PROBABILITIES AND FUZZY SETS IN THE MARKET EVALUATION OF RENEWABLE ENERGIES - THE SOLARGIS EXPERIENCE

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Abstract - This paper presents the methodology developed for the SOLARGIS project - an EU JOULE project for the integration of renewable energies in dispersed electricity production, supported in a GIS platform. The paper discusses the methodologies for the assessment of the efficiency and market of isolated system for dispersed rural electrification. The models form a mix use of probabilistic and fuzzy set concepts in representing resource and planning uncertainties.

Keywords - Dispersed Generation, Renewable Energies, GIS, fuzzy, Planing, Wind, Photovoltaic.

1. INTRODUCTION

The policy defined by the European Union (EU) towards the New Renewable Energies (NRE) can be considered a success: for instance, the increase of wind energy penetration in the EU is noticeable and grew together with the enlargement of the technological offer and the decrease in specific costs. Talking about 1 MW wind generators is not surprising nowadays, when only a few years ago we were still at the level of tens of kW. Today, the EU industry dominates the world market in the offer of reliable and economic wind generation solutions. Wind generation became, in many cases, directly competitive with conventional generation. This explains why in Europe the words "alternative energies" are scratched out from the engineering and public domain vocabulary - common engineering practice must take in account NRE together with conventional generation in order to optimize solutions, with no discrimination (NRE are adopted not because of any ecological fundamentalism, but because they prove to be the adequate option).

The world market for NRE is very important and developing countries represent an important share: due to the incomplete electrification of their territories and the extensive use of not so cost effective generation solutions (diesel generation is extensively used, and constraints in financing lead to the adoption of options with smaller investment but with higher running costs), the NRE and the dispersed generation solutions have a true economical opportunity to originate innovative distribution system expansion schemes and policies.

Under the JOULE program of the EU, a consortium of institutions developed a project called ***SOLARGIS***, aiming at **the identification**, in a region, **of the right technologies** for distribution network expansion **and the places economically feasible** for each one. Extensively supported on a GIS (Geographical Information System), the ***SOLARGIS*** approach has been tested in six regions in the world, three in developed countries (Andalucia, Spain; Sicily, Italy; Crete, Greece) and in three developing countries (Tunisia; India; Cabo Verde).

The ***SOLARGIS*** project is described in detail in [1, 2].

Examples and descriptions may be found at

- http://www.inescn.pt/~lproenca/solargis/solargis.html
- http://www-cenerg.cma.fr/~st/solargis.html

The ***SOLARGIS*** consortium is composed of:

- ARMINES, France
- CIEMAT, Spain
- CONPHOEBUS, Italy
- CRES, Greece
- INESC, Portugal
- NMRC, Ireland
- RAL, United Kingdom

The paper will be mainly devoted to the definition of an electrification policy in developing regions, where the traditional grid expansion scheme may compete with unconventional dispersed generation.

This paper includes a short description of the main characteristics of the project, and refers to the combines use of probabilistic models and fuzzy models to represent uncertainties in the decision aid environment provided. The probabilistic approaches are specially used to model energy resources, such as wind energy availability, which will be the center example of the paper. Fuzzy models have two roles: in a smaller scale, they are used to reflect the inaccuracy of wind models in the results; in a larger scale, they are used to model uncertainties about energy demand and technological or implementation costs.

2. RESOURCE IDENTIFICATION

One of the most important preliminary tasks in SOLARGIS is the mapping of the available solar and wind resources, by building grids for renewable energy resources.

2.1. Wind

For Cabo Verde, we have adopted the WA^{S}P model[3] to derive the wind potential. We have prepared the orography and roughness data in the GIS and exported them to the WA^{S}P software. Wind speed series obtained at meteorological stations have also been introduced and treated taking in account physical obstacles around the stations.

