and B, cannot be achieved with a particular technology.

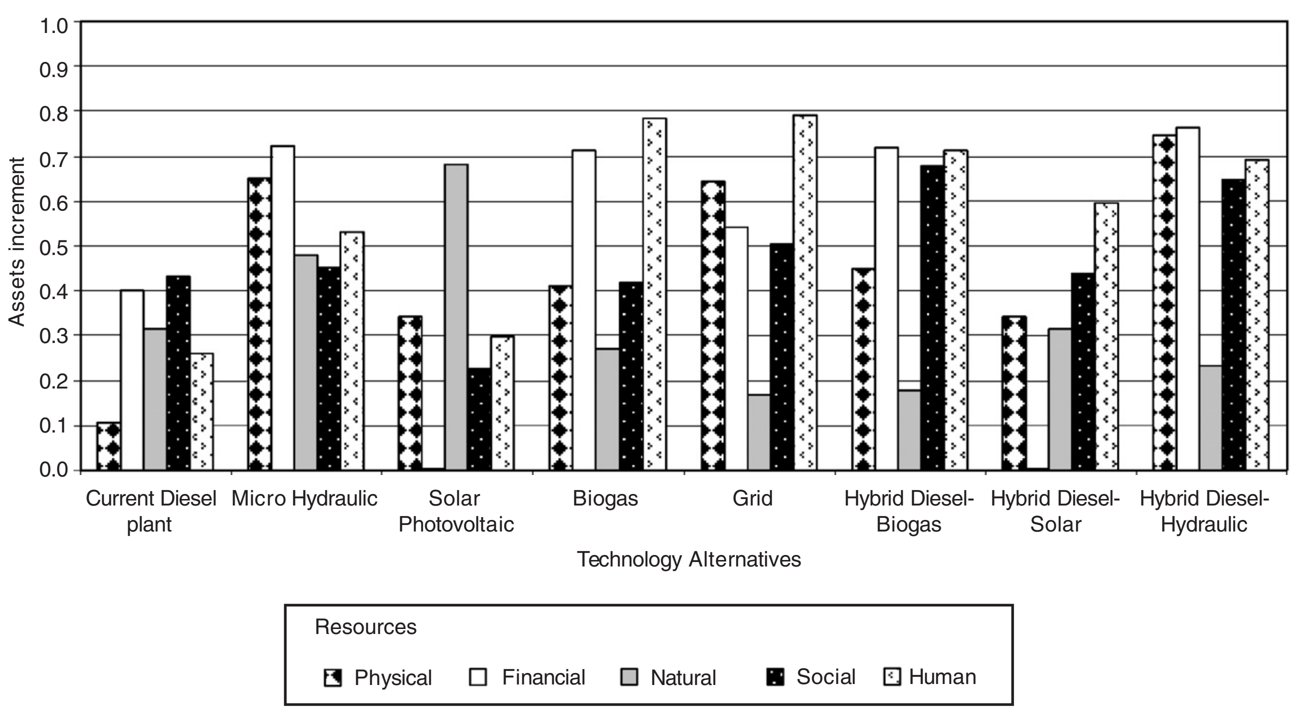

Fig. 2. The impact* of energy technologies on resource livelihoods, San José de Cravo Norte II, Colombia, 2003 (*Energy impact index (EII)).

lower than that for a new hybrid micro-hydro and diesel solution.

Finally, the human capital available to SJCN II is low (i.e., 0.3) and it is expected that it would increase significantly by the implementation of any of the suggested energy options. Owning more energy assets that contribute to a more robust infrastructure would encourage local achievements, such as better health standards, more years in education and the use of appliances that help obtain information and entertainment (i.e., light, radio and TV). Further, the acquisition of new skills by the population can result from owning new technological equipment. However, any increase in human capital would depend upon the complexity of the technology (i.e., operation and maintenance); the more complex the technology, the smaller the improvement in human assets that would be achieved.

Farmers in SJCN II owned very few energy resources, i.e., physical assets (0.1), although they possessed more social assets (0.4). The potential for the development of each asset with the provision of energy varied, therefore, according to its initial state, while, at the same time, each technological solution would impact the resources in a different way. Physical capital could be developed by 0.6 points, social capital by 0.2 points (see Table 3). Table 3 shows the trade-offs between the extent that a resource would have, or have not, achieved had one, rather than another option been selected.

