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# Fuzzy Decision-Making Approach for Sustainable Energy Planning in Isolated Regions: “Energy Fuzzy-On” Software Application

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The main aim of this paper is to evaluate a new software application to support experts involved in decision-making in the field of sustainable energy planning in isolated regions. The prototype named Energy Fuzzy-On is designed for this purpose. It implements various fuzzy concepts (fuzzy rules, fuzzified input data, fuzzy variables utilized by fuzzy terms and related fuzzy sets) chosen to obtain reasoning in case of unclear, uncertain, or even incomplete input data for reaching a conclusion about them. These data are input for a linear fuzzy multi-objective decision model developed in GAMS, where two objectives, environmental and economic objectives are minimized to obtain a set of non-dominated solutions. These solutions are used as input for a fuzzy multi-attribute model developed in the fuzzy toolbox of MATLAB. The environmental and economic criteria together with the social and technical criteria are used as inputs for choosing the most sustainable alternative. Finally, the tool is assessed in Medio Atrato-Chocó, a small, isolated village of West Colombia, where currently the energy service is supplied by small diesel generator sets. The selected and most sustainable solution, for a planning horizon of ten years, is composed of a hybrid system (54 % diesel generators, 39.3 % small hydro and the rest with gasification of biomass, from agricultural waste).

## 1. Introduction

Energy generation plays a decisive role in the socioeconomic and environmental development of any territory. A society with access to electricity creates conditions to improve social welfare (Gaye, 2007), education, income, health, and agricultural productivity (León Esteban et al., 2018). According to the World Bank (2021), considerable progress has been made since 2010 on various aspects of the Sustainable Development Goal 7, but progress has been unequal across regions. While more than one billion people gained access to electricity globally over the last decade, COVID’s monetary impact has made basic electricity services unaffordable for more than thirty million people, the majority located in remote places in Latin America and the Caribbean, South-eastern Asia, and Sub-Saharan Africa. Accelerating the pace of progress across all regions and indicators will require stronger political commitment, long-term energy planning, and adequate policy and scale incentives to spur faster uptake of sustainable energy solutions. Long-term energy planning should prioritise access to grids and the installation of new renewable capacity in isolated areas (World Bank, 2021). However, in many cases, the excessive cost of expanding the power lines usually leads to economically infeasible projects. In addition, remote areas and small isolated islands usually have a small energy demand per connection, so the national authorities are less inclined to connect these communities to the grid. As a result, the generation of energy based on local renewable sources becomes a solution with enormous potential (Gielen et al., 2019).
In Colombia, Law (1715) establishes a long-term energy capacity plan for promoting renewable energy sources and incentivizing investment. Also, several government entities have studied the possibilities of renewable energy development in remote areas; for example, the Ministry of Mines and Energy has proposed actions and challenges for the energization of isolated areas (with low income, reduced access to these zones, where the

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electrical supply service is characterized by adverse conditions such as: low coverage, reduced hours of service, typically supplied by diesel plants), with strategies such as the evaluation of sustainable investment projects of renewable energy and the improvement of energy efficiency practices (USAID, 2014). These projects suggest that the decision of choosing a sustainable solution for energy supply in isolated populations must include determining what, where, and when to build new generation units (Silva and Nakata, 2009).

However, it should be noted that there is no globally accepted approach or solution to choose a sustainable solution. On the contrary, the problem is overly complex, and the site-specific characteristics (e.g., geographical location) and technical details of a system affect the application and success of any given solution. Moreover, security of supply issues are major concerns that utilities usually face in developing countries. Due to this, sustainable, optimal and safe operations should be included in hybrid renewable energy systems, i.e., the integration of several types of energy generation equipment such as electrical energy generators, electrical energy storage systems, and renewable energy sources (Nazari-Heris and Mohammadi Iyatloo, 2018).

