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Environmental Sustainability Analysis of Technologies for Electricity Generation of Renewable Energy Sources in Non-Interconnected Areas from Colombia through the Use of Fuzzy Logic

Ana M. Rosso Cerón*, Viatcheslav Kafarov

Faculty of Chemical Engineering, Universidad Industrial de Santander, calle 9 carrera 27, Bucaramanga, Colombia
anarosso10@gmail.com

Environmental sustainability analysis of technologies for electricity generation of renewable energy sources (RES) was done using fuzzy logic, in order to compare and choose the best alternative for giving potential solutions to supply the electricity deficit in non-interconnected zones (ZNI per it initials in Spanish) from Colombia. The analysis took into account the availability of energy resources; energetic demand in each zone; and indicators of life cycle analysis (LCA) and environmental impact data from the literature. The results indicate that the small hydro technology is the first alternative on the departments of Amazonas, Caquetá, Chocó, Guaviare, Putumayo and Vaupés, while photovoltaic is the top in Guainía, Meta, Arauca, Casanare and Vichada.

1. Introduction

Nowadays, nearly 1.4 billion people still lack access to electricity (87 % of whom live in rural areas), and one billion has access only to untrusted networks of electricity. It is estimated that the capital investment needed to provide modern energy services to this population is on the order of $ 40 billion dollars per year until 2030. This represents about 3 % of the total investment in energy worldwide that is expected for this period (Grynspan, 2011).

In the Colombian case, approximately 421,000 households do not have electricity service, which 57% in not connect to the national grid (SIN per it initials in Spanish) (UPME, 2012), since most of these households are located in ZNI, characterized by low population density (4 %), public services limited and undeveloped, people's basic needs unsatisfied, covering almost 66 % of the national territory including nearby 1,200 settlements, 16 departments, 91 tows and 2 million people (Castro and Hernandez, 2010). Nevertheless, the implementation of renewable energy technologies for the generation of electricity in situ in developing countries is presented as a solution for these people who do not have this service (Zerriff, 2010).

The decision about choosing energy supply alternatives in rural populations has traditionally been from technical and economic criteria, leaving in the background the environmental issues (Rojas, 2012). The task of comparing this different alternatives in terms of their environmental issues, requires a tool that may take into account different qualities of environmental impacts (Eder et al., 2009). In this regard, several studies environmental analysis make use of three basic tools: environmental indicators (include topics such as: air, land and water), LCA (from cradle to grave) (Turconi et al., 2012) and further developed in (Pehnt, 2006), and multiple criteria decision methods (Wang et al., 2009) and then in (Liu, 2014). Regarding this last point, fuzzy logic, like criteria decision method, facilitates information management, due to it can be adapted a quantitative language in qualitative values and use logical rules that help describe several situations (Garcia, 2004).

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Consequently, this work evaluates and analyses, through fuzzy logic method, what electricity generation technology is more sustainable from an environmental point of view in ZNI. For this purpose, the current solution: diesel engine and renewable energy technologies (photovoltaic, small hydropower, wind turbines, and biomass combustion) were considered.

2. Study zones

Departments described by Law 788 of 2002 (Amazonas, Arauca, Caquetá, Casanare, Chocó, Guainía, Guaviare, Meta, Putumayo, Vaupés and Vichada) were chosen, since in these areas electricity facility is not permanent or even null, and in addition connection to SIN is almost impossible due to the distance to the national grid and geographical difficulties.

3. Power generation alternatives

With the aim of supplying the lack of electricity in ZNI have been established technologies such as generation from solar photovoltaic, wind turbines, small hydro, biomass combustion, and diesel engines, since ZNI has an average wind energy potential of about 6 m/s, a daily average solar potential close to 4.5 kWh/m^{2}y, water supply in terms of performance of 58 L/s-km^2, and the biomass source has a potential of 16 GWh/y (CORPOEMA, 2010).

4. Environmental indicators and citeria

The indicators for the environmental dimension were selected from the Department of Economic and Social Affairs **-**UNDESA that take into account air, land and water issues. These indicators were organized in two criteria: technological criteria, and demand-supply criteria and its values were quantified from literature sources relate to LCA (cradle to grave: extraction of raw materials, component manufacturing process, distribution and installation of technology, operation, maintenance, and disposal) and environmental impact for the assessed technologies, Table 1.