While few alternatives are better at improving one or more particular assets, particular trade-offs need to be taken into account because the same technology, if applied, might lead to the deterioration of other aspects of the community's wellbeing as seen above. Therefore, the calculation of the impact of various technologies, the assessment of technical but also social, human and environmental consequences, and the trade-offs likely to arise indicated that no single technological option was the best alternative for SJCN II (see Fig. 2).

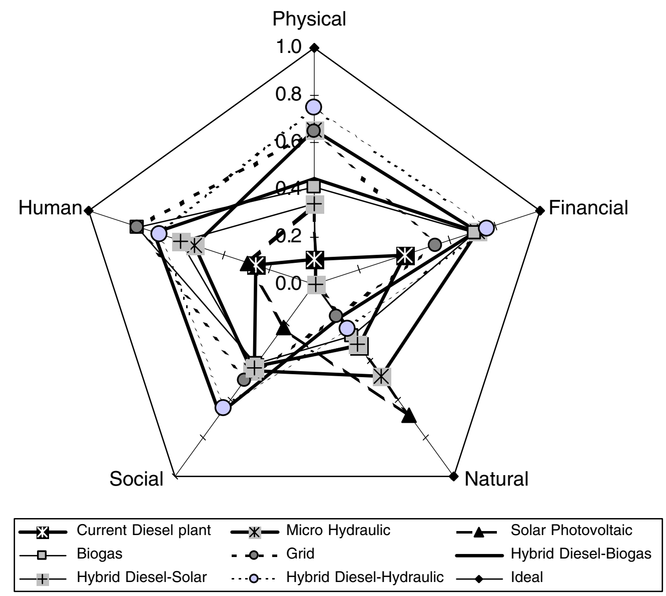

Fig. 3. The impact of energy technologies within the framework of sustainable livelihoods, San José de Cravo Norte II, Colombia, 2003.

Table 4
Scores for most appropriate technology options, SJCN II, 2003

Solution number	Energy technologies	Score of appropriateness*
1	Hybrid diesel–hydro	1.0
2	Micro-hydro	0.9
3	Grid	0.8
4	Biogas	0.7
5	Hybrid diesel–biogas	0.6
6	Hybrid diesel–solar	0.4
7	Diesel plant	0.1
8	Solar photovoltaic	0.0

*The larger the score, the most appropriate the technology.

7. Selecting a technology option for SJCN II

Selecting an option can be a complex task. However, because modelling the results was also possible through the geometric shape of the pentagon (as explained above) it was possible to ascertain more clearly possible changes to the community baseline. The pentagon representation enabled prospective impacts of a technology to be seen in a single figure, so avoiding the fragmentation of information that usually emerges from a table (i.e., Table 2) or a bar chart (i.e., Fig. 2), despite the indisputable need for them. The pentagon also enabled to visualise each capital individually (see Fig. 3). The borders of a pentagon obtained in this way showed how the total livelihood would look like after a number of years where a particular energy technology solution had been in operation. The various pentagons shown in Fig. 3 are the modelled outcome of each technology exercising a different impact on SJCN II. These shapes were configured within the framework of an optimal livelihood state for SJCN II, that is, an ideal pentagon which indicates the highest possible level of each development whereby all the assets are fully and equally developed (i.e., Capital = 1; see above). The internal pentagons simulate the state of livelihoods with the current diesel generator that supplies energy for 12% of the population; and the estimated livelihoods that could be attained should a particular energy option be implemented.

The SURE program identified an energy option that is closer to the ideal pentagon as the best technology option for SJCN II. It produced scores for each possible energy alternative where the highest given rating is 1 and the lowest is 0. A hybrid solution that included the existing diesel generator and the addition of a micro-hydro power plant emerged as the best alternative (solution 1, with a score of 1; see Table 4). The next best option was a micro-hydro plant alone, with a slightly lower score (0.9) than solution number 1. The current diesel plant alone was the least recommended solution of all (0.0). Yet, the actual final choice would depend upon the decision-makers' preferences in relation to the priorities and financial possibilities that had been identified during the survey.

Solution 1 would generate up to the 45 kW h that is, the power needed to meet the demands identified in the survey. The current diesel plant would continue to generate 5 kW h and the additional 40 kW h would be supplied by the new micro-hydro plant.