Several computer tools are available to assess hybrid energy performance, which aids the designer to analyze the integration of renewable sources. In Sinha et al. (2014), different computational simulation tools of hybrid renewable energy systems were analyzed, and their performance was compared. Computing tools and simulation programs/software are the most common tools for evaluating the performance of hybrid renewable energy systems. Using computer simulations, the optimum sizes for the components of a hybrid renewable energy systems can be determined by comparing the performance and energy production cost for different system configurations. Several software tools are available for this purpose, such as HOMER energy, $H_2$RES, RETSCREEN, Energy Plan, among others. In terms of modelling time-horizon, a multi-year outlook is seen to be most predominant among the surveyed tools (Chang et al., 2021). To our knowledge, no research deals with how to optimally select a hybrid renewable energy system prior to the design based on a variety of both quantitative and qualitative uncertain and imprecise interrelated criteria.

Mahmud et al. (2018) concluded that none of the existing available tools is applicable for analyzing all types of energy systems. Potential applications need to be further explored. Moreover, selecting an appropriate software tool for a particular energy-management system is a challenging task as there is little information available and several software tools to pick from. Each tool has its own strengths and limitations, and making a right choice is critical for accurate and feasible analyses. The development of models, algorithms, and computer facilities for the integration of the energy sector software programs should consider the integration of software models of the energy sector, related to the models' input and output data, assuring the uncertainty and consistency of data and studies. It is necessary to have planning tools that offer a working method that allows for the management of variables of interest, which uses the chain of energy simulation and optimization models developed for isolated areas. However, these tools are not enough to make the decision, because they do not take into consideration expert´s opinion (Quijano-Hurtado, 2012).

Multicriteria decision making analysis is perhaps the most appropriate tool for the holistic evaluation of the sustainability (Wang et al., 2009) since it allows for the understanding of the different points of view and supports the decision-making process by creating a set of relationships between the various alternatives, criteria, conflicting objectives, multiple interests, and perspectives. Most of these models leave aside the impression in the data and the opinions of those who make decisions. To address these problems and deal with this type of non-probabilistic uncertainty, there are systems based on fuzzy mathematic, to denote systems that exploit the tolerance for imprecision, uncertainty, and partial truth to achieve manageability, robustness, low solution cost, and better rapport with reality (Haber et al., 2014).

The novelty of this research is assessing a new soft computing tool, named Energy Fuzzy-On, to support experts involved in decision-making in the field of sustainable energy planning in isolated regions. Energy Fuzzy-On implements various fuzzy concepts chosen to obtain reasoning in case of unclear, uncertain, or even incomplete input data for reaching a conclusion about them. These data are input for a linear fuzzy multi-objective decision model, where two objectives, environmental and economic objectives are minimized to obtain a set of non-dominated solutions. These solutions are used as input for a fuzzy multi-attribute model. The environmental and economic criteria together with the social and technical criteria are used as inputs for choosing the most sustainable solution (Rosso-Cerón et al., 2021).

## 2. Energy Fuzzy-On description

The architecture of Energy Fuzzy-On is described in Figure 1, it is divided by two dashed lines: the left side shows the inputs for the tool; the center includes the components involved in the internal process (sub-tool Excel for processing parameters, sub-tool GAMS-General Algebraic Modeling System and sub tool-MATLAB) and the right side proves the outputs obtained with the graphical user interface. Energy Fuzzy-On offers users the ability to use optimization properties of GAMS and allows its execution directly in MATLAB, which controls all internal operations.