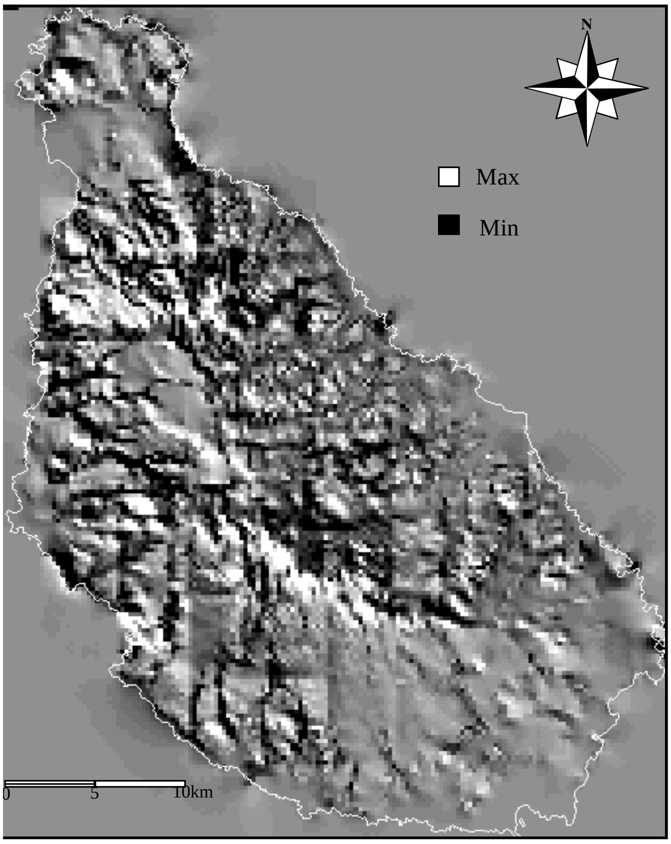

Figure 1 *Annual mean wind speed grid at 10 m in Santiago Island, Cabo Verde*

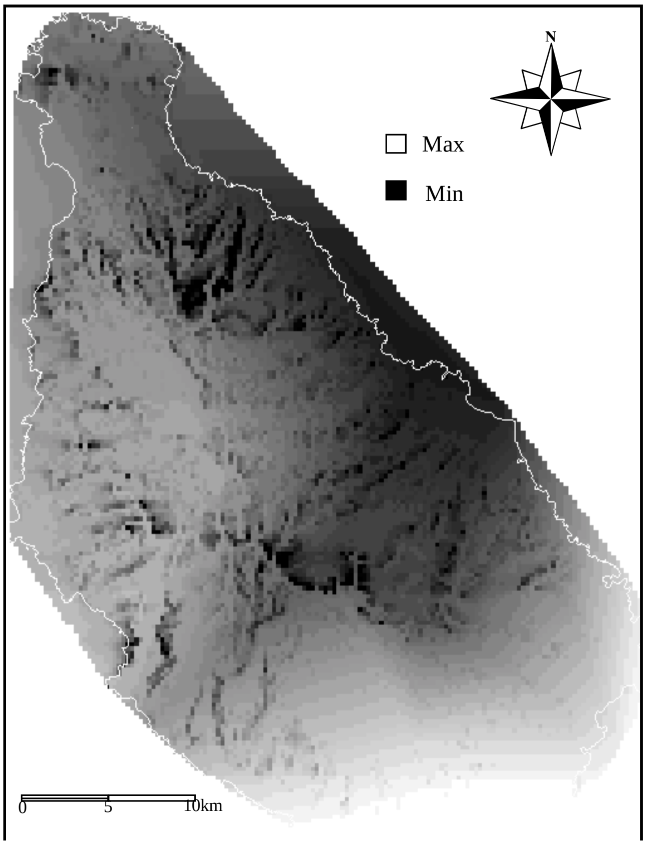

Figure 2 G*lobal irradiation grid for a specific month*

We obtained from the WA^{S}P model the scale and shape parameters for Weibull distributions for the average wind speed in a grid over the regions under study, and exported them to the GIS in order to build the wind grids for the islands (Figure 1).