The cost per kW h would be US$ 1024 and the total initial investment would therefore be US$ 40,960. This solution would provide electricity for at least 30 years for between 90% and 100% of the population. It was anticipated that the quality of the service would be similar to that received by beneficiaries connected to the national grid. A biogas plant in SJCN II would cost slightly less (US$ 36,000, or US$ 900 per kW h;) than the micro-hydro plant, but would not satisfy the requirements arising from other priorities. On the other hand, the installation of a 40 kW h photovoltaic system would require an investment roughly three times larger (i.e., US$ 170,000) than that required for a new micro-hydro plant. The cost of connecting to the grid would exceed US$ 300,000, at a cost of US$ 10,000 per km of grid extension.

Significant improvements to the physical (+0.6, financial (+0.4) and human assets (+0.4) of SJCN II would occur if such a hybrid solution were implemented (see Table 5). However, the social asset may increase only slightly (0.2). The physical, human and financial resources that SJCN II possessed would be beneficially affected by the provision because these require precisely a better developed physical infrastructure. The natural capital would suffer some deterioration due not only to the new intervention in the local environment (i.e., the construction of a new micro-hydro plant) but because the diesel generator would continue to pollute the air and making noise. Moreover, a section of the river that would be used for the construction of the micro-hydro plant would be slightly damaged.

For SJCN II, having 0.7 physical capital (see Fig. 4) as the result of more satisfactory energy provision would mean: 30 years of reliable electricity service; flexible energy service; lower dependency on fossil fuels (had they chosen to expand the existing diesel generator, or connect to the grid), and provision of supply for at least 18 h per day of (likely) uninterrupted service to all sectors of demand. The supply would facilitate the operation of a health centre, school, houses and water supply system as requested by prospective users. The score lower than 1.0 represents the assets that cannot be improved further through energy technology solutions. Hence, it should be improved in other ways, such as by implementing government projects, mostly health and education programmes. The number equal to 1 indicates that the use of the selected technology would enhance the community infrastructure but further improvement requires progress through socio-infrastructure projects, where only one of them is the implementation of energy supply alternatives.

New energy infrastructure would allow a total level of 0.8 of financial assets, i.e., an improvement of 0.4 from the existing supply (see Table 5). Such a change would be the outcome of both direct and indirect intervention: approximately 30 local jobs would be generated during the construction phase of the energy project, and 40% more employment opportunities would arise in animal husbandry, handicrafts, business and services. It is probable that further employment would arise as a consequence (e.g., milk industry). In the long term, the only resource of SJCN

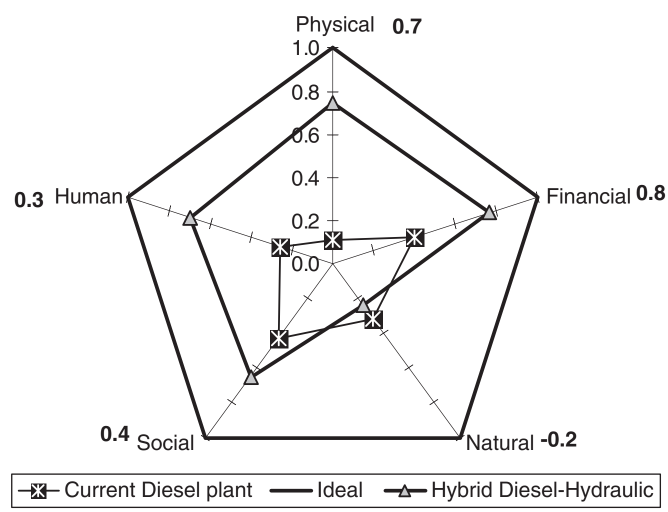

Fig. 4. The state of resource livelihoods with two energy alternatives*, SJCN II, Colombia, 2003 (*The energy impact index scores outside the pentagon correspond to the new reached level of resources with the new energy infrastructure).

Table 5
Potential development that can and cannot be met by energy technology alone, SJCN II, Colombia, 2003

Livelihoods resources	Potential development due to energy technology			Further potential development
	Diesel plant only	Diesel + micro-hydro plant	Total improvement	With diesel + micro and other development policies
Physical	0.1	0.7	0.6	0.3
Financial	0.4	0.8	0.4	0.2
Natural	0.3	0.2	−0.1	0.8
Social	0.4	0.6	0.2	0.4
Human	0.3	0.7	0.4	0.3

II that would not improve as a result of a new electricity solution is the environment. It is, however, likely that provision of electricity from a micro-hydro grid would somewhat reduce the need for firewood. Some changes in the community social networks would occur due to the probable participation of local people in the construction phase, use, operation and maintenance of the micro-hydro plant. As part of enlarged social capital, a local administration committee might also be formed to manage the plant and to collect electricity consumption tariffs. Finally, the improvement to human assets in SJCN II would be marked (0.4) and would enable a total human resource level of 0.7. In other words, it would translate into improvements in the lives of 400 people. For example, there would be a potential growth of 60% in education (i.e., the school could accommodate more children; more school space as well as more teaching hours would be made available), and a significantly improved standard of health could be achieved through quality electricity service expansion. Coping with the complexity of the technology—which has been qualified as medium—offers villagers the opportunity to acquire new skills.