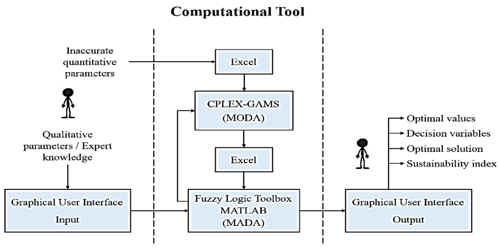


*Figure 1: Architecture of the computational tool (Energy Fuzzy-On)*

## 2.1 Sub-tool in GAMS for the fuzzy multi-objective decision analysis model

Energy Fuzzy-On software has a fuzzy multi-objective decision analysis model, which is based on a bottom-up model, which contains an energy demand module, an available energy resources module, and an energy conversion plants module (solar photovoltaic, wind generators, gasification of biomass, small hydro, traditional diesel engines, and transmission grids). Due to unavailability or imprecision of input required data (quantitative parameters: annual demand forecasting, new capacities, emission factor, fuel cost, investment cost, operation and maintenance costs, available energy resources, and the budget) over the decision horizon, Energy Fuzzy-On assumed them to be fuzzy in nature. These parameters were estimated from historical data obtained from the International Energy Agency, and Colombian institutions such as the Energy Mining Unit, the Bank of the Republic, and the National Administrative Department of Statistics. The general model consists of minimizing the total present value and the $CO_2$ emission, considering constraints of design, operation, and budget, Eqs. (1) and (2). The whole model and the proposed method of solution is described by Rosso-Cerón et al. (2019). The set of Pareto alternatives, decision variables, total present value and $CO_2$ emissions of the system are obtained in Energy Fuzzy-On using GAMS CPLEX solver and the Epsilon constrain method.

$$\text{Min } f_i(x) = \hat{D}_i x \quad i = 1, ..., k \tag{1}$$

$$\text{Subjec to}: \hat{A}x \le \hat{b} \text{ and } x \ge 0 \tag{2}$$

$\hat{D}_i$ is the vector of coefficients of the k-th objective function, $\hat{A} = [\hat{a}_{ij}]_{kxn}$ is a technological matrix, $\hat{b} = (\hat{b}_i, ..., \hat{b}_b)$ is the vector of available resources, and $x = (x_i, ..., x_n)t$ is the vector of the decision variables.

## 2.2 Sub-tool in MATLAB for the fuzzy multi-attribute analysis model

Energy Fuzzy-On considers the opinion of energy planning experts for assessing imprecise qualitative parameters, which are not easily calculable in the context of isolated areas (Rosso-Cerón et al., 2019): technological (efficiency, maturity, reliability, access routes), environmental (pollutant residues, land required, habitat impact) and social (job creation and social acceptance). Those parameters are employed in a fuzzy multi-attribute analysis model for classifying and choosing the most sustainable alternative from the set of Pareto. The fuzzy multi-attribute analysis model consists of three stages: fuzzification, inference systems, and defuzzification. With the fuzzification, the input parameters (criteria) and the output criterion (sustainability index) are transformed into fuzzy sets (degree of membership between 0 and 1, represented by linguistic terms and numerical scales). For the input criteria, the linguistic levels are low, middle, and high convenience, meanwhile for the output criteria the linguistic scale is low, middle, high, and remarkably high sustainable. The fuzzy inference system allows the association of the input criteria (C1: total present value/economic criterion, C2: technological criterion, C3: environmental criterion-including the $CO_2$ emissions, and C4: social criterion) of each Pareto alternative with the output criterion by using eighty-one logical rules (if then statement, Figure 2). The defuzzification (from fuzzy toolbox of MATLAB) is used to convert this result into crisps values.

## 2.3 Graphic user interface

When the interface is executed, a file menu appears with two options “New analysis” and “Exit” (Figure 2). New analysis allows deleting all the information in the window while the exit option closes the application and the other open windows. The option “Resource available in the area” allows the user to select the energy resource (solar, wind, hydro, biomass, diesel) available in the studied area depending on the situation. If the user wishes to analyze the extension of transmission grids, the option “yes” must be selected. If the user has selected none of the resource buttons, the platform does not allow the next stages. This window requires the entry of information in 3 editable text boxes of the parameters necessary for consensus (Delphi method): NE: number of experts, Betha: variable necessary for the consensus model (0.5 which implies the most likely scenario), IS: integration step for the