2.2. Solar

To map the available solar energy resources in Cabo Verde islands, an innovative method was developed:

1. Calculate, for a clear day, the beam and the diffuse irradiance I_b and I_d on a solar panel, taking in account: altitude, visibility, climatic zone, orography, angles between solar rays and terrain slop, panel inclination, ground albedo, shadows.
2. Find, for each hour of the day, a global irradiation grid GIh.
3. Integrate along a typical day in each month the hourly global irradiation grids, to give the grid of monthly global irradiation on clear day, GHhc.
4. Compare the calculated grid values GHhc with measured values Hh at meteorological stations and determine a attenuation factor Ktc=Hh/GHhc and define an attenuation grid GKtc
5. Do GKtc x GHhc to obtain a global irradiation grid GHh.

Figure 2 displays an example of a irradiation grid showing the effects of local climate, orography and shadows.

3. ISOLATED SYSTEMS - Potential Markets

We refer to isolated systems as the ones that are not connected to the main electric network. We have considered several types of systems as a solution to rural electric power supply: individual systems supplying houses or medium size systems supplying groups of consumers like small towns. The isolated systems considered by SOLARGIS are composed of:

- Small individual Photovoltaic (PV) Systems powering isolated houses. Those systems include batteries to store electric energy and an inverter, if necessary, for supplying AC loads.
- Small individual wind energy systems powering isolated houses. Those systems, as the previous ones, include batteries and inverter.
- Small individual systems, wind or PV with no storage, for water pumping
- Small Diesel or Gasoline Generators (named GD and GG), supplying isolated houses. Those systems are used to compare the performance of renewable and non renewable sources of energy.
- Wind/Diesel systems (W/D) to supply small towns. The W/D systems we mention are medium dimension (between 30kW and 300kW), supplying little LV networks. They include a diesel generator, a wind energy generator and other auxiliary equipment such as batteries, charge controller, inverters, emergency power supply, etc.

- Diesel systems to power small towns. They have the same dimension of D/E systems. They use the same type of equipment, except for the wind energy generator.

Besides isolated systems, we also considered the costs of network expansion, in order to compare all the electrification solutions. In this calculation we admited that a medium voltage (MV) line would supply the secondary substation of the group of consumers that could alternatively be supplied by diesel and W/D systems.

The Leveled Electricity Cost (LEC) for small systems powering individual charges is calculated using the annualized costs, i.e., year equivalent costs deduced from tha application to investments of opportunity cost rates or expected internal return rates. In this case, we have: the generator annualized cost C_{ger}; the batteries, C_{bat}; the inverter, if needed, C_{inv}; yearly fuel consumption whenever used, C_{com} and a tax of CO_2 emission, C_{co^2}.

$$LEC = \frac{C_{ger} + C_{bat} + C_{inv} + C_{com} + C_{CO2}}{AES}$$

Some of those costs depend of the accessibility of each particular place.

The ratio between the maximum possible energy to be generated and the Annual Energy Supplied (AES) to the load is the *performance factor*, typical for each particular technology. We used experimental performance factors in each case.

The LEC for Diesel systems and for W/D systems, supplying consumer groups through a low voltage network (LV), can be computed like this:

$$LEC = \frac{C_{WT} + C_D + C_{bat} + C_{inv} + C_{com} + C_{CO2} + C_{LV}}{AES}$$

For this type of systems, we have wind turbine costs and diesel generator costs. The fuel cost reflects the system performance. For each place we will have a typical consumption curve that reflects the generator characteristics, wind energy or diesel.

In W/D systems, the fuel consumption curve depends of the probability density function of the load (normal) and the probability density function of the wind speed (Weibull).The cost of the low voltage network powered by this system is called C_{LV}. The length of this network can be computed by a model implemented in GIS, which is a function of electric load density, not described in this paper.

To allow the comparison of several electrification solutions, we also calculate the LEC for a conventional solution of connection to the nearest electric network. This calculation includes the existing network costs as well as the costs of connecting the new secondary substation and the network using low voltage.