It is, however, noticeable that there is still a disparity between the demands met by the most appropriate technological solution and the SURE postulated most developed, if ideal, state of assets for SJCN II. Yet the degree of improvement that is attainable with the application of additional and sustainable solutions is highly significant (Table 5, third column). The potential for development of each asset with the provision of energy varied according to its initial state, and the capacity of the technological option to provide for a particular demand. However, there is still a large potential for improvement of the community resources (last column) and it is likely that these would be achieved by the introduction of further social policies that complement energy policy. For example, physical capital could still be developed by further 0.3 points, social capital could be developed by 0.4 points (see Table 3).

The computer program proved useful to address the problem of determining the most appropriate energy options for SJCN II. While improvements are likely through the use of energy technology, it was evident that the creation of further problems was also possible, while, importantly, crucial trade-offs would also take place (e.g., slightly more environmental damage would ensue from the implementation of a hybrid of diesel and micro-hydro sources than with a diesel and solar solution, or a photovoltaic solution which would, however, be very expensive). These findings show that while the use of energy technology to promote sustainable rural livelihoods is necessary, it must be approached from a dynamic and comprehensive perspective in order to appreciate and factor in its many linkages.

The problem which the model addressed involved the formulation and selection of an energy supply system that would best suit the energy demands and possibilities in SJCN II, while guaranteeing high energy systems performance in the long term and enhancing local livelihoods. In this framework, the model simplified the task of evaluating the different energy options that would best fit with the community while maximising its resources and thereby contributing to poverty reduction in this poor rural Colombian community. A particularly useful aspect of SURE was that uniquely, and unlike any other DSS (i.e., *Homer*, and *LEAD*), it succeeded in incorporating within the model the assets, demands and priorities of the target community.

8. Conclusion

The application of a newly designed tool (SURE) to model complete assessment and planning systems can demonstrate to policy-makers how the provision of particular energy technologies may positively affect certain aspects of a community's livelihood while impacting negatively on others. It is a valuable contribution to the project of bringing affordable, sustainable energy to poor rural communities in the developing world. This information can be crucial for a community searching for feasible solutions to concrete problems as well as for national government programmes targeting sustainable rural development in specific areas. How the baseline could be changed is usually an aspect little explored in calculations by experts. This methodology, however, enabled the identification of farmers' priorities in uniform format. SURE works on the assumption that in order to satisfy the population's requirements and expectations, and also to seek a lasting operational order of the energy systems, previous assessment is required of the several dimensions of the problem, and a variety of sources informing the decision were thus consulted. The SURE approach represents a step forward in illuminating the role of energy provision for poverty reduction. It also promotes solutions that are environmentally and socially sustainable in the long term.

Whether energy provision is pushing poor and remote rural communities towards or away from improved SL remain a key issue, and one that still lacks consensus at the policy level. Yet, this paper has described and systematically analysed the possible positive impacts of effective, affordable and clean energy on a community. The extent to which human and social resources can be enhanced when more energy is made available has been shown. Furthermore, financial assets—an important indication of the overall enhancement of the conditions of the population for poverty reduction—can rise significantly as a result of new income generation activities that would be enabled by reliable, less expensive and locally generated electricity.

It is complex because a compromise solution with funding representatives such as local government, experts, and community leaders must be reached. Furthermore, the selection is not completely free of uncertainties because there are inherent limitations of qualitative criteria that are also employed by the model. Another concern is whether the community would accept the final outcomes of the model.

When a technology or group of technologies must be selected by policy decision-makers attempting to juggle investment capacity, local requirements and existing conditions, it is likely that the SURE system can be used to calculate the most appropriate energy solution, that is, the one that both fulfils a population's priorities and reduces poverty. Further, selection of the best energy options needs to measure the sustainability impact of energy technology on the community and so it is necessary to have a disaggregated view of the factors at community level that can be impacted by energy development, as well as a complete vision of the community. This was achieved by framing the analysis within a SLA.