consensus model (0.1 is suggested). The next step is to press the “Add” button to generate the list of experts to consider, minimum 9. After selecting the expert to edit and clicking on “Edit”, the main window sends the user to the secondary window (to edit parameters) where the user must enter the relative index of the expert-RIE. Finally, “Save” is given, and the RIE is stored. The procedure is repeated with the rest of the experts. Also, there are two buttons that allow access to the other two windows, “Index” and “Alternatives”.
By clicking on the “Index” button, a window is created where the user must enter the values of the sub-criteria, evaluated by the experts, Figure 4. These values are added in global criteria (environmental, technological, and social). Finally, with the button “Alternative” (Figure 5), the user enters the value that each expert gives to each sub-criterion according to the technology available in the tested area (between solar photovoltaic, wind generators, gasification of biomass, small hydro, traditional diesel engines, and transmission grids). To finish, the “Calculate” button is pressed, which starts the internal processing (fuzzy inference system), the stage is displayed in a progress bar. The resulting optimal alternative is displayed, the sustainability index and the solution parameters: optimal ($CO_2$ emissions and total present value of the alternative-cost contribution matrix).

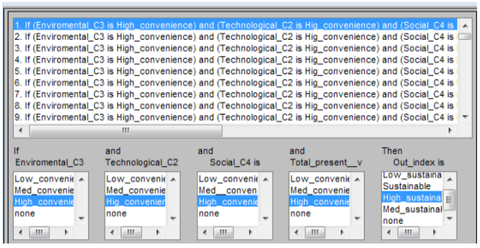


*Figure 2: Rules editor*

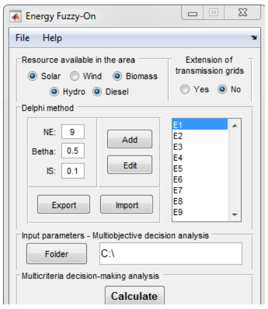


*Figure 3: Main window*

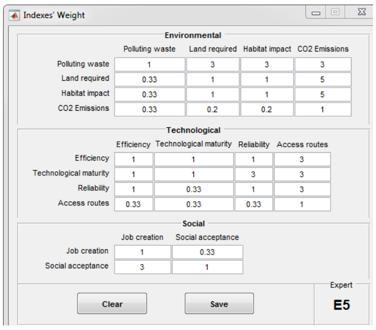


*Figure 4: Third sub-window-weight of sub-criteria*

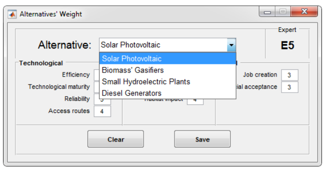


*Figure 5: Third sub-window-weight of alternatives*

## 3. Results and discussion

The computational tool was run on for the case of Medio Atrato-Chocó, a small urban isolated village in the west of Colombia. As reported by the SUI (2017), it belongs to a 100 % isolated zone. As the base year was selected 2014, when energy demand corresponded to 182,318 kWh, supplied with 204 kW of diesel generators. The village has a multi-annual average daily radiation between 4.0 and 4.2 kWh/m$^2$, for the possible use of solar source, rainfall, and average flow rates of 5,000 mm/y and 710 m$^3$/s, respectively, for the possible implementation of small hydro. In addition, the residual biomass potentials are around 20.9 GWh/y (62.3 % of plantain, 33.6 % of sugar cane and the rest of cassava). As waste for the possible implementation of biomass gasifiers was chosen the rachis, leaves, and discarded of the plantain. In addition, energy consumption per user (household), starting with 238,325 kWh up to 880,000 kWh in the last period, with annual rate of 20.92 %.
To illustrate the application of Energy Fuzzy-On, 12 Pareto alternatives were generated. In the Figure 6, the bar chart shows the energy matrix of each alternative of Pareto of the entire planning horizon provided by Energy Fuzzy-On. Renewables systems could take part in more than half of the generation matrix, from A10 to A12. Alternatives A2 to A12 involve the implementation and generation with small hydro plants, reaching its maximum contribution with renewables (64.1 %) with A12, while the contribution with diesel plants decreases to 35.9 %. This value is reflected in a diesel fuel saving of 51.96 % and an increase in the amount of solar photovoltaic of 26.2 % and 37.9 % of small hydro among the alternatives of the ends from the Pareto front.
The computational tool was applied and the alternative with the highest sustainability index was selected. The alternative with the highest sustainability index was the A8, with a value of 0.81, followed by A7, A10, A11, A6, A12, A5, A9, A4, A3, A2, and A1. The most sustainable alternative (8) consists of implementing 454 kW of small hydro, 60 kW of biomass gasifiers and 128 kW of diesel generators, to be installed in 2015, where the current diesel plant continues to operate as rolling reserve. These capacities are represented with a hybrid system matrix, diesel generators accounts for the half of the matrix and the rest are of small hydro with 39.3 % and biomass gasifiers with 6.2 %. The total present value of the system is also supplied by Energy Fuzzy On, and it is equivalent to 1.79 M USD, capital cost makes up 73.8 % of the total cost, and the rest of the cost is composed of exactly 10.9 % fixed operation and maintenance cost, 7.7 % fuel cost, and the rest for variable operation and maintenance cost. In relation to $CO_2$ emissions, the value is 2.21 kt for the entire horizon and a saving of 42.85 % in the amount of diesel consumed compared to the base year.