Table 1: Indicators of technological and demand-supply criteria

Indicator	**Value range per technology** Photovoltaic	Wind turbines	Small hydro	Biomass combustion	Diesel engine
Low and high technological criteria values (Evans, et al. 2009, Naddeo, et al., 2013, Turconi, et al. 2012; and Pehnt, 2006)					
GHG emission [g/kWh]	45-190	9-55.4	9-60	27-310	260-700
Nitrogen oxides (NO_x) emission [g/kWh]	0.17-0.34	0.04-0.31	0.03-0.37	0.05-2.5	0.82-0.9
Sulfur dioxide (SO_2) emission [gr/kWh]	0.30-0.40	0.03-0.11	0.03-0.07	0.05-2.5	0.23-6.0
Particulate matter (PM) emission [g/kWh]	0.09-0.15	0.04-0.10	0.02-0.10	0.01-0.1	1.28-1.4
Water consumption [m^3/kWh]	0	0-1	0-0.02	1.1-2.1	0
Land use [m^2/kWh]	16-64	30-60	13-75	3-10	1-9
Waste generation [kg/kWh]	0	0	0	1,500-2,220	0
Low and high demand-supply criteria values					
Availability of resources	Solar radiation	Wind speed	Water potential	Waste biomass potential	Diesel market in ZNI
	2.5 - 7.0 [kWh/m^2]	0 - 11 [m/s]	Very Low, Low, Medium, High, Very High	0 – 11,000 [TJ/y] biomass permanent	2,000-900,000 [barrels / month]
Energy demand	0 – 3,300 [MWh/y per household], estimated from number of households without power from UPME, (2011) and the average energy consumption per household (kWh/month) (UNAL, 2006).				

5. Fuzzy logic method

In this stage, the indicators categorized under two criteria were assessed using the fuzzy logic tool MATLAB. In the case of technological criteria, were established as input variables, the nine values of each indicators (Table 1), and like output variable the % of technology assessment, which indicates the degree of impact on the environment (a higher value less impact).

5.1 Technological criteria assessment

The fuzzification of each input variable was made using two membership functions; one to describe low values of each indicator and other for high values. In the description of low values was taken the Z-shaped membership function (zmf), and for describing the high values was taken the S-shaped membership fun function (smf), were the value of a is equal to zero and the value of b equals the maximum value of the designated range each indicator, Figure 1.

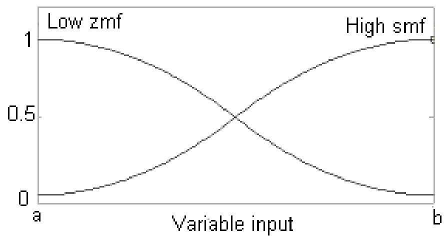


Figure 1: Fuzzification of the input variables

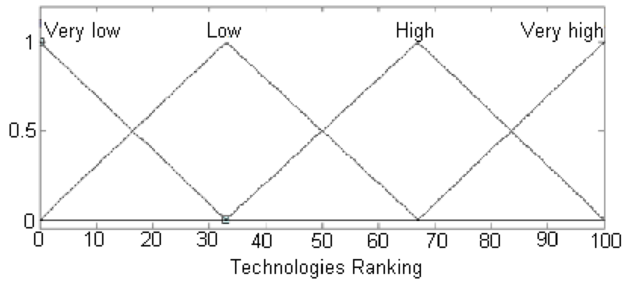


Figure 2: Responses of the output variable

The next step consisted in assigning the rules that define the system; the number of possible combinations (rulers) were 128 (2^n), where 2 indicates a binary system (low-high, from inputs) and n is the number of indicators.

The defuzzification of the results obtained from the rules set above and the output variable technology assessment was described using triangular-shaped membership function, which describe four categories per indicator: very low (6 - 7), low (4 - 5), high (2 - 3) and, very high (0 - 1), over a range of 0 - 100 %, Figure 2.

5.2 Supply-demand citeria assessment

The fuzzification of the input variables uses the same membership functions described for technological criteria; however supply-demand criteria used only two rules: the first represents the worst case scenario, poor supply and high demand result low assessment and the second represents the best scenario, higher supply and low demands result high assessment. The defuzzification is represented by the output variable "supply and demand" through zmf for describing low values and smf for describing high values

6. Formulation of the decision matrix (choice of alternatives)

The value of environmental sustainability is calculated by multiplying the values of the evaluation criteria of each alternative. These values allow establishing a ranking of the best alternatives being the best you get the highest score of the evaluation of environmental sustainability.

$$\begin{array}{c|c} & \begin{matrix} A_1 & A_2 & \cdots & A_n \end{matrix} \\ \hline \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_m \end{matrix} & \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & & x_{2n} \\ & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \end{array} \quad (1)$$

Where A is the alternative, C the criteria, and i the criteria value assessed for the j alternative.