The final step is a comparison between the several alternatives in order to create a competitiveness map. After finding the best system for each place, one may estimate and map the potential market for each renewable energy system.

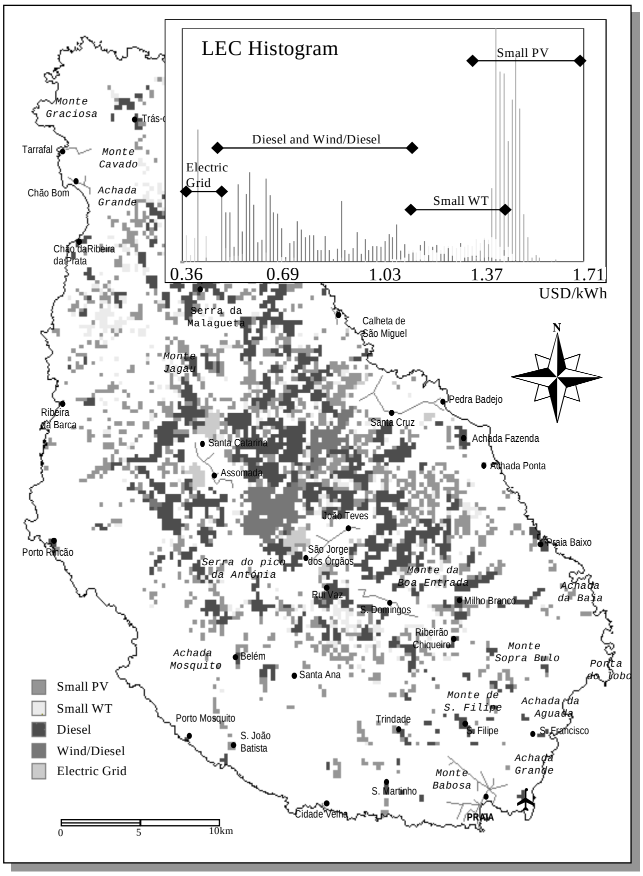

Figure 3 *Competitiveness map and LEC histogram showing the map of potential market - the best options in each location - and the energy price produced per each system, also taking in account the best option in each grid element, for Santiago Island*

Figure 3 gives us an example of competitiveness maps. The following scenario refers to actual equipment prices.

We consider that individual systems in Cabo Verde are capable of powering 400 Wh per day. The dimension of systems is computed according to the load.

For Diesel and W/D systems we consider that the generator has a power that equals twice the average load required by a particular consumer group.

The wind energy generators of W/D systems will have a power capacity that equals 1,5 times the average charge. This average is calculated using the population density function and an average consumption of 30 kWh per capita yearly (historical data for rural populations).

Regarding regions with a higher population density and located near the electric network, it may be feasible to expand the network.

The Wind/Diesel systems are usually feasible only in areas with good wind resources as well as high population density. The individual systems are quite expensive, say between 1,05 USD/kWh and 1,7 USD/kWh. However, they are the best solution for isolated areas with small population density.

4. UNCERTAINTY MODELS FOR SMALL STAND ALONE SYSTEMS

In the ***SOLARGIS*** approach, we have modeled the energy resources, such as wind availability, by a probabilistic model. Also, the behavior of each load has been modeled by a normal distribution around some central estimated value.

Other types of uncertainties must be considered, however.

First of all, the models that derive the wind availability are not exact: therefore we have associated some fuzzyness to the results of the model, namely to the scale factor A of the Weibull distribution giving wind speeds in each grid element. The same has been done to the average value (made fuzzy) of the global radiation in each grid element.

Second, we have associated fuzzyness to the average load value in each grid element. Third, we have defined several costs as fuzzy numbers, expressing lack of knowledge on their actual value; these include fuel costs as well as equipment costs.

We have therefore a decision aid environment that incorporates a mix probabilistic-possibilistic modeling.