Given that the application of a particular energy technology can lead to improvements in some dimensions while proving detrimental to others, there are certain implications that emerge from this study. Firstly, quantitative monetary valuation of such trade-offs could greatly assist policy decision-making. Additionally, there is evidently a need to expand the trade-off pentagons so as to illustrate not only how social groups within a community distribute benefits and burdens, but also how the different actors, i.e., the utility providers, the government and the community, play out.

Finally, it is claimed that an energy system solution would be effective when, in addition to high performance on technological and economic indicators, it also promotes positive change in the performance of other indicators that the target community regard as priorities. Application of the package is expected to assist in achieving long-term sustainable energy in rural areas. For any rural energy option to be technologically sustainable it must engage with technical as much as non-technical factors and thus the SURE DSS operates with information originating not only from professionals but also, most importantly, from the community. Only a very robust model could efficiently assist decision-makers. A determined government policy is needed that supports this type of approach to improve the living conditions of some of poorest populations in developing countries.

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References

Angel, W., Smith, R., 2000. Evaluación de alternativas y definición de un proyecto hidroeléctrico mediante el empleo de análisis multiobjetivo. XIX Congreso Latinoamericano de Hidráulica—Cordoba 2000, pp. 589–598.

Ashley, C., Carney, D., 1999. Sustainable Livelihoods: Lessons from Early Experience. Department for International Development (DFID), Russell Press Ltd., Nottingham, UK.

Bannister, A., 2002. The sustainable urban livelihoods framework—a tool for looking at the links between energy and poverty. Boiling Point, No. 48. Available at: 〈www.future-energy-solutions.com〉. Accessed: 13/06/03.

Barnes, D., 2000. Energy and poverty: strategies for assisting the rural and urban poor. Background paper for the World Bank energy strategy. World Bank, South Asia Region, Energy Sector Unit, Washington, DC.

Barnett, A., 2000. Energy and the fight against poverty. Available at: 〈www.livelihoods.org〉. Accessed: 14/04/03.

Beccali, M., Cellura, M., Ardente, D., 1998. Decision making in energy planning: the ELECTRE multicriteria analysis approach compared to a fuzzy-sets methodology. Energy Conversion and Management 39, 1869–1881.

Biswas, W.K., Bryce, P., Diesendorf, M., 2001. Model for empowering rural poor through renewable energy technologies in Bangladesh. Environmental Science and Policy 4, 333–344.

Borroto, B., Borroto, N., Vázquez, M., 1998. Alternativas energéticas para el desarrollo de asentamientos rurales ambientalmente sostenibles. Energía, 71–77.

Byrne, J., Shen, B., Wallace, W., 1998. The economics of sustainable energy for rural development: a study of renewable energy in rural China. Energy Policy 26 (1), 45–54.

Chambers, R., Conway, R., 1992. Sustainable rural livelihoods: practical concepts of the 21st century. IDS Discussion Paper, No. 296.

Chaurey, A., Ranganathan, M., Mohanty, P., 2004. Electricity access for geographically disadvantaged rural communities—technology and policy insights. Energy Policy 32 (15), 1693–1705.

DANE, 2000. Colombian National Department of Statistics 〈http://www.dane.gov.co/〉.

DEP, 2002. Dirección Ejecutiva de Proyectos, Ministerio de Energía y Minas del Estado Peruano, Law No. 27744, 31 May 2002 〈www.dep.mem.gob.pe〉. Accessed August 2002 (Spanish).

DFID, 2000. Sustainable Livelihoods Guidance Sheets. Department for International Development (DFID), London, UK.

DFID, 2002. Energy for the Poor: Underpinning the Millennium Development Goals. Department for International Development (DFID), London, UK.

Ellis, F., 2000. Rural Livelihoods and Diversity in Developing Countries. Oxford University Press, Oxford, UK.

Garcia, C., 1997. Metodología para evaluación de oferta y demanda de energía en zonas no interconectadas—Revisión 0. Ministerio de Minas y Energía y Unidad de Planeamiento Minero Energética (UNME).

Georgopoulou, E., Lalas, D., Papagiannakis, L., 1997. A multicriteria decision aid approach for energy planning problems: the case of renewable energy option. European Journal of Operational Research 103, 483–500.

Georgopoulou, E., Sarafidis, Y., Mirasgedis, S., Zaimi, S., Lalas, D., 2003. A multiple criteria decision-aid approach in defining national priorities for greenhouse gases emissions reduction in the energy sector. European Journal of Operational Research 146, 199–215.