7. Sensitivity analysis

Sensitivity analysis was performed removing technological indicators of water consumption and waste generation, since its value is zero in most of the technologies evaluated. Then the number of input variables was decreased up to 5 and the number of rules up to 32 combinations. Nevertheless, fuzzification was kept equal, but the number of categories responses decreased up to 3 High (0 - 1), medium (2 - 3) and low (4 - 5), over a range of 0-100 %, Figure 3.

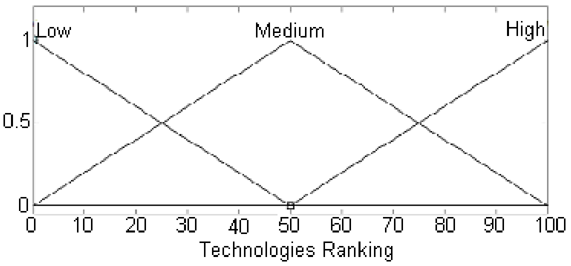
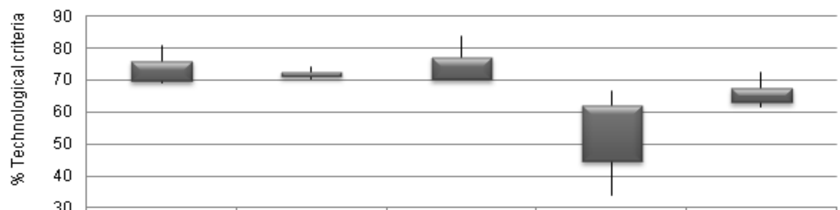


Figure 3: Response to the output variable of the sensitivity analysis

8. Results and analysis

Box plot shows (Figure 4) technological criteria ranges for each technology, where most of the combinations assessed (68 % of the data) are concentrated. It is noteworthy small hydro, photovoltaic, and wind turbines have the highest values with average of 74 %, 73 %, and 72 %, due to the low values of GHG, NOx, SO2, and PM emissions, on the other hand diesel engine and biomass combustion have an average of 65 % and 53 %, since the high value of emissions and a nonzero value in waste generation indicator.



	Photovoltaic	Wind turbines	Small hydro	Biomass combustion	Diesel engine
Opening	76	72	77	62	67
Maximum	81	74	84	67	72
Minimum	69	71	71	34	62
Closing	70	71	70	45	63

Figure 4: Diagram of technological criteria assessment

The results of the supply-demand criteria are shown in Figure 5; the departments of Meta, Putumayo and Amazonas have the best scenarios for implementation of the alternatives assessed, since the demand is low and the supply is high. In the cases of Meta the best option is biomass and diesel engine, in contrast for Putumayo and Amazonas the best option is small hydro.

In Chocó and Caquetá the best choice is the hydropower, since they have the worst scenario.

On the other hand, photovoltaic result the first choice in Arauca and Guainía, while wind turbines is not feasible due to the limited availability of the resource in the zona (wind speed under 4 m/s).

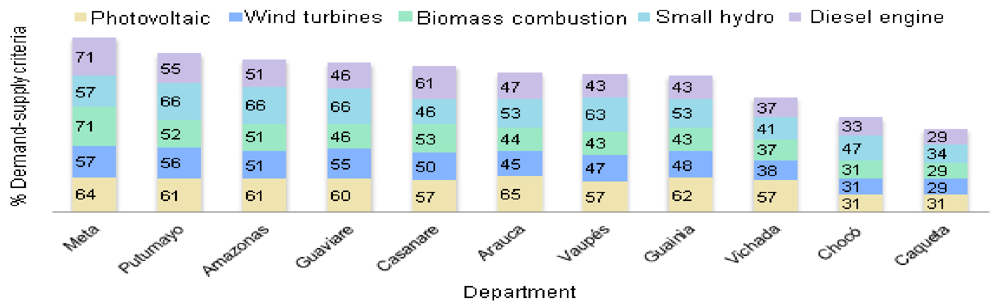


Figure 5: Demand-supply criteria ranking in ZNI

Figure 6 shows the results of the analysis of environmental sustainability, which was obtained from the decision matrix. It can be seen that biomass combustion have the lowest values of sustainability in all departments, even in those departments where the standard supply and demand for this technology was high like Meta and Casanare, due to GHG, NO_X, SO_2, and PM emissions and waste generation values are too high. On the other hand, diesel engines have better yield than biomass combustion, since has high supply and waste generation indicator is zero.