The (fuzzy) LEC calculations are based in a four step procedure.

4.1 Energy delivered by power sources

The energy production is dependent of a system capacity factor CF and energy resources on site. It is a p.u. value obtained in each case by dividing the rated generator power by the average supplied power.

Wind system

Based on large series of measures at the meteorological stations we derive distribution probability functions (Weibull) for the wind speed, namely the characteristic parameters *A* (scale) and *k* (shape). With a wind model WA^{S}P we interpolate the Weibull distributions in each geographical grid site to obtain a global region picture. The CF parameter is estimated from

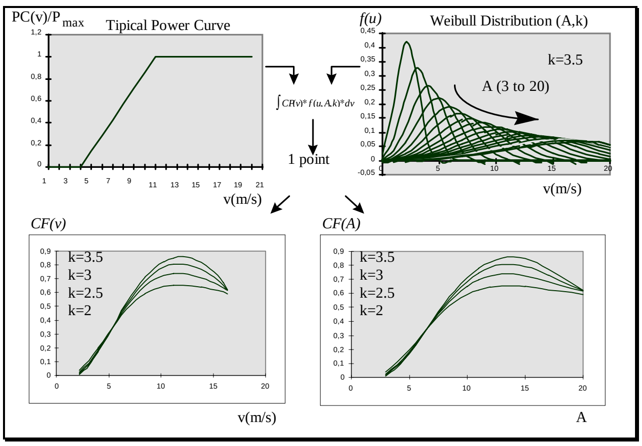

Figure 4 ***Methodology for constructing the CF curve.***

$$CF_k(A) = \frac{1}{P_{\max}} \int PC(v) * f_{A,k}(v) \cdot dv$$

where the curve *PC(v)* is a typical wind turbine power curve that represents the wind turbine production as a function of wind speed *v* and the function $f_{A,k}(v)$ is the Weibull probability distribution function of the wind speed at each specific site (Figure 4). The capacity factor curve *CF(A,k)* facilitates further calculations in the GIS.

The wind model results are less affected by imprecision at locations near the meteorological stations and on flat and homogeneous land.

We used triangular fuzzy numbers to describe the A uncertainty with a location dependence. Thus, the *CF* expectancy is a fuzzy number whose membership function is given by

$$\mu(CF_k) = \max\{\mu(CF_k(A)),\ \forall_A : CF_k = CF_k(A)\}$$

The functions CF_k are non-linear, as seen in Figure 4. Therefore, the fuzzy CF are not triangular even if raw fuzzy data are expressed as simple triangular numbers.

Solar system

In a specific photovoltaic panel, with area S, efficiency η_{stc} in standard test conditions and with annual mean global radiation G_h (kWh/m^2/year), the annual energy produced *AEP* is a fuzzy number whose membership function is derived from the fuzzy description of the radiation G_h :

$$\mu(AEP) = \mu(G_h)\ ,\ \ AEP = G_h * \eta_{stc} * A$$

The global radiation is geographically evaluated using the interpolation model described in 2.2. Similar to the wind models the result uncertainty increases with the distance to the meteorological stations.

4.2 Sizing

Based on the system production and load characteristics we estimate the nominal size of the system. The load curve characteristics can be described in a probabilistic way when we have a big number of consumers. However in our approach the number of consumers inside each grid element can be very small.

Thus we modeled the annual energy consumption as fuzzy number defined by its membership $\mu(AEC)$, which is calculated from the annual energy produced *AEP* and the performance factor *PF* and is given by:

$$AEC = AEP * PF \ \ \textit{(fuzzy multiplication)}$$

The performance factor is experimental value deducted from past similar system history and can be described as a fuzzy number also (representing a range of actual possibilities). For each of the possible systems we have the following fuzzy expressions, in the sections below.