Ghosh, D., Shukla, P.R., Garg, A., Ramana, V., 2002. Renewable energy technologies for the Indian power sector: mitigation potential and operational strategies. Renewable and Sustainable Energy Review 6, 481–512.

GLERS, 1990. Grupo Latinoamericano de Trabajo sobre Energización para un Desarrollo Rural Sostenible (GLERS). Energización para un desarrollo rural sostenible, Enfoque metodológico. Buenos Aires, Argentina.

Hobbs, B., Meier, P., 2000. Energy decisions and the environment. A guide to the use of multicriteria methods. International Series in Operations Research and Management Science 28, 100.

Huang, J., Poh, K., Ang, B., 1995. Decision analysis in energy and environmental modeling. Energy 20 (9), 843–855.

ICEL, 1994. Plan de energización de las zonas no interconectadas de la Orinoquía, Amazonía y Costa pacifica. Instituto Colombiano de Energía Eléctrica, Oficina de Planeación.

Kablan, M., 1997. Priorization of decentralized electricity options available for rural areas in Jordan. Energy Conversion and Management 38 (14), 1515–1527.

Kartha, S., Leach, G., 2001. Using modern bioenergy to reduce rural poverty. Report for the Shell Foundation, Stockholm Environment Institute.

Kolhe, M., Kolhe, S., Joshi, J., 2002. Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India. Energy Economics 24, 155–165.

Koroneos, C., Zairis, N., Charaklias, P., Moussiopoulos, N., 2005. Optimization of energy production system in the Dodecanese Islands. Renewable Energy 30, 195–210.

Mirasgedis, S., Diakoulaki, D., 1997. Multicriteria analysis vs. externalities assessment for the comparative evaluation of electric generation systems. European Journal of Operational Research 102 (2), 364–379.

Munda, G., Nijkamp, P., Rietveld, P., 1994. Qualitative multicriteria evaluation for environmental management. Ecological Economics 10 (2), 97–112.

NREL, National Renewable Energy Laboratory, 2003. HOMER, The optimization model for distributed power. Accessed 13/8/2004 〈http://www.nrel.gov/homer.default.asp〉.

Olalde, F.R., Quintana, P.C., Martínez, Y.I., Cherni, J.A., 2004. Hacia una perspectiva sobre el aprovechamiento eficiente de nuestros recursos en comunidades rurales azucareras. Revista Centro Azúcar Cuba 1, 34–41.

Polatidis, H., Haralambopoulos, D., 2002. Normative aspects of renewable energy planning; a participatory multicriteria approach. The International Society for Ecological Economics, Ecological Economics working paper series.

Santos, P., Linares, P., 2003. Metodología de ayuda a la decisión para la electrificación rural apropiada en países en vía de desarrollo. Universidad Pontificia Comillas, Madrid-España.

Smith, R., Mesa, O., 1996. A rural electrification expansion model. International Transactions in Operational Research 3, 319–325.

Smith R., Pulgarín, A., 2002. Optimización multiobjetivo con algoritmos genéticos: desarrollo de un modelo para electrificación rural. XI Congreso latinoiberoamericano de investigación de operaciones—Chile.

Smith, R., Mesa, O., Dyner, I., Jaramillo, P., Poveda, G., Valencia, D., 2000. Decisiones con múltiples objetivos e incertidumbre, 2ª edición. Facultad de Minas, Universidad Nacional de Colombia, Medellín.

Takase, K., 1997. The crises of rural energy in developing countries. In: Kaya, Y., Yokobori, K. (Eds.), Environment, Energy and Economy—Strategies for Sustainability. United Nations University, pp. 283–330.

UPME, 1999. Unidad de Planeamiento Mino-Energético, Ministerio de Minas y Energía, Línea base geo-referenciada para la formulación del plan de suministro de energía para las zonas no interconectadas de Colombia.

UPME, 2000. Unidad de Planeamiento Mino-Energético, Ministerio de Minas y Energía. Establecimiento de un plan estructural, institucional y financiero, que permita el abastecimiento energético de las zonas no interconectadas, con la participación de las comunidades y el sector privado.

Watson, S., Ter-Gazarian, 1996. The optimisation of renewable energy sources in an electrical power system by use of simulation and deterministic planning models. International Transactions in Operational Research 3 (3/4).

Yu, P.L., 1973. A class of solutions for group decisions problems. Management Science 19, 936–946.

Zeleny, M., 1973. Compromise programming. In: Cochrane, J.L., Zeleny, M. (Eds.), Multiple Criteria Decision Making. University of South Carolina Press, Columbia.