Wind turbines have less sustainability values than diesel engines in Arauca, Caquetá and Meta departments, since supply-demand criteria become predominant on the technological.

The small hydro is the best option for the departments of Amazonas, Caquetá, Chocó, Guaviare, Putumayo and Vaupés, because it has lower emissions than the other alternatives and the high water potential.

In the department of Caquetá options small hydro, photovoltaic, wind turbines and diesel engines have similar environmental sustainability values, which mean that any alternative can be used.

Finally, in the department of Chocó and Vichada, the best options are small hydro (35 %) and photovoltaic (42 %).

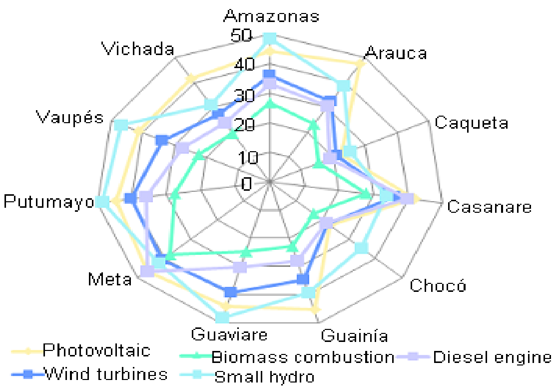


Figure 6: Radial scheme of environmental sustainability assessing

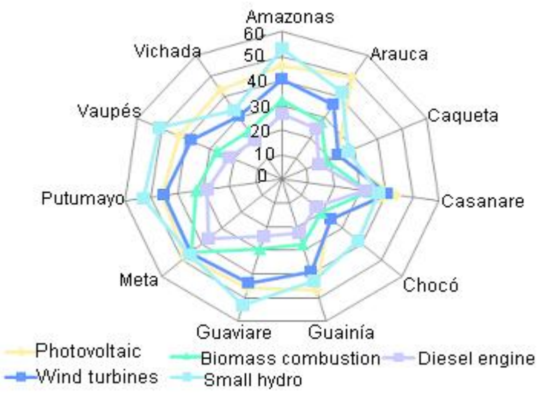


Figure 7: Radial scheme of environmental sustainability assessing of the sensitivity analysis

Additionally, in Figure 7, it is observed that small hydro, photovoltaic, and wind turbines remain the same ranking in each department; however diesel engine becomes the worst performance in all departments because it has the highest values on emissions.

With relation to sensitivity analysis, Figure 8 shows the results for technological criteria. Photovoltaic, wind turbines and small hydro alternatives remain the same trends when this criteria is performing with five indicators, but the value of combustion biomass increases and changes to the last place the diesel engine.

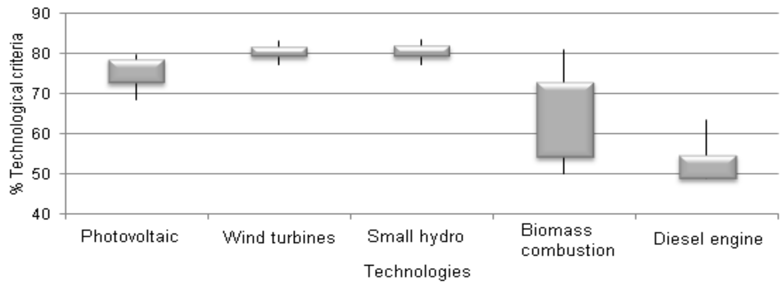


Figure 8: Diagram of demand-supply criteria assessing of the sensitivity analysis

9. Conclusions

The use of fuzzy logic method facilitates multi-criteria analysis that allows the interaction of quantitative values with qualitative characteristics, enabling a better interpretation of the data obtained from the evaluation of each criterion.

Electricity supply in ZNI considering the environmental point of view, constitute major alternative technologies small hydro, photovoltaic and wind turbines, leaving in background the biomass combustion and diesel engine, since the low availability of the resource in all departments which are part of this study, except the departments of Meta and Casanare.

Excluding water consumption and waste generation on environmental indicators for sensitivity analysis, technology diesel generators became less sustainable and combustion of biomass to get better results, since the high values of the emissions indicators.

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