Wind system

We admit availability energy storage for reserve time *(RT)* of one week. In these conditions the wind turbine fuzzy nominal power P_n is given by:

$$P_n = \frac{AEC}{FC * PF * 8760}$$

The battery fuzzy nominal capacity C_b is given by:

$$C_b = \frac{AEC * 1.2 * RT}{PF * 8760 * 0.8}$$

(coefficient 1.2 is a safety factor; coefficient 0.8 is a discharge depth).

Photovoltaic system

The fuzzy peak power P_{PV} for the array is given by:

$$P_{PV} = \frac{AEC}{G_h * PF}$$

Diesel system

We size the diesel systems for supplying the mean load with 60% of their capacity. We define for each diesel system a fuzzy annual work duration *AWH*, in hours (which is related to its useful life time). The rated power P_h is then

$$P_n = \frac{AEC}{AWH * 0.6}$$

4.3 Investment estimation

The specific annual cost for each system is dependent of the market conditions and nominal power of the system.

The membership function for fuzzy investment I is calculated as showed in Figure 5 (where the fuzzy I of several distinct technologies is exemplified), taking in account that

$$\mu(I) = \mu(y) \quad , \quad \forall Pn: y = I(Pn)$$

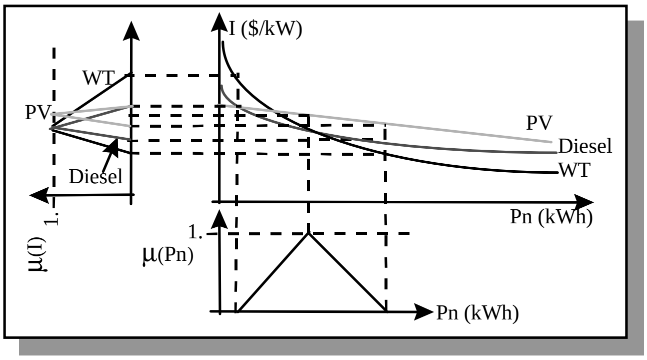

Figure 5 *Constructing the membership function for the specific cost of several technologies*

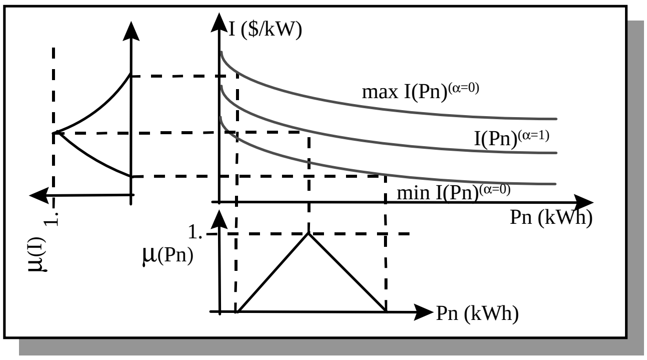

Figure 6 *Constructing the membership function for a specific cost based fuzzy curve.*

where $y=I(Pn)$ denotes any of the functions relating the nominal Power with the specific cost per kW, for the several technologies (curves obtained from suppliers).

The PV systems are composed by modules, thus the specific investment is practically constant. The specific investment for wind and diesel systems decreases for larger systems. As we can see, the uncertainty for diesel and wind systems is very high when we supply (uncertain) small loads.

As we can see in Figure 6 if the cost curve is also fuzzy the new membership function for the specific investment is characterized by having, at each membership level α, an interval definition I_α such as

$$I_\alpha = \bigcup \left\{ \min I_\alpha(Pn), \max I_\alpha(Pn) \right\}, \forall Pn \in Pn_\alpha$$

where Pn_α represents the interval or α-cut at level α of the fuzzy load *Pn*.