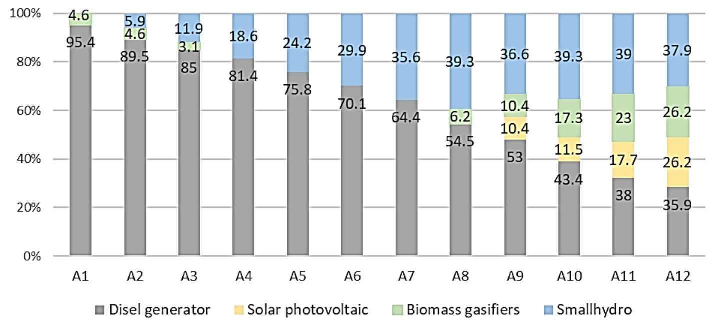


*Figure 6*: *Energy matrix of Pareto alternatives*

## 4. Conclusions

In this work is assessing a new software application to support experts involved in decision-making in the field of sustainable energy planning in isolated regions. The soft computing tool named Energy Fuzzy-On is a tool for aiding the integration of hybrid sustainable renewable energy systems. The tool consists of three sub-tools: one in Excel for the evaluation of quantitative parameters associated with energy systems; a fuzzy multi-objective decision analysis model developed in GAMS to determine Pareto efficient alternatives and a fuzzy multi-attribute analysis model to classify these Pareto alternatives, using qualitative parameters that represent the opinion of experts in the field of energy. To our knowledge no research deals with how to optimally select a hybrid renewable energy system prior to the design based in a variety of both quantitative and qualitative uncertain and imprecise interrelated criteria. The tool offers users the ability to use all the optimization properties of GAMS and allows its execution directly within MATLAB, which controls all internal operations. The qualitative parameters, necessary for the GAMS fuzzy multi-objective decision analysis model, are entered by the user, in an excel file, which is part of the tool. GAMS receives the quantitative parameters from excel, to execute the fuzzy multi-objective decision analysis model.

To test the effectiveness of the computational tool, the case of Medio Atrato-Chocó was established. Twelve Pareto solutions were obtained from the fuzzy multi-objective decision analysis model and then they are taken to MATLAB. The qualitative parameters, inputs from multi-attribute analysis model, are brought to MATLAB through the user interface. The fuzzy multi-attribute analysis model classifies the Pareto alternatives with the highest sustainability index. The best alternative consists of implementing 454 kW of small hydro, 60 kW of biomass gasifiers and 128 kW of diesel generators, to be installed in 2015, and the current diesel plant continues to operate as rolling reserve. The hybrid energy system matrix is composed by 54.4 % diesel, 39.9 % small hydro, and 6.2 % biomass gasifiers. The total present value is equivalent to 1.79 M USD, which are divided into 73.8 % capital cost, 10.9 % fixed operation and maintenance cost, 7.7 % fuel cost, and the rest corresponds to variable operation and maintenance cost. In relation to $CO_2$ emissions, the value is 2.21 kt for the entire planning horizon.

Although the application of the developed tool is conducted in isolated areas, it is also applicable to energy systems in other regions. As future work, it is expected to add a sub-tool for the selection of heating systems for paramo areas in Colombia.

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