4.4 LEC calculations,

The LEC is calculated as a function of the annual costs of the system components and the capacity factor. All investment factors are therefore reduced to year costs or annualized values by operating as usual with expected internal return rate values. The following equation relates to operations on fuzzy parameters obeying the rules of fuzzy arithmetic:

$$LEC = \frac{I_{ger} * Pn + I_{bat} * C_b}{AEC} + F_p * F_c$$

The fuzzy LEC for each individual system is calculated using the fuzzy annualized investments of the generator I_{ger} as well as the batteries investment I_{bat}, fuzzy fuel price *Fp*, a typical fuel consumption for diesel F_c. The membership functions for these numbers may be very simple (triangular), based only on a most credible value and on an interval of accepted values (such as defined by the sentence: *the likely cost of a generator of type X will be 10, and the cost will not be below 9 or above 12 monetary units*). More basic still, they could describe just intervals of uncertainty about the costs or loads. On the contrary, more elaborate linguistic/fuzzy interfaces may be used. It is out of the scope of this paper, however, to describe these in detail.

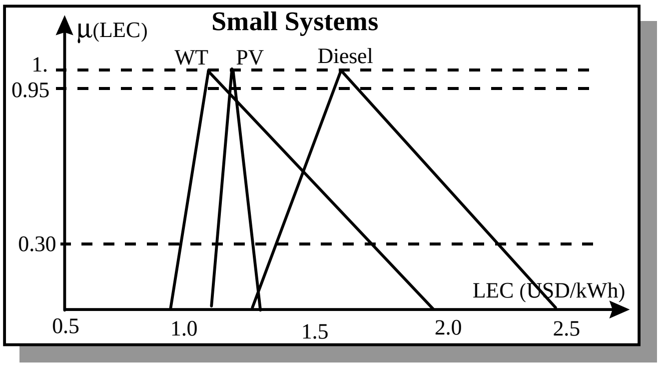

Figure 7 *Fuzzy LECs for a specific grid element depending on the technology adopted*

As a result, we get a LEC map described by fuzzy numbers. We have therefore a fuzzy description of the best system in each place. According to the results of this methodology, there can be several electric power solutions in the same grid element.

The user can define a range of uncertainty and observe the impact of each parameter in the final results. This allows him to evaluate the risk component of the decision making process. As we can see in Figure 7, for a low degree of uncertainty (α-level 0,95) the WT system is a robust solution. However, for a high degree uncertainty (α-level 0,3) all systems can be considered as alternatives for that grid element.

In order to reach a final proposal, for each grid element, we adopted a defuzzification procedure based on the TDC (Total Distance Criterion) [4]. It is a technique that may allow us to introduce a parameter value favoring either risk aversion or risk attraction, and this flexibility is regarded as most convenient in decision aid environments such as SOLARGIS.

With the defuzzified results, we have available a suggestion for the most convenient technology at each location, taking in account uncertainties in data.

6. CONCLUSIONS

The SOLARGIS methodology allows one to readily identify the business opportunities for renewable, and develop new concepts for system planning and electrification. The assessment of the market potential and market value for Renewable is also an important result, both for manufacturers and for politicians, allowing the development of new industrial and commercial activities and new concepts in territory electrification.

The visualisation of the results with a GIS enhances the understanding, by planners, of the consequences of the options under consideration. We have now available a tool that can systematically screen out a region and help distribution system planners to understand all the possibilities at hand and their economic impacts.

This paper has described, with the possible level of detail, one of the additions of the INESC team for the SOLARGIS methodology: the modeling of uncertainties, either in load growth or load dispersion, or in costs such as fuel or equipment, using a fuzzy set description. This fuzzy modelling had to be married with probabilistic descriptions of primary renewable energy resources, building a mixed probabilistic-possibilistic model for uncertainties.

By representing each type of uncertainty with the most adequate model, the *SOLARGIS* platform becomes a true decision aid environment, useful both for utilities and for policy makers and with application either in industrialized countries or in developing regions.

ACKNOWLEDGEMENT

The authors wish to express their public gratitude for the full cooperation obtained from ELECTRA, the public utility in Cabo Verde.

They wish also to thank IICT - Instituto de Investigação Científica Tropical, Lisbon, Portugal, for the support given in the data collection procedure.

A special word is also addressed to all members of the SOLARGIS team, for the sound friendship forged during the days of challenging work and cooperation developed.

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